



Navigating the intersection between postponement strategies and additive manufacturing: insights and research agenda

Lorenzo Bruno Pratavia ^{a,b}, Amer Jazairy ^c and Ismail Abushaikh ^b

^aDipartimento di Management, Università di Verona, Verona, Italy; ^bCentre for Logistics, Procurement, and Supply Chain Management, Cranfield School of Management, Bedford, UK; ^cDepartment of Maritime Business Administration, Texas A&M University, Galveston, TX, USA

ABSTRACT

Postponement is a popular principle used to improve supply chain responsiveness and increase customisation by delaying manufacturing and logistics operations until more accurate market demand information is available. In business environments where responsiveness and customisation are increasingly important, additive manufacturing (AM) has recently emerged as a high-potential manufacturing technology. Due to changes in customer behaviours that affect product life cycles and variety, AM could disrupt traditional manufacturing and greatly impact postponement decisions. However, the intersection between postponement and AM is largely underexplored. This study aims to investigate the intersection between postponement and AM to meet the escalating demand for customised products. We conceptualise opportunities and challenges related to when customisation is introduced, concerning the positioning of the customer order decoupling point and to where customisation takes place, as operations could shift across supply chain tiers or even jurisdictions. By shedding light on the intersection of postponement and AM and its implications for customisation, this study formulates a research agenda focusing on five main postponement improvement dimensions: uncertainty, volume, lead time, supply chain design, and environmental sustainability. Moreover, it formalises a set of managerial implications to pragmatically foster the strategic implementation of AM across different postponement scenarios.

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1. Introduction

Product customisation is critical to create and retaining satisfied customers, entailing changes in physical or non-physical product characteristics that yield a wide array of options or variants for customers (Berry and Cooper 1999; Waller, Dabholkar, and Gentry 2000). As customisation is often associated with increased supply chain costs (e.g. inventory carrying costs and transport costs) (Zinn and Bowersox 1988), supply chain professionals have developed several strategies to enhance customisation by increasing its responsiveness while containing such costs (Feitzinger and Lee 1997). Postponement has been a key strategy here due to its effectiveness in balancing customisation needs with cost control (Ramón-Lumbierres et al. 2021; Skipworth and Harrison 2004). Today, postponement is consistently mentioned as one of the central features of customisation (Cholette 2009; Zinn 2019), given its propensity to improve responsiveness by delaying manufacturing and/or logistics operations until more precise information about market demand is available (Harfeldt-Berg and Olhager 2024).

However, the markets for many manufactured goods are changing, evolving from scenarios characterised by homogenous, mass-produced goods that attempt to satisfy customer requirements through product variants (i.e. mass customisation) (Piller, Moeslein, and Stotko 2004; Turner, Merle, and Gotteland 2020) to other scenarios where heterogeneous goods are produced to meet individual customers' requirements (Pallant, Sands, and Karpen 2020; Schulz et al. 2023). In business contexts where responsiveness and customisation are increasingly important, additive manufacturing (AM) has emerged as a transformative force in manufacturing (Eyers et al. 2022; Jimo et al. 2022). AM (or 3D printing) involves creating a three-dimensional object by adding layers of materials, in contrast to the traditional subtractive manufacturing method (Chen, Cui, and Lee 2021). As such, AM enables a quick and easy production of parts with a level of complexity that is not even conceivable when using conventional manufacturing techniques (Heinen and Hoberg 2019).

CONTACT Lorenzo Bruno Pratavia lorenzo.pratavia@cranfield.ac.uk; lorenzobruno.pratavia@univr.it Dipartimento di Management, Università di Verona, Verona, Italy; Centre for Logistics, Procurement, and Supply Chain Management, Cranfield School of Management, Bedford, UK

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Due to changes in customer behaviours which often result in shortened product life cycles and increased variety, AM could disrupt traditional manufacturing and greatly impact postponement decisions (Liu and Xu 2017; Minguella-Canela et al. 2017) – for several reasons. First, it can increase firms' responsiveness and enhance firms' opportunities to offer customisation (Moradlou and Tate 2018; Tuck, Hague, and Burns 2007). Companies could improve product variety by shifting their manufacturing strategy from Make-to-Stock (MTS) to, for instance, Make-to-Order (MTO) (Chen, Cui, and Lee 2021). This suggests implications related to when manufacturing operations occur based on customers' orders, thus concerning the positioning of the customer order decoupling point (CODP) (Olhager 2010; Zinn 2019). Second, manufacturing could be distributed from factories to retailers or even to end consumers, improving customer satisfaction through tailor-made products and faster response times (Ramón-Lumbierres et al. 2021; Yang, Burns, and Backhouse 2004). As AM uses 3D object scanners to add material and create an object, it potentially enables end consumers and business customers to customise products themselves (Zinn 2019). This highlights that AM could revolutionise where customisation happens (Li et al. 2024), potentially moving customisation operations across supply chain tiers if not jurisdictions in global settings (Norrman and PrataViera 2023). Moreover, shifting the CODP by using AM could reduce inventory waste and transport intensity, thereby supporting environmental sustainability efforts (Chen, Cui, and Lee 2021).

