

Exploring the Role of Additive Manufacturing in the Prosthetic Supply Chain: Qualitative Evidence

Abstract

Purpose – This study aims to evaluate the enhancement in prosthetic supply chain capabilities resulting from the implementation of additive manufacturing (AM) technologies. The study presents an emerging model outlining the key areas that undergo changes when integrating 3D printing technologies into the prosthetic supply chain.

Design/methodology/approach – Employing a qualitative approach, data were collected through field observations and 31 in-depth interviews conducted within various Jordanian organizations associated with the prosthetic industry and 3D printing technologies.

Findings – The findings suggest that the adoption of 3D printing technologies improves the prosthetic supply chain's capabilities in terms of customization, responsiveness, innovation, environmental sustainability, cost minimization, and patient empowerment. The study sheds light on the specific areas affected in the prosthetic supply chain following the adoption of 3D printing technologies, emphasizing the overall improvement in supply chain capabilities within the prosthetic industry.

Practical implications – This study provides recommendations for governmental bodies and prosthetic organizations to maximize the benefits derived from the use of 3D printing technologies.

Originality/value – This study contributes as the first of its kind in exploring the impact of 3D printing technology adoption in the Jordanian prosthetic industry, elucidating the effects on the supply chain, and identifying challenges for decision makers in an emerging market context.

Keywords: Additive manufacturing; Supply chain; Prostheses; Prosthetic supply chain; 3D printing; Jordan.

Paper type: Research paper.

1. Introduction

Advanced technologies such as additive manufacturing (AM), artificial intelligence (AI), Internet of Things (IoT), and blockchain in supply chains lead to cost savings, optimized logistics, improved accuracy, and increased trust among stakeholders, thereby driving competitive advantage and customer satisfaction (Younis *et al.*, 2024). In recent years, AM has emerged as a standout technology compared to other advanced manufacturing techniques, offering unique advantages in customization, material efficiency, and rapid prototyping. AM, often referred to as 3D printing, is a revolutionary process that constructs objects layer by layer, allowing for unprecedented design flexibility and efficiency in creating complex geometries (Kunovjanek *et al.*, 2022). AM has found applications across various industries due to its versatility, cost-effectiveness, and ability to produce complex geometries. In aerospace, AM is used for lightweight and durable aircraft components, reducing fuel consumption and maintenance costs (Ishfaq *et al.*, 2022). In automotive manufacturing, AM enables rapid prototyping, customization, and production of parts with reduced material waste (Vasco, 2021). Additionally, in the consumer goods sector, AM facilitates the customization and production of personalized products, from jewelry to fashion accessories (Kunovjanek *et al.*, 2022).

In the medical field, AM is utilized for patient-specific implants, surgical guides, and dental devices, enhancing treatment outcomes and patient care (Bhargav *et al.*, 2018). AM has significantly impacted the prosthetics industry globally, enabling advancements in design customization, production efficiency, and patient care. In many countries, especially those with limited access to traditional prosthetic manufacturing infrastructure, AM has democratized prosthetic production, allowing local clinics and healthcare facilities to produce affordable and customized prosthetic devices on-site (Al-Emam, 2016; Buonafede *et al.*, 2018; Saunders, 2018). Multinational corporations have also embraced AM in prosthetics, leveraging its capabilities to streamline production processes, reduce lead times, and improve product quality. By adopting AM technologies, multinational corporations can centralize design and manufacturing operations while providing tailored solutions to meet the diverse needs of prosthetic users worldwide (Buonafede *et al.*, 2018).

The prosthetic industry advances artificial devices designed to assist individuals with missing upper and/or lower limbs in performing functions that the natural parts would typically handle (Arifin *et al.*, 2017; Beckerle *et al.*, 2019). The use of 3D printing technologies in the prosthetic industry aims to create high-value and innovative lower and upper limbs with higher accuracy in production and individualization in customization (Zuniga *et al.*, 2017; Manero *et al.*, 2019). 3D printing technology serves as both a supplementary and fully functional tool in prosthetic device production, printing final products, not just prototypes, due to technological advancements (Durach *et al.*, 2017; Wankhede *et al.*, 2024). The AM prosthetic supply chain has many features that surpass those of the traditional prosthetic supply chain (Attaran, 2017).

Over the past two decades, the Jordanian market has undergone a significant evolution in the adoption of AM technologies. Beginning in the early 2000s with initial explorations primarily in academic and research settings, Jordan gradually transitioned towards a more robust AM ecosystem throughout the 2010s. During this period, concerted efforts from the government, industry, and educational institutions were directed toward building awareness, fostering innovation, and developing the necessary infrastructure to support AM adoption (Masa'deh *et al.*, 2023). This led to the emergence of commercial applications across various sectors, including healthcare, construction, and consumer goods, with AM playing a pivotal role in accelerating product development, enhancing customization, and expanding market opportunities (Allouzi *et al.*, 2020; Masa'deh *et al.*, 2023).

The growth of AM in Jordan has brought about transformative changes in the manufacturing landscape, marked by increased efficiency, enhanced innovation, and job creation. With the adoption of AM technologies, Jordanian manufacturers have been able to produce complex parts with greater speed, flexibility, and cost-effectiveness, enabling them to compete on a global scale (Masa'deh *et al.*, 2023). Moreover, the expansion of the AM industry has fueled skill development initiatives and entrepreneurship, contributing to the development of a vibrant ecosystem of startups, service providers, and skilled professionals. Looking ahead, Jordan is poised to further leverage the potential of AM to drive economic growth, innovation, and competitiveness across industries, positioning itself as a regional hub for advanced manufacturing and technology-driven solutions.

In Jordan, the relatively new use of 3D printing technology in prosthetics is still in its early stages, with the first 3D printed prosthetic device provided to an amputee in 2017 (Saunders, 2018). Since then, the Jordanian government, alongside public and private healthcare institutions, has collaborated to advance the application of 3D printing technologies in prosthetics. The aim is to produce prosthetic devices for upper- and lower-limb amputees in Jordan and other Middle Eastern countries. Jordan's prosthetic sector has witnessed significant growth, enhancing patient experiences through collaboration with governmental agencies and international companies, resulting in more comfortable, lighter, preferred, and cost-effective prostheses (Al-Emam, 2016). Jordan distinguishes itself in the realm of rehabilitation, spurred by an influx of refugees from war-affected nations (Abushaikha *et al.*, 2021). This has necessitated the establishment of a resilient healthcare system and the provision of prosthetic devices. This makes the Jordanian context an interesting one to investigate the role of AM in the prosthetic supply chain. This study aims to investigate how incorporating 3D printing technologies in the prosthetic industry will affect the prosthetic supply chain capabilities in a developing country setting, and develop a model to improve the applicability of AM in the prosthetic supply chain. Thus, our study tries to answer the following research question (RQ):

RQ. How does the incorporation of 3D printing technologies impact the prosthetic supply chain?

This study is structured as follows. Section 2 reviews literature related to 3D printing technologies and their impact on the prosthetic industry and supply chain practices. Section 3 illustrates the resulting theoretical model. Section 4 presents the research methodology. Section 5 elucidates the analysis part of this study. Section 6 provides a discussion of the findings. Finally, Section 7 presents the conclusions, implications, and directions for future research.

2. Literature review

2.1. The evolution from conventional to AM prosthetic supply chain

The global need for prosthetics is rising due to an increasing number of amputees, with over 10 million people requiring lower-limb prosthetics. Designing both upper and lower prosthetics involves considerations such as functionality, user-friendliness, comfort, weight, size, appearance, sound, energy, efficiency, adaptability, durability, customization, modularity, and cost (Al-Emam, 2016; Beckerle *et al.*, 2019). Beckerle *et al.* (2019) emphasized the importance of accurately analyzing and modeling bioactive components to produce advanced prosthetics mimicking natural human body parts. Traditional methods for manufacturing prosthetic sockets involve scanning residual limbs, creating test molds, and using conventional methods like vacuum forming or injection molding, and the process often includes creating a test socket by heating a thermoplastic sheet in an oven to form around a mold, with subsequent checks and adjustments to ensure fit, which can take 2-3 weeks (Beckerle *et al.*, 2019). An intermediate part called a liner, made of gel or silicon, is sometimes used between the socket and the residual limb to increase efficiency. However, manufacturing sockets without physical and mechanical mistakes is challenging, leading to lower patient satisfaction. Ribeiro *et al.* (2021) underscored the limitations of traditional prosthesis manufacturing methods, including heavy manual labor,

high costs, inflexibility in redesigning, and labor intensity. Chowdhury *et al.* (2023) highlighted discomfort and dysfunction caused by conventional manufacturing of joint prosthetics, noting that customized prosthetics improve patient outcomes by considering anatomical characteristics, simplifying procedures, reducing surgery time, and increasing device durability, particularly in hip stem surgeries.