Although both postponement and AM are acknowledged as relevant enablers for customisation (Zinn 2019), previous studies limitedly discussed the nuanced opportunities and challenges that arise when intersecting postponement and AM (Chen, Cui, and Lee 2021; Ramón-Lumbierres et al. 2021). Here, there is a significant gap in understanding the implications that AM might have on postponement strategies, leaving a conspicuous void in the scholarly discourse. As such, we aim to explore the implications of the interaction between postponement and AM by positing the following research question: *What opportunities and challenges can arise from the intersection between postponement and AM?*

This study contributes to extant knowledge by bringing together two different bodies of literature (i.e. postponement and AM), elaborating available academic contributions with analytical conceptual research and providing a strategic platform from which future research is launched (Alvesson and Sandberg 2020). Conceptual studies facilitate the identification and classification of extant research while also offering possibilities to challenge existing paradigms through generating new ways of

understanding (Cronin and George 2023). By reviewing and combining the available literature about postponement and AM, we place a spotlight on their intersection and illustrate opportunities and challenges related to integrating AM into postponement strategies. This is instrumental to formulate a set of recommendations for future research, constructing an accessible agenda that unveils a portfolio of theoretical opportunities and lay the foundations for future inquiries to accelerate knowledge production. Further, this study contributes to the ongoing discussion of real-life applications in manufacturing systems and logistics, which could inform practice and future directions. Building upon a thorough analytical framework on the opportunities and challenges of AM across different postponement strategies, this study also offers a 2×2 matrix for supply chain managers that guides the strategic implementation of AM across various postponement scenarios, based on given production volumes and customisation needs.

In Section 2 and 3 we summarise the extant literature about postponement strategies and AM, respectively. Section 4 unpacks the opportunities and challenges concerning when and where postponement can intersect with AM. These combinations are instrumental to formulate an agenda that drives future research recommendations, as offered in Section 5. Lastly, concluding remarks are presented in Section 6 along with research limitations.

2. Postponement strategies

The economics of manufacturing have long favoured the simplicity of 'high-volume – low-variety' manufacturing, where repetition yields economies of scale and individual customer preferences are not considered in the manufacturing process (Eyers et al. 2022; Van Hoek 2001). Although increasing variety improves the chances of an individual customer finding the option that they require (Halman, Hofer, and Van Vuuren 2003), offering variety can increase manufacturing costs and complexity (Ramón-Lumbierres et al. 2021), as well as inventory carrying and transport costs (Skipworth and Harrison 2004). In this context, the principle of postponement was first proposed as a method to improve efficiency in marketing systems (Alderson 1957; Bucklin 1965). Later scholars and practitioners suggested implementing the postponement principle to determine the nature of customer involvement in the supply chain (Waller, Dabholkar, and Gentry 2000; Zinn and Bowersox 1988) and at which stage of manufacturing or distribution the customer becomes involved (Lampel and Mintzberg 1996). If companies engage the customer at some point in the fulfilment process, they can postpone the execution of

manufacturing operations so that a customised product is the one that is ultimately produced for the specific customer rather than satisfied by a pre-determined variety (Olhager 2003).

2.1. When to execute manufacturing operations?

Postponement generally concerns delaying manufacturing and/or logistics operations until more precise information about the market demand is available (Van Hoek 2001; Zinn and Bowersox 1988). Firms need to determine which operations should be executed according to forecasts, and which ones should be executed 'as late as possible' or once customers' orders are received (Boone, Craighead, and Hanna 2007). By delaying decisions on final supply chain configuration or inventories' location, firms delay commitment to specific customers or markets and cope with demand uncertainty (Pagh and Cooper 1998; Yang and Burns 2003), thus increasing responsiveness to customer demands while containing supply chain costs (Jafari, Eslami, and Paulraj 2022; Skipworth and Harrison 2004).

Consequently, postponement applications can significantly contribute to the customisation of both goods and services (Cholette 2009; Van Hoek 2001). The step when a product is committed to either a location or a final form, usually triggered by a customer order, has been termed as 'order penetration point' (Olhager 2003; Sharman 1984;) or more commonly as 'customer order decoupling point' (CODP) (Olhager 2010; Van Hoek, Commandeur, and Vos 1998a;). Olhager (2003) argued for the strategic importance of inventory at the decoupling point as it serves as the basis for delivery promises, since delivery time and inventory availability are computed with that inventory in mind (Zinn 2019). In postponed manufacturing applications, for example, customising products at an intermediate stage in the supply chain (i.e. after receiving customer orders) allows a firm to combine rapid and reliable delivery with improved responsiveness to customer needs (Salvador and Forza 2004; Van Hoek 2001).

Different postponement strategies have been suggested based on the notion of CODP, ranging from standardised 'Ship-to-Stock' (STS) and 'Make-to-Stock' (MTS) production through to engaging the customer in assembly ('Assembly-to-Order' – ATO), manufacturing ('Make-to-Order' – MTO) or even product design using 'Engineer-to-Order' (ETO) approaches (Gosling, Hewlett, and Naim 2017; Olhager 2003; Yang and Burns 2003). In an STS strategy, products are realised in many variations according to forecasts and shipped in anticipation of demand to retail stores where customers can choose from available options in stock (Ben Naylor,

Naim, and Berry 1999). Conversely, an MTS strategy involves manufacturing based on forecasts while the distribution to stores takes place after receiving customers' orders (Rudberg and Wikner 2004). In MTO, all manufacturing and assembly operations are driven by customer orders (Akkerman, van der Meer, and van Donk 2010; Olhager 2010). In an ATO strategy, there is an internal CODP dividing the internal material flow into two sections, leading to MTS-type operations for parts manufacturing upstream of the CODP and MTO-type operations for the assembly of finished goods downstream of the CODP (Harfeldt-Berg and Olhager 2024). If products need unique engineering design or significant customisation to be manufactured according to specific customer requirements, they are developed from scratch for each customer with an ETO strategy (Molina, Velandia, and Galeano 2007). When moving upstream the CODP (from MTS to ETO), the order-to-delivery lead time increases for customers as they will receive products after choices are provided. However, with postponed manufacturing, product customisation can be separated from the speculative manufacturing of basic materials and components (Skipworth and Harrison 2004). This separation frees primary manufacturing to focus on large economic runs of standard products or generic components and modules (Cooper 1993). Moreover, local variations in taste and product formulation can be integrated into the process if driven by orders (Brun and Zorzini 2009). The principle of postponement thus reaches beyond enabling the delivery of customised products to support an expansion of customer choice in terms of product variety, and postponing the final configuration of products enables an expanded offering of product variety in a cost-effective way (Feitzinger and Lee 1997).

2.2. Where to execute manufacturing operations?

Customisation can take place at the latest possible moment in the manufacturing process, yet still in the manufacturing plants, as further information (or the customer's order) is received (Van Hoek 2001; Zinn and Bowersox 1988). As an example, Cooper (1993) cited the manufacturing of television sets in Wales for the European market, whereby common parts were assembled in a 'Eurochassis' with customisation to a specific European country happening later in the manufacturing process. In turn, Van Hoek, Commandeur, and Vos (1998b) extended postponement across the downstream supply chains by suggesting that final customisation may also happen at the point of product delivery to the customer. This highlights that when designing postponement strategies what matters is not only when, but also where manufacturing operations take place (Lee 2010;

PrataViera et al. 2020). Manufacturing locations, as well as the place and form in which stock is held, can have a major impact on a company's overall performance (Lee 2010). For example, Hewlett-Packard has reported double-digit savings in supply chain costs by applying postponement in distribution networks (Feitzinger and Lee 1997). Similarly, Dell Computers based a significant share of its competitive approach on its strategy of close-to-the-market customisation and on the direct-delivery capabilities of postponement (Van Hoek 2001).

In global supply chains characterised by long international transport lead times, moving downstream operations from home regions to destination regions can allow companies to move the CODP closer to end consumers (Cohen and Lee 2020). With distribution points being closer to the market, it could be feasible for companies to delay operations until receiving the customers' orders, while at the same time respecting order-to-delivery lead time requirements (PrataViera et al. 2020). Moreover, global supply chains are affected by factors such as government regulations, subsidies provided by governments, customs tariffs, international trade and transport considerations, differences in workers' knowledge and expertise, and differences in international manufacturing costs (Hantsch and Huchzermeier 2016; MacCarthy and Atthirawong 2003). Faced with the many customs duties and free-trade agreements currently in place, companies need to (re)design their postponement strategies if they intend to achieve the right level of product customisation in each market region (Choi, Narasimhan, and Kim 2012; PrataViera et al. 2020).

3. Additive manufacturing

AM as a manufacturing process was first introduced in the late 1980s as a rapid prototyping technology that involves creating a three-dimensional object by adding layers of materials, as opposed to the traditional subtractive manufacturing method (Chen, Cui, and Lee 2021). In the last decades, it has emerged as a revolutionary technology in the manufacturing landscape, offering unparalleled opportunities for customisation within supply chains (Jimo et al. 2022; Li et al. 2024; Petrovic et al. 2011). The advent of AM implies a departure from traditional subtractive manufacturing methods, enabling the creation of individual parts directly from a 3D computer model (Heinen and Hoberg 2019; Zijm, Knofius, and van der Heijden 2019).

This layer-by-layer construction of objects based on digital models eliminates many of the constraints inherent in conventional manufacturing technologies (Eyers et al. 2022). Here, previous research highlighted that