Businesses frequently use 3D printing to quickly prototype new designs so they can test them with smaller inputs before putting them into large-scale production. Increasing the material base will encourage other industries to adopt 3D printing and will change how their supply chain operates, including food industries, aerospace industries, medical industries, and merchandise industries (Chen, 2016). If the usage rate of 3D printing technologies increased worldwide in different industries, this would contribute to changing the national and international supply chains to new business models and new compositions.

Studies have shown that 3D printing technologies have the potential to improve efficiency, customization, flexibility, and sustainability in various industries, particularly in the prosthetic sector. Challenges like ensuring product quality, addressing raw material availability, and managing manufacturing lead times must be addressed. Attaran (2017) explored the impact of 3D printing technologies on supply chain configuration, capabilities, and logistics in medical prosthetics. The concept of the AM supply chain streamlines manufacturing processes, fosters innovation, and enhances efficiency (Attaran, 2017). Adopting AM technologies leads to improved efficiency, customization, decentralized manufacturing, enhanced product development processes, cost reduction, sustainability, and agility, as stressed by Attaran (2017). Key stakeholders include machine vendors, material manufacturers, software providers, logistics operators, and research centers. Attaran (2020) highlighted the potential for digital design transformation resulting from 3D printing technologies, leading to decentralized manufacturing and shortened time between production and sale. Kritzinger *et al.* (2018) affirmed that AM technologies can reduce component requirements by integrating assembly activities and transitioning from mass production to on-demand production. Kunovjanek and Reiner (2020) found that AM technologies simplify supply chains, reduce waste and lead time, enhance product functionality, support sustainability, and reduce costs, making them suitable for the prosthetic industry with its low production volumes.

2.2. 3D printing production process and customization

Manero *et al.* (2019) outlined four crucial stages in 3D printing prostheses: core design, customized design, engineering integration, and printing. Lu *et al.* (2019) explored titanium alloy composites for lower limb bone defect reconstruction, emphasizing 3D printing's integration with scanning and imaging. Kunovjanek and Reiner (2020) investigated 3D printing for anatomical models in medical education, stressing the simplicity of AM technologies compared to traditional methods. Attaran (2020) highlighted streamlined 3D printing processes, aligning with the view of Bozkurt and Karayel (2021) on rapid prototyping. Chowdhury *et al.* (2023) pointed out 3D printing's advantages in prosthetic production and proposed AM supply chain models. Hussaini *et al.* (2023) advocated for 3D printing for upper-limb prostheses in Uganda. AM technologies offer production flexibility, shorter lead times,

efficient diversification, enhanced supply chain performance, and competitive advantage (Handal, 2017; Javaid *et al.*, 2022).

Digitization through computer-aided design (CAD) and computed tomography (CT) scanning enables customization (Chowdhury *et al.*, 2023). Yoo *et al.* (2021) underscored AM's efficiency in reducing raw material consumption. Handal (2017) and Kuswanto *et al.* (2023) emphasized improved customization, faster production, lighter weight, and increased resource efficiency, ideal for medical applications. The integration of AM technologies into the prosthetic industry transforms customization, providing faster production, lower rejection rates, increased customization, lighter weight, advancements in biocompatible materials, and improved resource efficiency, enhancing both the prosthetic industry and patient quality of life (Jamróz *et al.*, 2018; Leite *et al.*, 2019; Kunovjanek and Reiner, 2020; Tuteski and Kočov, 2020; Ribeiro *et al.*, 2021; Singh *et al.*, 2024). Soares *et al.* (2021) shed light on AM technologies' impact on supply chains, shifting order penetration to the design/manufacturing process. Customer-centric approaches enhance satisfaction as suggested by several scholarly works (e.g., Durach *et al.*, 2017; Holmström and Gutowski, 2017; Ryan *et al.*, 2017; Dandis *et al.*, 2021). 3D printers are increasingly employed in job shop operations, creating secondary components for assembly lines and warehouses (Ryan *et al.*, 2017). Suitable for low-volume production in the medical industry, AM technologies require improved cost-efficiency for larger volumes (Rogers *et al.*, 2016; Rogers *et al.*, 2017; Chan *et al.*, 2018). AM technologies enhance supply chain production systems by providing increased flexibility and catering to specific customer needs. 3D printers, with their layer-by-layer approach, find application in the prosthetic industry, streamlining design and eliminating assembly time, cost, and effort (Holmström and Gutowski, 2017; Singh *et al.*, 2024). Chan *et al.* (2018) and Soares *et al.* (2021) highlighted the shortened product development cycles and reduced costs facilitated by AM technologies through digitizing production processes, particularly benefiting small organizations and industries with tight timelines.

2.3. Time efficiency

Time efficiency in the prosthetic supply chain is the capability of supply chain activities to swiftly and effectively deliver prosthetic devices to end-users, minimizing lead times, reducing delays, and optimizing processes from procurement to delivery, ultimately ensuring timely access to prosthetic solutions (Ma *et al.*, 2020). Liu *et al.* (2018) conducted a study revealing that 3D printed scapula prostheses require significantly less preparation and production time compared to traditional methods. The digitalization of the production process not only results in decreased surgery times but also reduces costs, medical risks, and overall manufacturing time, contributing to faster and more efficient fabrication of prosthetic devices (Tuteski and Kočov, 2020; Ribeiro *et al.*, 2021). Advanced AM technologies revolutionize industrial supply chains by offering unparalleled agility and responsiveness. Through the direct fabrication of parts from digital designs, AM significantly reduces design-to-production time, lead time, time-to-market, response-to-changes time, delivery time, order cycle time, and customer response times compared to traditional manufacturing methods. By enabling rapid prototyping, on-demand production, and seamless customization, AM enhances supply chain efficiency and competitiveness, ultimately leading to improved customer satisfaction and market

responsiveness (Attaran, 2017; Kritzinger *et al.*, 2018; Bozkurt and Karayel, 2021). The integration of 3D printing technologies in prosthetics not only reduces patient rehabilitation time but also, with the use of electron beam melting (EBM) technology, decreases fabrication time by one-third compared to traditional casting methods (Ribeiro *et al.*, 2021; Chowdhury *et al.*, 2023).

2.4. Production quality

Production quality in the prosthetic supply chain represents the adherence to established standards and specifications during the manufacturing process of prosthetic devices. It encompasses the safety, functionality, durability, and customization of prosthetic products to effectively meet the individual needs and preferences of end-users, thereby ensuring the delivery of high-quality, reliable, and effective prosthetic solutions (Martinez-Marquez *et al.*, 2019). Kritzinger *et al.* (2018) found that AM technologies enhance structural performance and durability. Arifin *et al.* (2017) also emphasized the importance of high-quality prosthetic devices and the need for further research. Additionally, Martinez-Marquez *et al.* (2019) studied the management of medical device quality and safety in the medical industry, highlighting the need for better quality control practices. They emphasized integrating scanning technologies like magnetic resonance imaging (MRI) and computed tomography (CT) with 3D printing to improve device quality and preoperative planning, but increased lead time. They also highlighted the importance of high-quality prosthetic devices and the need for further research on 3D printing technologies.

2.5. Cost efficiency

Cost efficiency in the prosthetic supply chain denotes the effectiveness of supply chain activities in minimizing expenses and resource utilization while delivering high-quality prosthetic products and services. It entails the strategic management of production, transportation, inventory, and other operational costs to maximize value and optimize the allocation of resources, ultimately ensuring the affordability and accessibility of prosthetic solutions to end-users (Kim and Kim, 2019). Some scholars (e.g., Mashambanhaka, 2019; Arthaya and Ivan, 2023) emphasized 3D printing's benefits in prosthetic production, enhancing patient satisfaction and providing a cost-effective alternative to traditional methods. Sirinterlikci and Swink (2015) proposed cost and time reductions through recyclable materials and wood particulates. Ni *et al.* (2019) noted that while 3D printed metallic medical devices, including prosthetics, incur metal costs, overall costs are lower than traditional manufacturing. Attaran (2017) identified cost improvements in traditional supply chains after adopting AM technologies. Mahadik and Masel (2018) showcased reduced transportation costs through digitalized manufacturing and point-of-use production, developing an AM cost estimation tool. Musso *et al.* (2022) found that adopting 3D printing technologies with fewer intermediaries leads to lower costs. Tuteski and Kočov (2020) and Javaid *et al.* (2022) reported reduced production costs for prosthetic devices with AM due to lower raw material costs. Chowdhury *et al.* (2023) highlighted the feasibility of 3D printed prostheses and potential inventory elimination, yet economic comparisons in existing literature are lacking. According to Attaran (2020), sourcing prosthetics during the Syrian civil war proved challenging due to high costs and logistical difficulties. 3D printed prosthetics significantly reduced production costs,

providing quicker patient access. However, Kuswanto *et al.* (2023) noted limited use in developing or conflict-ridden countries, despite high amputee rates. Properly implemented, 3D printing can address psychosocial effects in amputees globally and meet the unmet need for culturally appropriate prosthetic technology.

2.6. Prostheses functionality

Prosthesis functionality in the prosthetic supply chain encompasses the design, production, and delivery of prosthetic devices that effectively restore lost or impaired physical functions to individuals with limb deficiencies or amputations. It refers to the ability of prosthetic solutions to closely replicate the functionality of natural limbs, enabling users to perform various activities of daily living, occupational tasks, and recreational pursuits with optimal comfort, mobility, and usability (Highsmith *et al.*, 2016). Functionality is paramount in prostheses; thus, 3D printing technologies offer efficiency improvements and address limitations in traditional manufacturing to enhance functionality and reduce discomfort (Oladapo *et al.*, 2021; Chowdhury *et al.*, 2023). Lu *et al.* (2019) found that 3D printing enhances prosthetic stability, mechanical performance, and patient satisfaction through highly porous interface-structured prostheses with rigid fixation screws. Beckerle *et al.* (2019) stressed the significance of high-quality finished surfaces in prosthetic sockets for optimal functionality and patient comfort, underscoring the need for accurate scans and diagnoses. 3D printing technologies enable the production of complex prosthetic devices with controlled thicknesses and high-precision microstructures (Martinez-Marquez *et al.*, 2019; Tuteski and Kočov, 2020), resulting in increased stiffness, strength, flexibility, and comfort (Zuniga *et al.*, 2017; Jamróz *et al.*, 2018). These advancements enhance patient satisfaction, aesthetic value, and ease of use (Manero *et al.*, 2019), with 3D printing technologies providing well-fitted, functional devices without technical barriers (Mendoza-DeCal *et al.*, 2023). In addition, Binedell *et al.* (2021) reported that a patient preferred a 3D printed arm for its overall performance, precise size, usability, and suspension in comparison to conventionally manufactured devices, emphasizing its security, lightweight nature, and user-friendliness.

2.7. Accessibility to prostheses

Accessibility to prostheses in the prosthetic supply chain refers to the availability, affordability, and suitability of prosthetic devices for individuals with limb deficiencies or amputations. It encompasses factors such as geographical proximity to prosthetic services, financial affordability of prosthetic devices, cultural appropriateness of prosthetic solutions, and the presence of supportive healthcare infrastructure and services. The goal is to ensure that individuals in need have equitable access to high-quality prosthetic care, regardless of their socioeconomic status, geographic location, or other barriers (Ward-Sutton *et al.*, 2020). The global accessibility of 3D models for prosthetic devices has increased through 3D printers and segmentation algorithms, yet logistical challenges in low- and middle-income countries hinder customer satisfaction. Addressing this, many scholars (e.g., Arifin *et al.*, 2017; Manero *et al.*, 2019; Kuswanto *et al.*, 2023) suggested utilizing AM technologies for customized prosthetic production near the point of use. According to Attaran (2020), AM allows on-demand manufacturing of replacement parts by local distributors in remote locations. Corsini *et al.* (2022) stated that 3D printing technologies enable in-country or on-site production, eliminating

the need for finished goods to cross national borders. Javaid *et al.* (2022) asserted that 3D printing integrates manufacturing more directly with the point of use, altering relationships between service providers, suppliers, and consumers. Medical device companies can enhance design and testing capabilities through internal investments in 3D printing technology (Attaran, 2020). Consequently, the adoption of AM technologies has significantly impacted supply chain aspects like cost efficiency, production flexibility, finished product properties, sustainability, supply chain strategy, and resource efficiency.

2.8. Supply chain strategy and configuration

Supply chain strategies, focusing on lasting improvements and competitive advantages, differ between traditional and AM medical supply chains. Traditional models rely on make-to-stock and demand forecasting, while AM medical supply chains adopt engineer-to-order and function as pull supply chains (Shouche *et al.*, 2016; Rogers *et al.*, 2016). AM technologies reshaped supply chain strategies, promoting lean and agile approaches, reducing inputs, enabling swift market responses, and enhancing responsiveness to customer requirements through small production volumes (Durach *et al.*, 2017; Handal, 2017). For example, AM offers significant advantages over traditional lean manufacturing, especially in the prosthetics sector. Lean manufacturing focuses on minimizing waste and maximizing efficiency through established processes like Just-In-Time production and Six Sigma (Al-Tahat and Bwaliez, 2015; Bwaliez and Abushaikh, 2019; Ta'Amnha *et al.*, 2023), while AM enhances these principles by providing greater design flexibility, reducing lead times, and lowering costs. Corsini *et al.* (2022) underscored that placing a 3D printer further downstream supports a user-focused supply chain with efficient quality and production control, though this may not be economically viable for mass manufacturing industries (Durach *et al.*, 2017; Kunovjanek and Reiner, 2020).

AM technologies enable on-demand production, diminishing reliance on future demand forecasting and high inventory levels, maximizing customer value, and enhancing supply chain competitiveness (Handal, 2017). Engineer-to-order AM supply chains benefit from ultra-postponement, while speculation strategies suit mass-production supply chains (Minguella-Canela *et al.*, 2017). Javaid *et al.* (2022) noted that 3D printing immediately impacts the medical supply chain by increasing distributed production and digitizing inventory, disrupting product lifecycles.

AM technologies play a crucial role in enabling customization and active customer participation in order fulfillment (Ryan *et al.*, 2017). Shouche *et al.* (2016) predicted the emergence of well-planned, customized medical device supply chains driven by patient information and doctor recommendations. Durach *et al.* (2017) and Corsini *et al.* (2022) suggested that 3D printing technologies would shorten humanitarian supply chains and encourage more regional manufacturing. Rogers *et al.* (2017) highlighted the integration of AM technologies in supply chain management, emphasizing localized manufacturing processes as well as reduced lead times and transportation costs. Liao *et al.* (2019) proposed a supply chain mapping framework for medical devices, emphasizing customization. Ryan *et al.* (2017) predicted that 3D printing technologies would revolutionize mobile manufacturing, reducing lead times, inventory volumes, and transportation costs. Handal (2017) and

Holmström and Gutowski (2017) highlighted the benefits of smaller suppliers in AM supply chains, reducing complexity. Musso *et al.* (2022) noted that AM forces a paradigm shift, requiring supply chain redesign. Moreover, Corsini *et al.* (2022) emphasized the absence of a one-size-fits-all model, allowing organizations to choose different network configurations based on context and product specifics.

Effective data management is emphasized for successful 3D printing technology implementation in AM supply chains, promoting integration, information sharing, and visibility, resulting in increased innovation and customer value (Chan *et al.*, 2018; Bwaliez, 2023). These technologies enhance supply chain integration, stakeholder collaboration, and competitiveness, reducing inaccurate data and offering promise for customer-centric sectors such as prosthetics (Handal, 2017; Sidhu *et al.*, 2019). As noted by Binedell *et al.* (2021), 3D printing technologies enable intricate innovations in prosthetic design.