AM could improve batch processing to fulfil customers' demand (Gunther et al. 2014). This is increasingly relevant to address market uncertainties by catering to diverse customer preferences and evolving market demands (Li et al. 2024; Nie et al. 2023). For example, many companies (e.g. after-sales service providers) have been attracted by the opportunity that AM offers to digitalise their inventories, since it allows for reducing stock levels by producing spare parts on demand (Cantini et al. 2024; Heinen and Hoberg 2019; Sgarbossa et al. 2021). Moreover, AM can enable the production of intricate and complex geometries that are often challenging or impossible to achieve with traditional manufacturing methods (Heinen and Hoberg 2019; Sethuraman, Parlaktürk, and Swaminathan 2023). To address the trade-off between volume and variety, AM offers opportunities to create bespoke products tailored to individual customer preferences, thus enhancing customer satisfaction but also opening avenues for targeting niche markets (Sethuraman, Parlaktürk, and Swaminathan 2023). AM applications could concern the creation of prototypes (i.e. rapid prototyping), the production of tools to support conventional manufacturing processes (i.e. rapid tooling), or the direct manufacturing of end-user parts (i.e. rapid manufacturing) (Eyers et al. 2022). AM's rapid prototyping capabilities could facilitate on-demand manufacturing by allowing for quick adjustments based on real-world testing and user feedback, while rapid tooling could further reduce manufacturing lead times (Eyers et al. 2022). Rapid manufacturing can also offer several benefits, including feasible small-batch production, economical single-unit production for bespoke products, and reductions in both lead times and inventories (Holmström et al. 2010). AM showcases potentials for localised production and distributed manufacturing (Ramón-Lumbierres et al. 2021), enabling products to be produced closer to the point of consumption through rapid manufacturing (Eyers et al. 2022). Localisation can also encompass waste reduction opportunities as traditional manufacturing methods often result in material waste due to subtractive processes while AM builds objects layer by layer, minimising material excess (Delic and Eyers 2020). Moreover, AM can reduce transport costs as well as support sustainable practices by minimising the environmental impact associated with long-distance shipping (Moradlou and Tate 2018).

However, several barriers might impede the seamless integration of AM into supply chains, forming critical challenges for different supply chain actors (Sethuraman, Parlaktürk, and Swaminathan 2023). Cost considerations, both in terms of equipment and materials, create significant uncertainties and firms want to ensure

that AM outperforms conventional manufacturing techniques (D'Aveni 2015; Eysers et al. 2022; Khajavi, Partanen, and Holmström 2014; Minguella-Canela et al. 2017). While AM has witnessed a decline in costs over time, the initial investment in high-quality AM equipment can still be substantial (Westerweel, Basten, and van Houtum 2018). The costs associated with certain advanced materials used in AM processes can also be prohibitive, impacting the economic feasibility of widespread adoption (Sethuraman, Parlaktürk, and Swaminathan 2023). Moreover, material availability can be critical as not all materials suitable for traditional manufacturing processes are compatible with AM, and quality control presents significant challenges (Eysers et al. 2022). Achieving consistent quality across AM-produced items can be complex, particularly when using different materials or AM technologies (Heinen and Hoberg 2019). This variability raises concerns about meeting stringent industry standards and regulatory requirements, impacting the broader adoption of AM in certain sectors (Sethuraman, Parlaktürk, and Swaminathan 2023). Low-cost domestic machines could produce parts of a reasonable quality yet lack the performance, reliability, repeatability, and more sophisticated capabilities observed in industrial machines (Eysers et al. 2022). This might hinder the ability to produce certain products, particularly those requiring specific material properties (Tuck, Hague, and Burns 2007; Mellor, Hao, and Zhang 2014). Furthermore, the limited scalability of AM processes poses further challenges for mass production, especially for large quantities of identical items (Ramón-Lumbierres et al. 2021). The layer-by-layer construction inherent in AM processes can be time-consuming, limiting its efficiency for high-volume manufacturing (Jimo et al. 2022). Further, supplying specific materials to individual locations for AM can create additional complexity compared to scenarios where materials are delivered and stored at factories (Eysers et al. 2022).

4. The intersection between postponement and AM

The evolution from mass customisation to scenarios where companies consider the exact requirements for any customer to provide an unlimited number of product variants urges companies to rethink their supply chains (Eysers et al. 2022). In this context, the extant literature underscores the transformative potential of AM in enabling customisation within supply chains (Heinen and Hoberg 2019). The advantages of AM, including bespoke production and increased responsiveness, seem to align well with the postponement principle (Minguella-Canela et al. 2017; Zinn 2019). Although

AM could enhance postponement strategies (Liu and Xu 2017; Moradlou and Tate 2018), potential advantages must be weighed against existing challenges such as scalability and quality control (Yang and Burns 2003). This section merges the two literature bodies presented in Sections 2 and 3 to explore the intersection between AM and postponement and discuss when and where such intersection can occur. We emphasise the opportunities and challenges linked to this intersection, as this can foster further exploration into how the integration of AM can be strategically harnessed with postponement strategies to meet the demands of a dynamic and customised market. To synthesise the untapped potential for improving operations through combining postponement with AM, we identified four critical dimensions that build on the postponement opportunities formalised in the seminal paper by Van Hoek (2001): uncertainties, volume, lead time, and supply chain design – added to environmental sustainability due to its rising relevance for postponement research (Budiman and Rau 2021).