2.9. Supply chain sustainability

Adopting AM technologies enhances environmental sustainability in industrial supply chains by reducing processing steps, managing material waste, and promoting recycling (Attaran, 2017; Kunovjanek and Reiner, 2020). Zagel *et al.* (2017) emphasized the sustainability of 3D printing in the prosthetic industry, highlighting its potential for recycling materials like Polypropylene and Polyethylene, especially with low-cost 3D printers. Corsini *et al.* (2022) noted additional environmental and financial advantages in local manufacturing of 3D printer filaments, repurposing waste materials into useful resources and supporting the circular economy. Ni *et al.* (2019) stressed the importance of materials like stainless steel, cobalt-chromium alloys, and titanium alloys in 3D printing medical devices, acknowledging challenges like toxins release and elasticity differences (Liu *et al.*, 2018). 3D printing of prosthetic limbs involves computer-controlled adjustments in dimensions, material quantity, and structure, with considerations for design structures like grids, honeycombing, and diagonals. Trade-offs are necessary as increasing infill can enhance weight and stability but also lead to higher material usage (Zagel *et al.*, 2017). AM technologies streamline supply chain manufacturing, reducing assembly, energy consumption, weight, and waste, promoting sustainability by minimizing raw material usage, enhancing resource efficiency, and minimizing the carbon footprint (Kunovjanek and Reiner, 2020; Sharabati *et al.*, 2020). Furthermore, Attaran (2020) noted that 3D printing has a minimal environmental impact since it uses only necessary materials, producing little waste.

2.10. Challenges of adopting AM technologies

The prosthetic industry grapples with challenges in 3D printing software expertise, hindering customization and accuracy levels despite the positive impacts of 3D printing technologies (Ribeiro *et al.*, 2021). Olsen *et al.* (2021) noted that while 3D scanning and printing can be beneficial, professional guidance is essential to avoid issues common in traditional socket manufacturing. Challenges in 3D printing adoption, such as high costs, technological limitations, material scarcity, professional shortages, and inadequate regulations were highlighted by Rogers *et al.* (2016) and Durach *et al.* (2017). Chan *et al.* (2018) pointed out barriers in 3D printing for supply chains, including a lack of regulations and open-source

models, suggesting stricter regulations to protect intellectual property rights, especially for medical devices. However, Kuswanto *et al.* (2023) proposed creative solutions for Indonesians with disabilities, combining 3D printing, open-source design, penta-helix cooperation, and the circular economy. Holmström and Gutowski (2017) emphasized challenges in implementing AM technologies in supply chains including high material costs, unstable processing conditions, and slow building speeds. Das *et al.* (2023) identified limited compatible prosthesis materials, printability issues, defects, and low mechanical strength as challenges in the 3D printing of prosthesis materials. Accordingly, 3D printing technologies present challenges in AM supply chains, potentially impacting prosthetic supply chains as common production tools.

3. Theoretical model

Researchers emphasized challenges in the prosthetic industry such as high costs and limited medical care availability, prompting decision-makers to adopt 3D printing technologies. The study revealed significant impacts of AM technologies on various aspects of the prosthetic supply chain, influencing customization, responsiveness, innovation, environmental sustainability, and cost minimization. A theoretical model, presented in **Figure 1**, was developed to analyze the AM technologies' impact on the supply chain.

[Take in Figure 1]

4. Methodology

4.1. Research design

Utilizing an exploratory research approach, this study investigated the application of AM technologies in prosthetic supply chains to address a limited literature gap (Alase, 2017; Azungah, 2018). A theoretical model was developed qualitatively to collect, analyze, and interpret empirical data. The study focused on understanding the adoption of AM technologies in prosthetic supply chains through a qualitative approach emphasizing interpretation and exploratory data (Kohlbacher, 2006; Towers *et al.*, 2020). The study employed the triangulation technique, combining data from interviews, observations, and literature reviews with a specific focus on methodological triangulation, sequentially applying different data collection methods to enhance confidence in interpretations (Amaratunga and Baldry, 2001; Kohlbacher, 2006).

4.2. Interviews

Employing convenience sampling and snowballing strategies (Voss *et al.*, 2002; Kurpjuweit *et al.*, 2019), the study conducted 31 interviews with key individuals in Jordanian prosthetic and 3D printing organizations over two months as illustrated in **Table 1**. Interviewees had an average experience of six years and six months, with interviews typically lasting for 60 minutes. **Appendix A** presents the interview guide used in this study.

[Take in Table 1]

4.3. *Observational data*

The study explored the adoption of AM technologies in the prosthetic supply chain through relevant actions, observations, and insights during interviews and field visits. The researchers documented observations, considering factors like timing, location, and purpose. As external observers, the researchers were classified as non-participant observers, ensuring accurate and meaningful notes (Towers *et al.*, 2020).

4.4. *Validity and reliability*

Ensuring research quality and credibility, the study prioritized validity and reliability, drawing on techniques from Kohlbacher (2006) and Forero *et al.* (2018). Employing methods such as using a checklist of interview topics, providing guidelines to interviewees, asking repeated questions, recording and transcribing interviews, analyzing data promptly, and employing triangulation, the researchers enhanced research quality. To maintain credibility, they accurately interpreted data from various sources, including interviews, without compromising the original meanings (Riege, 2003). Feedback from five interviewees was sought and incorporated to improve credibility. Reviewers confirmed the model's clarity and thoroughness in the prosthetic supply chain, and the researchers included personal reflections in the interview process to potentially address future inquiries.

4.5. *Analytical techniques and data coding*

The researchers used a descriptive qualitative research strategy to analyze empirical data by categorizing it and extracting meaningful findings into themes. The process involved organizing data and systematically extracting findings by reducing large amounts of data into meaningful categories. The aim was to enhance accuracy and credibility as well as eliminate ambiguities in the resulting categories (LeCompte, 2000; Jacelon and Dell, 2005; Alase, 2017).

In qualitative research, the coding process is instrumental in deriving results from empirical data (Vaughn and Turner, 2016). However, various challenges such as managing large volumes of data, selecting appropriate tools for data management, ensuring effective data sorting, maintaining consistency during coding, and achieving successful interpretation may arise. To address these challenges, researchers engaged in reductionistic activities as proposed by Jacelon and Dell (2005) and Vaughn and Turner (2016). The systematic procedures for analyzing raw data are delineated by LeCompte (2000) and Jacelon and Dell (2005). These procedures involve organizing data from interviews and observations into tables, deriving initial codes from transcripts and observations, identifying sub-categories, defining categories based on a common focus, developing themes to establish meaningful patterns, and interpreting each theme by summarizing data into sub-chapters. The structure of the revised model is then constructed. Notably, the data analysis process commenced before data collection, as the researchers translated interviews into English, transcribed them, and tabulated the data even before the completion of all raw data collection.

4.6. *Research context*

Jordan stands out in the field of rehabilitation, driven by an influx of refugees from war-affected nations (Abushaikh *et al.*, 2021). This has prompted the need for a robust healthcare system

and the provision of prosthetic devices. 3D printing technologies are now utilized in Jordan's prosthetic industry, with Médecins Sans Frontières (MSF) providing the first prosthesis to a Jordanian patient in 2017 at a hospital in Amman (Saunders, 2018). Jordan's prosthetic sector has witnessed significant growth, enhancing patient experiences through collaboration with governmental agencies and international companies, resulting in more comfortable, lighter, preferred, and cost-effective prostheses (Al-Emam, 2016).

Major contributors to Jordan's prosthetic field include governmental hospitals such as the Jordanian Royal Medical Services and The National Center for the Rehabilitation of Amputees, providing multi-movement upper prostheses, manufacturing, training, rehabilitating, and equipping both upper and lower limb prostheses. Additionally, Al-Bashir Hospital supplies prostheses to 400-500 disabled patients monthly, and Al-Hussein Medical Center for Rehabilitation of Amputees leverages CAD technology to advance the local prosthetic industry (Petra, 2015; Al-Emam, 2016). Numerous partnerships and donations in the prosthetic and rehabilitation fields have been formed by non-governmental organizations (NGOs), international organizations, and Jordanian counterparts. **Figure 2** illustrates the key actor groups involved in the prosthetic supply chain.

[Take in Figure 2]

5. Analysis

Thematic analysis is a method used to analyze qualitative data by identifying and interpreting meaningful themes, which are then summarized in an analytical conclusion to enhance their credibility and validity (Alhojailan, 2012; Castleberry and Nolen, 2018; Ta'Amnha *et al.*, 2021). In the following tables, the data gathered from the interviews and observations were analyzed to inform our findings.

Table 2 shows that the prosthetic industry embraces 3D printing for diverse customization options in materials, designs, and colors. 3D printing allows full customization of prosthetic hands and sockets, enhancing patient fitting. Implementation of 3D printing initiates pre-orders of raw materials, altering inventory strategy. The adoption of 3D printing transforms production strategy to design-to-order, tailoring prosthetic designs. This has been supported by the Founder of 3D Printing Services Center F who clarified:

"...our strategy is design-to-order, where, we have already the raw materials in stock and when there is a new order, we serve him based on the available raw materials. It should be noted that we have pre-made designs on our website and customers can select from them and then we can customize it for him" (Founder, 3D Printing Services Center F).

[Take in Table 2]

Evidence from interviews and observational data show that the Integration of 3D printing technologies significantly enhances accessibility to prostheses in remote areas, and responsiveness to the patient requirements and market needs. The localization of 3D printing in remote areas and refugee camps improves accessibility to NGOs and other providers of medical services, as shown in **Table 3**.

[Take in Table 3]

As shown in **Table 4**, qualitative evidence suggests that 3D printing enhances prosthetic supply chain innovation, allowing for specialized device production and new design creation. Lightweight 3D printable materials and precise control of material infill ratio contribute to enhanced prosthetic functionality by reducing weight and increasing precision.

[Take in Table 4]

Table 5 provides an overview of the environmental sustainability category, which emerged from the data analysis. Interviewees asserted that the implementation of 3D printing shifts waste generation points from manufacturing to finishing stages in prosthetic supply chains.

[Take in Table 5]

As shown in **Table 6**, adopting 3D printing technologies to produce prosthetic devices has reduced the related costs extremely, which is reflected in the prices of the devices. The adoption of 3D printing enhances cost efficiency in prosthetic supply chains by reducing testing, supply base, and transportation costs. Interviewees clarified that 3D printing significantly cuts prosthetic production costs, resulting in a 16% to 25% price reduction.

[Take in Table 6]

Observational evidence also suggested that integration of 3D printing in prosthetic supply chains improves patient empowerment, as shown in **Table 7**. 3D printing enhances production accuracy by reducing human errors and digitalizing processes. This is also supported by one interviewee who stated: “...when the device is ready to be fitted on the patient, we conduct 3 testing times by making the patient try to utilize the functions of the device and experience wearing it” (Prosthetics and Orthotics Specialist, Rehabilitation of Amputation Center). Similarly, a respondent from one NGO clarified: “Adopting the 3D printing technologies in the prosthetic supply chain would make patients more empowered, where they will receive their devices faster than before and their requirements will be met more in an accurate manner” (Prosthetic Specialist and Head of Workshops, Medical Equipment & Services Center A).

[Take in Table 7]

6. Discussion

6.1. Discussion of the findings

The findings suggest that the implementation of 3D printing technologies contributed to enhanced customization and postponement, altering the order penetration point and refining postponement strategies (Leite *et al.*, 2019; Manero *et al.*, 2019). Ultra-postponement affects inventory and production, prompting changes in raw material composition and reduced volume (Attaran, 2020; Kuswanto *et al.*, 2023). Organizations now tailor material purchases to patient needs, aligning inventory with customization. 3D printing eliminates finished products and prosthetic components inventory (Beckerle *et al.*, 2019). Production shifts to design-to-order or engineer-to-order, contingent on organizational capabilities and policies (Ryan *et al.*, 2017; Ribeiro *et al.*, 2021; Javaid *et al.*, 2022).

The adoption of 3D printing technologies has heightened innovativeness in the prosthetic supply chain, impacting factors like 3D printing inputs, labor skills, digital tools, and the new product development (NPD) process (Chowdhury *et al.*, 2023; Leite *et al.*, 2019; Manero *et al.*, 2019). The supply chain exhibits increased flexibility and responsiveness among partners (Attaran, 2017; Durach *et al.*, 2017; Handal, 2017; Rogers *et al.*, 2017; Chan *et al.*, 2018). In Jordan, 3D printing services' enhancement involves changes in supply base, assembly line, delivery, warehousing, and the emergence of new supply chain parties (i.e., 3D printing service providers, local resellers of raw materials and printers, 3D printers' suppliers, technical and design advisors, NGOs, and manufacturing hubs). Integration among departments and patients improves through follow-up systems, online databases, storytelling, task management software, and remote work. Jordanian decision makers prioritize partnerships, alternative response strategies, and remote work in prosthetic contexts.

The findings also suggest that the prosthetic industry in Jordan has successfully integrated 3D printing technologies, leading to waste reduction, and lowered environmental impacts, which is consistent with prior studies (Zagel *et al.*, 2017; Ni *et al.*, 2019; Attaran, 2020; Corsini *et al.*, 2022). Existing literature supports that this adoption significantly enhances the prosthetic supply chain's efficiency, affecting time, cost, and resource aspects (Rogers *et al.*, 2016; Ni *et al.*, 2019; Tuteski and Kočov, 2020; Javaid *et al.*, 2022; Kuswanto *et al.*, 2023). On the other hand, while 3D printing technologies improve the quality of prosthetic production processes and devices, they minimize the operational cost (Arifin *et al.*, 2017; Martinez-Marquez *et al.*, 2019; Corsini *et al.*, 2022).

Finally, the adoption of 3D printing technologies in the prosthetic supply chain enhances patient empowerment, accessibility, and availability of designs and devices (Arifin *et al.*, 2017; Leite *et al.*, 2019; Manero *et al.*, 2019). On-site 3D printing and the simplicity of learning and applying these technologies increase accessibility to 3D printed prosthetics, improving after-sale services and competitiveness in the Jordanian market. Patient satisfaction, a key objective, is assessed through direct feedback, social media ratings, recommendations, and surveys (Ni *et al.*, 2019; Tuteski and Kočov, 2020; Binedell *et al.*, 2021; Kuswanto *et al.*, 2023).

6.2. Revised model

After analyzing the empirical data and conceptualizing the themes and categories, the revised model was structured, based on the relationships between the dimensions. **Figure 3** illustrates this revised model, showing the impact of AM technologies on the Jordanian prosthetic supply chain's capabilities. Emerging dimensions are indicated with dashed boxes.

[Take in Figure 3]

7. Conclusions

7.1. Theoretical implications

The study delves into the adoption of 3D printing in Jordan's prosthetic industry, emphasizing its impact on supply chain capabilities. It provides a detailed analysis of changes in the prosthetic supply chain following 3D printing adoption, underlining the significance of these technologies in the industry. The findings suggest that the adoption of 3D printing technologies improves the prosthetic supply chain's capabilities in terms of customization, responsiveness, innovation, environmental sustainability, cost minimization, and patient empowerment. The study sheds light on the specific areas affected in the prosthetic supply chain following the adoption of 3D printing technologies, emphasizing the overall improvement in supply chain capabilities within the prosthetic industry.

This study makes several contributions. First, while earlier research has focused on firm-specific 3D printing implementations, this study provides an understanding of the implications at a supply chain level. Second, it provides rich-description qualitative evidence of the role of 3D printing in the prosthetic supply chain, which is an underexplored industry context. Finally, this study provides evidence from an emerging market perspective, addressing recent calls in the literature for a better understanding of the implementation of AM in several national settings. Due to its unique characteristics, 3D printing appeared to bring benefits to the different actors in the prosthetic supply chain including medical services providers, NGOs, and patients. The 3D printing-enabled prosthetic supply chain has contributed to improved accessibility and availability of devices, leading to patient empowerment, improved prostheses functionality, better after-sale services, and increased competitiveness among Jordanian prosthetic organizations. This has improved patient quality of life and meeting expectations.

Our research findings diverge from existing literature, as they indicate that patients experience enhanced patient empowerment within the production process of their 3D printed prostheses. This is attributed to the implementation of an enhanced postponement strategy and a novel product development process that prioritizes the patient's role as a central figure. Consequently, findings postulated that patients exhibited greater satisfaction when their needs and requirements were aligned with expectations. The findings suggest that patient empowerment was improved due to several factors, including improved compatibility between the 3D printed device and the patient's body, expedited fulfillment of their requirements, reduced costs, enhanced specifications, lighter weight, and improved aesthetics of the 3D printed prosthetic devices. Furthermore, the ability to produce most 3D designs at higher

quality and affordability as well as the ease of redesigning 3D printed prostheses in a shorter timeframe have further contributed to the enhancement of patients' quality of life.