Postponement can reduce demand uncertainties by delaying product finalisation, and integrating AM could enable scenarios where manufacturing happens only after certain demand is received (Moradlou and Tate 2018). Nevertheless, uncertainties surrounding AM's scalability and material compatibility remain critical (Eysers et al. 2022). Moreover, volume considerations are central to understanding AM's applicability across different production scales as they greatly impact product variety (Minguella-Canela et al. 2017; Yang and Burns 2003). If standalone postponement allows manufacturing to move beyond large volumes achieved through exploiting scale economies to making 'batches of one' (Van Hoek 2001), combining it with AM could enable producing unique parts for individual customers – offering potentially infinite product variety enabled by the digital design (Heinen and Hoberg 2019). Therefore, companies need to carefully balance production volumes and the degree of customisation required by customers (Minguella-Canela et al. 2017). However, while AM excels in agile batch processing and customisation, challenges can arise in meeting volume demands (Gunter et al. 2014). Lead time represents another critical aspect to consider, as rapid prototyping and localised manufacturing capabilities inherent in AM offer potential reductions of the order-cycle time (Eysers et al. 2022). If postponement enables accurate response to customers while performing manufacturing operations within the order-cycle time, the inclusion of AM may further reduce lead times (e.g. by conducting AM operations at the customers' premises) (Ramón-Lumbierres et al. 2021). However, layer-by-layer AM processes can be time-consuming and material constraints may also

limit its efficiency in high-volume manufacturing settings (Jimo et al. 2022). Logistics complexities and material sourcing intricacies are also critical to successful supply chain design (Heinen and Hoberg 2019). Postponement reduces operational complexity while improving flexibility (Van Hoek 2001), and its combination with AM could streamline manufacturing processes and provide cost and time efficiencies (Liu and Xu 2017). However, adjustments in traditional supply chain structures might be needed to accommodate material sourcing complexities and adapt inventory management strategies (Eyers et al. 2022). Lastly, postponement can minimise inventory-related waste, preserve valuable resources, and lessen carbon emissions (Budiman and Rau 2021; Yang, Yang, and Wijngaard 2005). For instance, by delaying the final stages of manufacturing, the amount of finished inventory and associated resource wastage – like product obsolescence at the product's end-of-life – can be substantially reduced (Jabbarzadeh, Haughton, and Pourmehdi 2019; Simão, Goncalves, and Rodriguez 2016). Combining postponement with AM could further reduce transport intensity, affecting both costs and GHG emissions, while the technology's additive approach can minimise material waste and support sustainability efforts (Moradlou and Tate 2018). Digital design could also minimise

waste and obsolescence, aligning with the principles of resource efficiency (Delic and Eysers 2020; Zijm, Knofius, and van der Heijden 2019).

Figure 1 illustrates the analytical framework supporting this study, where the identified critical dimensions are combined with different postponement strategies (i.e. when operations might take place according to the degree of customisation and CODP positioning) and the supply chain tiers where the same operations could be executed – laying the foundation to analyse AM's opportunities and challenges associated with each combination.

4.1. When do AM and postponement intersect?

In business environments characterised by accelerated product life cycles and erratic consumer behaviours, companies could use AM to improve responsiveness and move from MTS to MTO strategies (Chen, Cui, and Lee 2021). This suggests implications related to when customisation takes place, revisiting CODP positioning (Zinn 2019). Moradlou and Tate (2018) suggested that AM supports postponement strategies by delaying product manufacturing until the product specifications and demand are available, highlighting that AM could reduce