7.2. Practical implications

The study recommends promoting the adoption of 3D printing in the prosthetic supply chain, particularly focusing on lower limb prostheses. It emphasizes the significance of integrating AM technologies in the Middle East's prosthetic industry. Collaboration among various stakeholders, including medical service providers, NGOs, AM technology providers, and other prosthetic organizations is encouraged.

Supply chain managers can benefit from the study's findings by integrating 3D printing into the prosthetic supply chain to enhance customization, responsiveness, innovation, environmental sustainability, cost efficiency, and patient experience and involvement. For instance, the study suggests that 3D printing empowers patients by involving them early in the production process, offering customized options, addressing individual needs, and ensuring prompt service delivery, ultimately leading to increased patient satisfaction. Additionally, 3D printing improves prosthetic satisfaction through enhanced compatibility, quick customization, cost reduction, lighter weight, better appearance, and easier redesign; thus enhancing life quality.

However, the findings reveal significant obstacles faced by the Jordanian prosthetic industry in integrating 3D printing technologies. Key challenges include insufficient experience, limited local demand, lack of design expertise, absence of relevant academic programs, high customs clearance costs, difficulty in sourcing compatible printers, inadequate government support, and limited training opportunities. Additionally, the industry struggles with constraints in both design and printing processes, limited awareness among patients and prosthetic organizations, government restrictions on imports, and the limited durability of 3D printed prostheses. Cultural resistance, outdated infrastructure, specific printer limitations, insufficient integration of technical and medical aspects, and a lack of market competitiveness further compound these issues. Despite these hurdles, the industry is in a pilot and developmental stage, viewing 3D printing as a supplementary tool. Although still in its early stages, 3D printing technology has the potential to revolutionize prosthetic manufacturing by enabling rapid production and customization of affordable devices tailored to patient needs, potentially surpassing traditional production methods over time.

7.3. Ethical Implications

The application of 3D printing in the prosthetic industry introduces several ethical concerns alongside its numerous advantages, such as quick production, cost-effectiveness, and customization. Quality and safety issues arise as customization is possible with 3D printing, yet the paramount importance of maintaining high standards for prosthetics' quality and safety must be upheld. Accessibility and equity issues are also prominent; while 3D printing has the potential to lower costs, this does not guarantee that prosthetics will become more affordable for all individuals, especially in the Jordanian context where refugees are key beneficiaries. Access may vary based on geographical location, socioeconomic status, and technological

literacy, making it imperative to ensure equitable distribution and access to 3D printing technology to prevent escalating existing disparities in healthcare. Additionally, the use of 3D printing in prosthetics necessitates the collection and storage of sensitive information, such as medical histories and anatomical scans. Protecting patient confidentiality and preventing unauthorized access or misuse of this data is crucial to safeguarding data privacy and security.

7.4. Limitations and future research directions

This study has several limitations which pave the way for numerous research opportunities. This study focused specifically on the Jordanian context, which limits the ability to extrapolate the findings to other nations. Hence, it is recommended that future research be conducted in various international settings to enhance the validity and generalizability of the results. Additionally, exploring comparative results among respondent groups from different cultures would be particularly intriguing. The study's generalizability is also constrained by qualitative evidence, suggesting the need for future survey-based studies. Furthermore, this study unveils dimensions of the Jordanian prosthetic supply chain, emphasizing the impact of new parties, production quality enhancements, and market competitiveness. Hence, it is suggested to conduct further exploration of these dimensions and perform cost analysis to evaluate the viability of integrating 3D printing technologies into the prosthetic supply chain. It would be also interesting for future researchers to investigate how small and medium enterprises (SMEs) would operate in such a context and how they can benefit from AM to support supply chain capabilities. Lastly, as this study adopted a cross-sectional approach conducted within a specific timeframe, comprehending the enduring impacts of 3D printing on the prosthetic industry's sustainability necessitates a longitudinal study or a field experiment. Such endeavors would involve collecting data over an extended duration to provide deeper insights into the subject matter.

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Appendix A: Interview Guide

- What are the methods/technologies you use to produce prostheses?
- Tell me about the use of 3D printing for your products. How long have you been using it and why did you decide to use it?
- How does this benefit your supply chain?
- What are the main areas, processes or operations that would be changed after adopting 3D printing technologies in prostheses’ production network?
- How and when do you involve your clients in the prostheses’ production process?
- How could adopting 3D printing technologies impact the innovativeness in the prosthetic industry?
- How could applying 3D printing technologies affect the prosthetic supply chain structure (configuration)?
- What are the challenges of adopting 3D printing in your supply chain?
- How does adopting 3D printing technologies in the prosthetic industry affect the order lead time, cost, and service level?
- Do you think adopting 3D printing technologies in the prosthetic industry affect the availability and accessibility of prostheses in the market?
- How do you measure patient satisfaction with the manufactured 3D printed prosthetic devices?
- How do you measure the quality of the produced prostheses?

- Do you recommend applying 3D printing technologies in other Jordanian prosthetic organizations? Why/why not?

Tables and Figures

Table 1: Overview of interviews
Source(s): Authors' own work

Organization name	Business area	Interviewee position	Experience in the field	Minutes	Used language	Recorded (Yes/No)
3D Printing Services Center A	Providing 3D printing services	Managing director	2 years	60	Arabic	Yes
Medical Equipment & Services Center A	Supply market with various medical devices	Executive manager	5 years	70	English	Yes
3D Printing Services Center B	Providing 3D printing services and selling 3D printers	General director	7 years	100	Arabic	Yes
Rehabilitation of Amputation Center	Providing prostheses, orthoses, medical devices, and rehabilitation services	Prosthetics and orthotics specialist	4-5 years	50	English	Yes
3D Printing Services Center C	Providing 3D printing services, in addition to support the innovativeness	Technical team leader	7 years	80	English	Yes
Medical Equipment & Services Center A and NGO A	Manufacturing prosthetic devices and providing rehabilitation services	Prosthetic specialist and head of workshops	13 years	120	Arabic	No
Faculty of Rehabilitation Sciences	Providing upper-limb prosthetic devices	Upper-limbs consultant	8 years	52	English	Yes
Medical Equipment & Services Center B	Providing upper-limb prosthetic devices	Technical director	36 years	40	Arabic	Yes
NGO B	Providing 3D printed prostheses	3D printing department officer	10 years	48	Arabic	No
3D Printing Services Center D	Providing 3D printing services, selling 3D printers, raw materials, and maintenance services	Chief operations officer (COO) and a partner	5 years	130	Arabic	Yes
NGO C	Supporting refugees and providing rehabilitation services for them	Procurement and logistics assistance	3 years and 5 months	60	English	Yes
NGO B	Providing 3D printed prostheses	Medical engineer / 3D printing engineer	2 years and 3 months	36	Arabic	Yes
3D Printing Services Center E	Providing 3D printed prostheses	Co-founder, project manager, and 3D printing specialist	2 years	54	Arabic	Yes
Follow-up interview with 3D Printing Services Center E	Providing 3D printed prostheses	Co-founder, project manager, and 3D printing specialist	2 years	25	English	Yes
3D Printing Services Center F	Providing 3D printing services	Founder	2 years	31	Arabic	Yes
NGO D	Providing disabled with medical devices	Project coordinator	2 years	45	Arabic	Yes
NGO E	Supporting disabled by providing rehabilitation services	Logistics officer	4 years	52	English	Yes

NGO E	Supporting disabled by providing rehabilitation services	P&O technical officer	7 years	43	English	Yes
NGO E	Supporting disabled by providing rehabilitation services	Rehabilitation project manager	7 years	20	English	Yes
3D Printing Services Center G	Producing prostheses by 3D printing technologies	Technical advisor	3 years and 6 months	80	English	Yes
3D Printing Services Center G	Producing prostheses by 3D printing technologies	Technical manager	2 years	60	English	Yes
NGO Z	Supporting disabled by providing rehabilitation services	Program manager	4 years	45	English	Yes
NGO Z	Supporting disabled by providing rehabilitation services	Project manager	5 years	55	English	Yes
NGO Z	Supporting disabled by providing rehabilitation services	Project coordinator	2 years	70	English	Yes
NGO Y	Providing disabled with medical devices	Logistics officer	3 years	70	English	Yes
NGO Y	Providing disabled with medical devices	Logistics project manager	7 years	65	English	Yes
NGO Y	Providing disabled with medical devices	Senior Procurement officer	4 years	55	English	Yes
Medical Center A	Providing medical prosthetic services	Patient care manager	8 years	45	Arabic	Yes
Medical Center B	Providing medical prosthetic services	Project coordinator	5 years	52	Arabic	Yes
Medical Center C	Medical prosthetic services	Commercial manager	4 years	45	Arabic	Yes
Medical Center D	Medical prosthetic services	Project coordinator	3 years	50	Arabic	Yes

Table 2: Customization category
Source(s): Authors' own work

Representative quotes	First-order codes	Second-order codes	Theoretical dimension
<p><i>“Before adopting the 3D printing technologies in the Jordanian prosthetic sector, patients were forced to communicate with international organizations to produce prosthetic device based on their needs and requirements, but today with adopting the 3D printing technologies in the Jordanian prosthetic industry, they have more accessibility to the customized prostheses with diversity in sources”</i> (3D Printing Specialist, 3D Printing Services Center E).</p> <p><i>“3D printing technologies allow prosthetic service providers to offer more customized options to patients. Using the 3D printing technologies in the prosthetic industry provides a variety of materials and colors to be used in the patient's prosthetic device, which resulted in a variety of</i></p>	<ul style="list-style-type: none"> 3D printing technologies enhances prosthetic customization, resembling natural limbs closely. Full customization of prosthetic hands and sockets, enhancing patient fitting. Implementation of 3D printing technologies initiates pre-orders of raw materials, altering inventory strategy. Adoption of 3D printing technologies transforms production strategy to design-to-order, tailoring prosthetic designs. Addressing specific patient needs. 	<ul style="list-style-type: none"> Adoption of 3D printing technologies enhances customization in the prosthetic industry, influenced by patients' needs. Improved customization level after adopting 3D printing technologies. 3D printable raw materials impact inventory and supply strategies. Design-to-order and engineer-to-order strategies, influenced by 3D printing technologies, maximize customization in prosthetic production. 	<ul style="list-style-type: none"> Enhanced customization Design-to-order supply strategy

<p><i>prosthetic devices, where each device is unique in terms of the used materials, design, production time, finishing and so on” (Prosthetic Specialist and Head of Workshops, Medical Equipment & Services Center).</i></p> <p><i>“The high customization levels provided by the 3D printing technologies is another favorable feature, where the produced prostheses are not standard, but they are a 100% copy of the patient other natural hand that is absolutely different in specifications from those of other patients” (Medical Engineer / 3D Printing Engineer, NGO B).</i></p>			
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Table 3: Responsiveness category
Source(s): Authors’ own work

Representative quotes	First-order codes	Second-order codes	Theoretical dimension
<p><i>“...so, adopting 3D printing technologies in the prosthetic industry would make the prosthetic supply chain more flexible to be able to serve different cases in different locations with different conditions” (Upper-Limbs Consultant, Faculty of Rehabilitation Sciences).</i></p> <p><i>“If we compare the traditional manufacturing steps with those of the 3D printing technologies, they are significantly different, where some of the manufacturing steps are merged resulted in a huge reduction in the processing timeline (e.g., from 7-10 days to 1-2 days)” (Executive Manager, Medical Equipment & Services Center A).</i></p> <p><i>“Adopting the 3D printing technologies has shrunk the prosthetic supply chain significantly. I think the prosthetic supply chains are becoming closer to point-of-use with adopting 3D printing technologies” (3D Printing Specialist, 3D Printing Services Center E).</i></p> <p><i>“...some prosthetic devices need special environments and practices during the logistics activities, for example, the 3D printable raw materials would require special vans with the temperature-controlled system due to the sensitivity of the 3D printable raw materials to the heat” (Technical Director, Medical Equipment and Services Centre B).</i></p>	<ul style="list-style-type: none"> • Localization of 3D printing technologies in Jordan shortens the prosthetic supply chain and minimizes inventory. • Regional manufacturing hubs of 3D printing technologies reduces dependency on international sources, lowering shipping costs and time. • 3D printing technologies allows for temperature-controlled transportation to safeguard sensitive prostheses during transit. • 3D printing technologies enhance local accessibility of prosthetics through low prices and on-site printing by mobile providers. • Integration of 3D printing technologies significantly enhances accessibility to prostheses in remote areas. 	<ul style="list-style-type: none"> • Adoption of 3D printing technologies enhances supply chain flexibility and responsiveness. • Localization of production facilities near point-of-use streamlines logistics. • 3D printing technologies simplifies production, enhances designing flexibility, facilitates distance working, and shortens the lead time. 	<ul style="list-style-type: none"> • Localized supply chain configuration • Enhanced flexibility • Accessibility to resource-constrained environments

Table 4: Innovation category
Source(s): Authors' own work

Representative quotes	First-order codes	Second-order codes	Theoretical dimension
<p><i>"Also, the 3D printing technologies have allowed producing special parts that can't or hard-to-be made by the traditional manufacturing methods in less production costs"</i> (Founder, 3D Printing Services Center F).</p> <p><i>"The lightweight of the 3D printed device and the visual appearance, where adopting the 3D printing technologies to manufacture the upper-limb prostheses in our organization has helped to produce devices in a lighter weight, more customized devices in better functionality"</i> (Technical Director, Medical Equipment & Services Center B & 3D Printing Department Officer, NGO B).</p>	<ul style="list-style-type: none"> • 3D printing technologies enhances prosthetic supply chain innovation, allowing for specialized device production and new design creation. • 3D printing technologies improve prostheses' appearance, reduce weight, enhance functionality, and increase patient comfort through advanced production processes. • Lightweight 3D printable materials and precise control of material infill ratio contribute to enhanced prosthetic functionality by reducing weight and increasing precision. • Integration of 3D printing technologies in the prosthetic supply chain enhances functionality by improving appearance and reducing weight. 	<ul style="list-style-type: none"> • Improved printability and the use of 3D printable raw materials transform prosthetic designs. • Enhanced labor skills reduce reliance on hand-skilled labor in the prosthetic industry. • 3D printing technologies drives technological development, fostering innovation in the prosthetic supply chain. 	<ul style="list-style-type: none"> • Innovative prosthetic design and production

Table 5: Environmental sustainability category
Source(s): Authors' own work

Representative quotes	First-order codes	Second-order codes	Theoretical dimension
<p><i>"If there are any generated wastes, we try to reuse them if we can or dispose of them if they can't be reused again. Using the 3D printing technologies in the prosthetic industry would eliminate the generated wastes to be closer to zero"</i> (Prosthetic Specialist and Head of Workshops, Medical Equipment & Services Center A & NGO A).</p> <p><i>"Based on Technical data sheets of PLA and FlexFil materials, using these materials in manufacturing the prosthetic devices by the 3D printing technologies is environmentally friendly, where they are safe during manufacturing and on the human skin"</i> (COO, 3D Printing Services Center D).</p> <p><i>"The used 3D printable raw materials to build prostheses are biodegradable, unlike the traditionally used materials. Also, in terms of the generated wastes, the used raw materials in the traditional style are toxic and generatable of CO₂"</i></p>	<ul style="list-style-type: none"> • 3D printing technologies reduces waste, fumes, and toxic gases, minimizing environmental impact in prosthetic supply chains. • 3D printing technologies enables waste recycling, reducing pollution and lowering raw material inventory volumes and reproduction costs. • Implementation of 3D printing technologies shifts waste generation points from manufacturing to finishing stages in prosthetic supply chains. • More environmentally friendly prostheses, with biodegradability and reduced toxic gas generation. • Enhanced cleanliness in prosthetic production, eliminating messy activities. 	<ul style="list-style-type: none"> • 3D printing technologies in prosthetic supply chains reduces waste, lessening environmental impact. • 3D printing technologies enables recycling of generated waste in prosthetic supply chains. • Adoption of 3D printing technologies shifts waste generation points in the production process. 	<ul style="list-style-type: none"> • Waste reduction and management • Environmental impact and safety

gases, which could affect the internal and external environment, unlike the 3D printable raw materials” (P&O Technical Officer, NGO E).			
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Table 6: Cost minimization category
Source(s): Authors’ own work