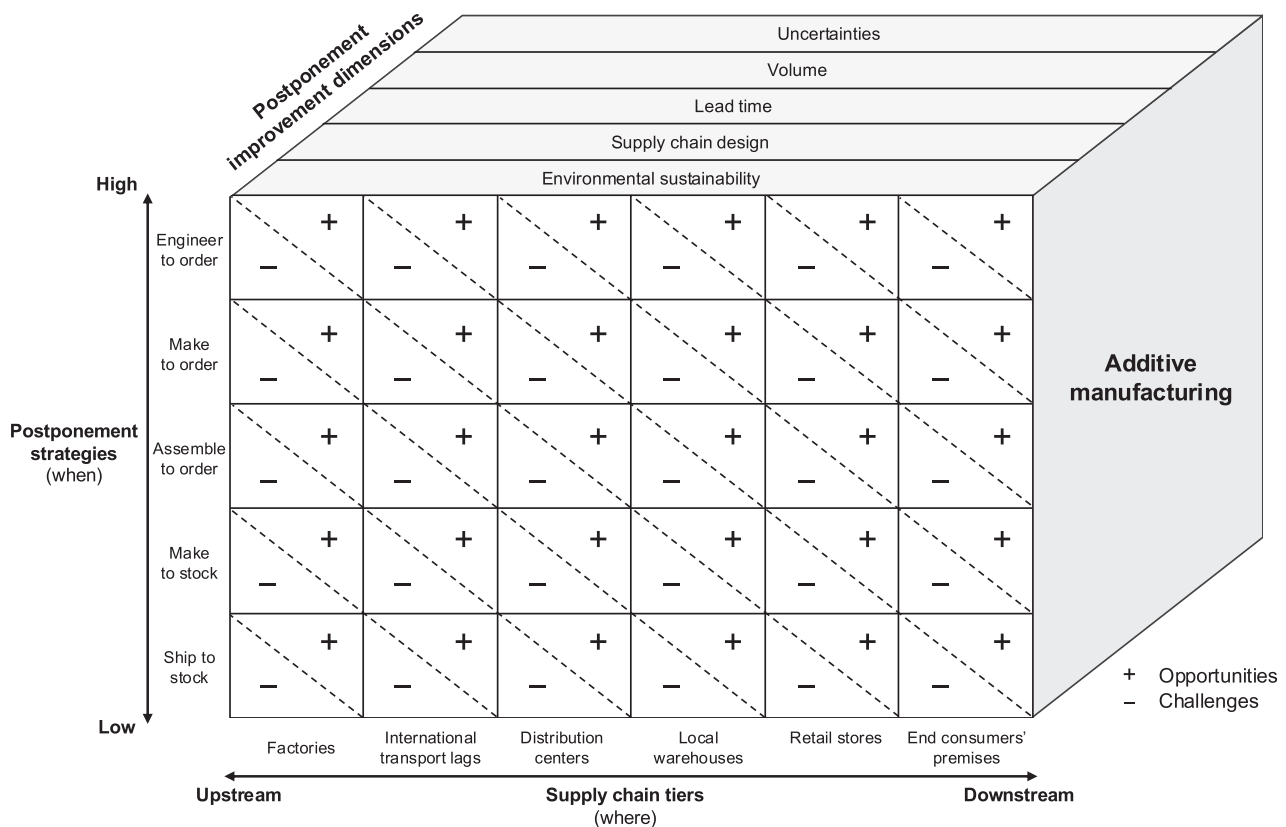


Figure 1. Analytical framework.

lead times, inventories, and transport volumes. Designing postponement strategies for a wide variety of products within heterogeneous industries requires carefully positioning the CODP to minimise uncertainty while guaranteeing the expected level of responsiveness. For example, Ramón-Lumbierres et al. (2021) investigated how AM could be used to accelerate the deployment of postponement strategies, developing a model to identify what operations to execute before or after receiving customers' orders. Within MTS strategies, AM could enable the cost-efficient manufacturing of customised products at scale, reducing order-to-delivery lead times and improving responsiveness to market trends. Moreover, companies could leverage rapid manufacturing to develop product designs that combine standardised and customised parts and components. Concerning ATO or MTO strategies, AM could facilitate high customisation with reduced assembly time, improving efficiency by manufacturing components just-in-time. While MTO or ATO approaches might involve additional manufacturing lead times, the shorter distribution channels enabled by AM could bring significant responsiveness benefits

along with short, if not null, delivery lead times. Moreover, AM could reduce lead times by enabling rapid production adjustments. AM could also allow for manufacturing unique parts or products, offering potential infinite product variety enabled by digital design. For example, companies in the consumer electronics industry might re-design their postponement strategies to address the product configurations demanded by individual consumers. Additionally, AM could reduce lead times from order to delivery, potentially reducing waste and obsolescence. Table 1 illustrates the potential opportunities related to introducing AM across different postponement dimensions and strategies.

Despite the discussed opportunities in Table 1, improving responsiveness should not shatter efficiency. While design flexibility and localised production might justify AM adoption, barriers including material limitations and cost considerations warrant careful consideration (Westerweel et al. 2021). AM supports virtualisation and decentralisation, but it can impact what operations to execute before or after receiving customers' orders, potentially increasing material and transport costs (Zinn

Table 1. Opportunities of AM at the intersection between postponement dimensions and strategies.

Postponement dimensions / strategies	Ship-to-Stock	Make-to-Stock	Assemble-to-Order	Make-to-Order	Engineer-to-Order
Uncertainties	Advanced AM machines lower demand uncertainty through rapid and localised production close to the point of demand.	AM enables more responsive in-store customisation via producing a variety of stock.	Advanced AM machines facilitate just-in-time assembly via rapid production of on-demand parts.	AM enables responsive order customisation through adapting production intervals with actual order details.	AM improves responsiveness to complex customer requirements via rapid prototyping and adaptive customisation.
Volume	AM enables economic production of small batches, aligning stock levels more closely with demand.	Through in-store customisation, AM supports stock variety without creating excess inventory levels.	AM streamlines assembly by producing on-demand parts without waste, reducing the need of large inventory.	Production via AM is directly tied to demand levels, reducing the need for holding large inventory volumes.	AM minimises inventory requirements of complex projects by producing only what is needed, when needed.
Lead time	Advanced AM machines can significantly reduce production lead times, enabling faster stock replenishment.	Through local manufacturing, AM boosts fulfilment speed and reduces lead times.	AM decreases the time from order to delivery by streamlining the production of customised components.	Direct AM production tailored to demand shortens lead times from the order penetration point to delivery.	Through rapid prototyping, AM accelerates completion of complex projects, lowering overall lead time.
Supply chain design	AM facilitates leaner supply chain networks with reduced buffer stocks and fewer supply chain nodes.	AM enables a more efficient supply chain that is adaptable to market demands with minimal excess inventory.	AM improves supply chain flexibility through late-stage customisation with reduced reliance on inventory and production space.	AM streamlines the supply chain's network by eliminating unnecessary production steps, directly serving customer demand.	AM lowers design constraints for bespoke complex orders, enhancing production speed and customer satisfaction.
Environmental sustainability	AM reduces waste and CO ₂ emissions by localised production, lowering excess inventory and transport volumes.	AM limits overproduction and excess inventory, aligning with eco-friendly manufacturing practices.	AM decreases material waste by producing only required components	AM minimises resource use and waste, as products are made specifically to fulfil an order.	AM supports sustainable practices by optimising design and material use for bespoke orders.