Representative quotes	First-order codes	Second-order codes	Theoretical dimension
<p>“...the costs of the traditional-made prostheses of the upper-limbs would be approximately JOD 600, but the same device that made by the 3D printing technologies would cost JOD 100. Different cost pools were affected after adopting the 3D printing technologies in the prosthetic industry, like the labor costs” (3D Printing Officer, NGO B).</p> <p>“The 3D printing technologies allowed to have a digital library of 3D designs of pre-printed prostheses, which could reduce the designing time on the designers by choosing the closer design to their new cases and modify them to fit new patients instead of designing a new one from scratch” (3D Printing Specialist, 3D Printing Services Center E).</p> <p>“In terms of human resources, lower labor volumes are required. Also, smaller production spaces would be required too” (Technical Director, Medical Equipment & Services Center B).</p>	<ul style="list-style-type: none"> • 3D printing technologies eliminates traditional molds, reducing prototyping costs in prosthetic supply chains. • 3D printing technologies reduce manufacturing costs, production time, and raw material prices in prosthetic supply chains. • Labor costs decrease with 3D printing technologies, minimizing labor volumes and associated expenses. • Modification costs decrease with 3D printing technologies, improving reproduction efficiency and reducing redesign costs. • 3D printing technologies reduces maintenance, replacement, warehousing, overhead, and tooling costs in prosthetic supply chains. 	<ul style="list-style-type: none"> • Adoption of 3D printing technologies in prosthetic supply chains reduces costs. • 3D printing technologies reduces prosthetic device prices in the supply chains. • Lower start-up costs in prosthetic supply chains. 	<ul style="list-style-type: none"> • Reduced operational cost

Table 7: Patient empowerment category
Source(s): Authors’ own work

Representative quotes	First-order codes	Second-order codes	Theoretical dimension
<p>“Our patients are becoming partners with us during the production process of their prosthetic devices, which making them more empowered in the prosthetic supply chain than before, because we are manufacturing based on their needs and specifications. This empowerment makes our patients more satisfied and comfortable” (3D Printing Specialist, 3D Printing Services Center E).</p> <p>“These new capabilities would empower our patients in the prosthetic supply chain more, where he thinks the prosthetic device is related to him more because he witnessed the device progress from scratch to the end. This allows us to meet their requirements, which are becoming closer to natural, and allow the production process to</p>	<ul style="list-style-type: none"> • 3D printing technologies empower patients by engaging them early in the production process. • offering customized options, addressing individual needs, and ensuring prompt service delivery, ultimately leading to increased patient satisfaction. • 3D printing technologies improves prosthetic satisfaction through enhanced compatibility, quick customization, cost reduction, lighter weight, better appearance, and easier redesign for enhanced life quality. • The use of 3D printing technologies in prosthetic supply chains enhances the 	<ul style="list-style-type: none"> • The adoption of 3D printing technologies in prosthetic supply chains has enhanced patient empowerment. • Incorporating advanced rehabilitation services. • Higher patient satisfaction. 	<ul style="list-style-type: none"> • Improving patient empowerment • Prosthetic service evolution

<p><i>create prosthetic devices with more improved specifications</i>” (Technical Team Leader, 3D Printing Services Center C).</p> <p><i>“Speaking with the patient and designing something with are always the focus of the project, where they need to be part of the process. We would mix the colors with them and recall one point of a pallet of different colors, where you can select which color, we can hold it up to their skin and say this is what color I want. As much involvement as possible with the patient. Having the patient involved throughout the process is absolutely a main point, where we need to understand what their needs are from the beginning”</i> (Technical Advisor, 3D Printing Services Center G).</p>	<p>integration of rehabilitation services into the prosthetic provision process.</p> <ul style="list-style-type: none"> Quality control points are shifted to the end of the production process with 3D printing technologies. 		
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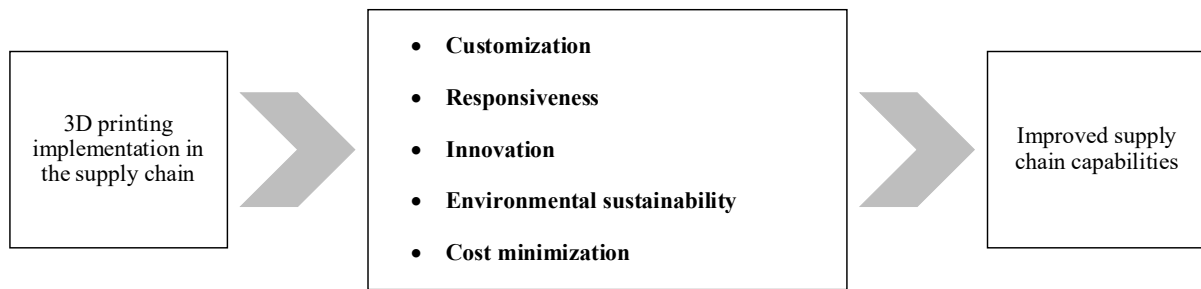


Figure 1: The impact of 3D printing on supply chain capabilities

Source(s): Authors’ own work

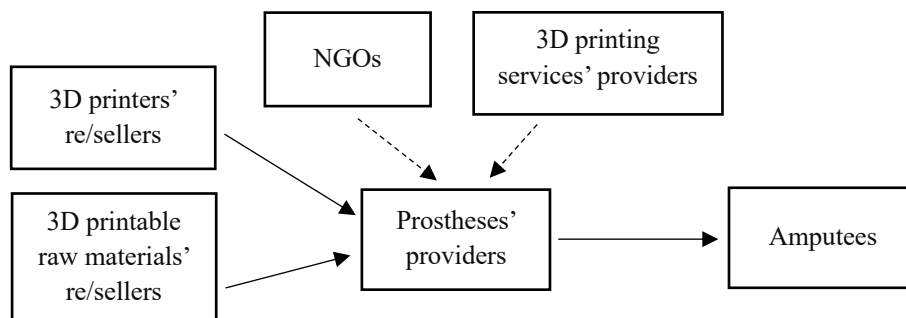
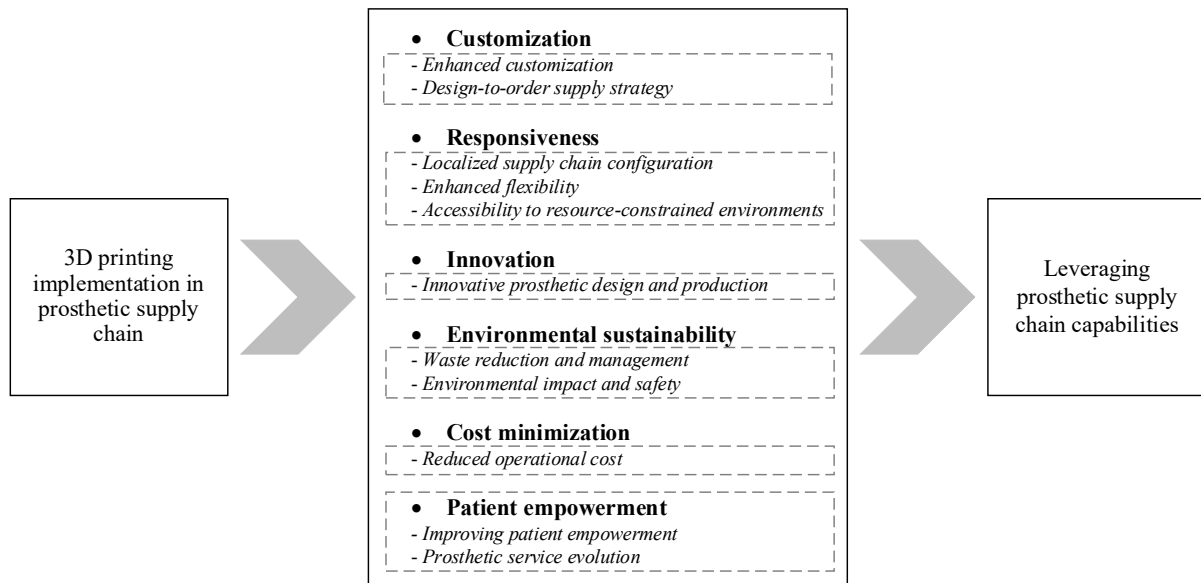


Figure 2: The actor groups involved in the prosthetic supply chain

Source(s): Authors’ own work



 Emerging themes/sub-themes are marked in dashed boxes

Figure 3: Emerging model
Source(s): Authors' own work