2019). The CODP is the most important stock point along the supply chain since the deliveries of finished goods to customers rely on the availability of all items that are strategically stocked at the CODP (i.e. the right mix of items with sufficient volumes) (Harfeldt-Berg and Olhager 2024). STS and MTS strategies could benefit from introducing AM, but critical issues could relate to inventory management for finished or semi-finished products as the positioning of the CODP determines the type of inventory to be held (Pagh and Cooper 1998; PrataViera et al. 2020). Companies could greatly benefit from introducing AM operations for customisation closer to customers in MTO and ATO strategies, as they could delay operations while respecting order-to-delivery lead time requirements from customers. However, coordinating the production of AM components with assembly processes requires tight integration, alongside just-in-time inventory models. Moreover, embedding AM into different postponement strategies requires considering the manufacturing complexity related to balancing the trade-off between geometry variations and mechanical properties of 3D printed parts. As decentralising manufacturing could require a new set of investments for tools and machinery (Moradlou and Tate 2018), companies need to carefully examine the trade-off between products (or specific components) realised through MTO, ATO, or MTS strategies. Also, several challenges emerge concerning the uncertainties in the availability, cost, and quality of resources for AM. Such challenges further extend to identifying and qualifying suppliers to enhance reliability in material supply for AM, potentially evaluating dual or multiple sourcing strategies for critical materials. When moving the CODP even further upstream in an ETO approach, highly customised projects may face constraints in AM capacity and expertise across supply chain tiers. International coordination of bespoke AM projects can complicate logistics and timelines, while providing on-site or near-site production for engineered orders might be critical in terms of both needed supplies and required manufacturing capabilities. Lastly, while AM has the potential to reduce transport intensity and lower GHG emissions, it may also generate waste from unused components or increase energy consumption when producing closer to demand points. As such, AM benefits must be carefully weighed against potential increases in material use and waste. Table 2 unpacks the challenges associated with introducing AM across different postponement dimensions and strategies.

4.2. Where do AM and postponement intersect?

Postponement strategies emerge from trading-off scale economies (achieved through centralisation of operations)

with local customer responsiveness through decentralised operations (Cooper 1993; Twede, Clarke, and Tait 2000). Nevertheless, operations could happen at different tiers along the supply chain (e.g. factories, warehouses, distribution centres, and markets) (Ramón-Lumbierres et al. 2021). The decentralisation of operations can affect the trade-off between supply chain costs and responsiveness, and conducting AM-based operations at different supply chain tiers can raise interesting opportunities related to reducing inventories.

One of the primary drivers facilitating the adoption of AM is its inherent design flexibility, which could reduce design to production times at factories, distribution centres, or local warehouses (Heinen and Hoberg 2019). AM could reduce inventory costs by enabling just-in-time production of parts, further enhancing the response to demand fluctuations. For example, companies can reduce the need for storing pre-manufactured goods, lowering warehouse demands and allowing complex and customised products to be made efficiently at factories. In addition, AM could support stock variety without large inventories through in-store customisation. Designs can be quickly changed, while new opportunities for design customisation could enable the optimisation of product design for functionality benefits (Holmström et al. 2010). Tools for moulding might no longer be required in an AM setup, and the elimination of tooling could reduce ramp-up time and cost. This could potentially allow for designing postponement strategies capable of accommodating a potentially infinite variety of products. Moreover, moving operations downstream towards the end consumers' premises might encompass an evolution from small batches to potential unique parts for each individual customer. Here, AM could enable cost-effective production of customised components and products tailored to individual preferences, supporting efficient and flexible distribution channels. In global supply chains characterised by long international transport lead times, moving customisation closer to end consumers can allow companies to delay operations until receiving the customers' orders if not enabling consumers to run customisation operations by themselves (PrataViera et al. 2020). Lastly, using AM could maximise customisation options for customers across various supply chain tiers, reducing waste and inventory costs by producing exactly what is ordered. Table 3 illustrates the potential opportunities related to introducing AM for postponement across different supply chain tiers.

On the flipside, combining AM with postponement strategies would vary at different supply chain tiers (e.g. factories, warehouses, stores), since scale economies might not justify dispersed production (Zinn 2019). Substantial investments can be required to purchase AM

Table 2. Challenges of AM at the intersection between postponement dimensions and strategies.

Postponement dimensions / strategies	Ship-to-Stock	Make-to-Stock	Assemble-to-Order	Make-to-Order	Engineer-to-Order
Uncertainties	Current forecasting modules may inaccurately predict AM stock needs, leading to overproduction or stockouts.	Challenges in balancing AM's production of customised components with fluctuating demand.	Managing just-in-time AM production of assembly parts requires advanced forecasting capabilities.	AM must manage demand variability and align production schedules with unpredictable order volumes.	AM's handling of unique customer requirements and frequent design changes increases complexity and potential for errors.
Volume	AM machines may struggle to meet high-volume demands, affecting inventory volumes and replenishment.	AM's bulk production risks obsolescence and challenges scaling production volumes to match demand.	Due to production speed constraints and demand fluctuations, AM risks inefficient assembly and excess inventory.	AM needs to efficiently scale production without maintaining excess inventory, while balancing small-batch production costs	Customised production may face limitations in scaling up efficiently for larger projects.
Lead time	Using outdated AM machines can increase lead times due to slower production intervals.	Balancing the benefits of AM customisation with the need for quick product availability can extend lead times.	Coordination of AM part production with assembly processes requires tight scheduling to avoid delays.	Customisation through AM can result in variable lead times, depending on the complexity of orders.	Complex bespoke orders may experience extended lead times as AM processes are tailored for each project.
Supply chain design	Adapting existing supply chain structure (e.g. retail space) for AM may require extensive planning and capital investment.	AM faces challenges in deciding between centralised production for economies of scale vs. decentralised for responsiveness	Coordination between producing AM components and assembly processes needs advanced integration between supply chain nodes.	AM demands a flexible supply chain design to accommodate varying specifications and order volumes.	Developing a supply chain that supports high customisation through AM involves substantial planning efforts.
Environmental sustainability	AM may create waste from unsold stock and yield high transport emissions due to large inventory distribution.	AM can result in high energy consumption and material waste from potential overproduction of customised stock.	AM's waste from unused components and high energy associated with frequent assembly line changes can affect sustainability.	AM offers potential for lower material waste compared to mass production, but higher energy consumption for small batches.	AM's high customisation in complex orders can lead to increased material waste and energy consumption due to frequent design and process changes.

machinery for rapid prototyping and rapid manufacturing, restricting the cases to which on-site AM is economically advantageous (Ahmed, Heese, and Kay 2023; Strong et al. 2019). Further challenges relate to assessing the capabilities and functions to offer variety at locations other than factories. New applications for mobile AM hubs are being studied and developed, moving AM to end consumers (Cui, Yang, and Di 2023). Yet, their economic feasibility is unknown, and further investigation is required. Moreover, both academics and practitioners need to understand what new materials are the most appropriate to feed AM. Significant challenges can relate to ensuring a steady and scalable supply of the required materials. Also, the cost of materials might change across supply chain tiers; AM parts are often more expensive than their traditional counterparts (Lolli et al. 2022) and must also be qualified in accordance with various standards (e.g. ISO). A limited number of businesses/institutions is now certified to qualify AM parts (Thomas-Seale et al. 2018), and this has a significant impact on the price of AM parts. Ensuring consistent quality and delivery times for direct shipments

can also be challenging, especially if AM is introduced closer to the end consumers' premises. Transitioning to on-demand production will also require significant changes in warehousing strategies (at both local warehouses and retail stores). Similarly, adapting retail stores to accommodate AM processes for customisation could create logistics hurdles due to the need to manage complex material supplies along with customers. On the one hand, inventory management would be more focused on raw materials, necessitating a shift in logistics planning. On the other, ensuring a seamless in-store assembly or customisation process could require new retail models and layouts, as retailers must manage customer expectations for customisation while respecting lead times and guaranteeing product availability.

The lack of precise standards and regulations also led to an increasing number of legal actions in recent years, mainly due to intellectual property infringement when producing AM parts (e.g. for respiratory valves during the fight against the Covid-19 pandemic (Tareq et al. 2021)). Fiscal and legal implications can also be different according to the various jurisdictions where AM

Table 3. Opportunities of AM related to postponement dimensions at different supply chain tiers.

Postponement dimensions / Supply chain tiers	Factories	International transport lags	Distribution centres	Local warehouses	Retail stores	End consumers' premises
Uncertainties	AM allows on-demand production at factories, reducing uncertainty in factory-level inventory.	AM reduces reliance on international transport by producing closer to demand, lowering demand uncertainties.	AM decreases demand forecasting errors by allowing closer to market production.	AM reduces need for large safety stocks in local warehouses, mitigating local demand uncertainties.	AM offers in-store production capabilities, reducing reliance on external supply and demand forecasts.	AM allows consumers to directly influence product customisation, reducing mismatch risk.
Volume	AM supports small-batch, on-demand production in factories, accommodating variable factory output.	AM reduces need for bulk international shipments, optimising transport volumes.	AM allows for scalable production at distribution centres, tailored to current regional demand.	AM enables efficient local warehouse stock levels to minimise excess inventory.	AM supports just-in-time production in stores, aligning inventory with actual sales volume and reducing inventory.	AM minimises overproduction by enabling personal fabrication or local manufacturing hubs.
Lead time	AM shortens factory lead times by producing parts and products on-site.	AM reduces lead times associated with shipping bulk products internationally by producing locally.	AM allows for quicker restocking and fulfilment cycles at distribution centres.	AM enables faster local replenishment by producing items closer to demand points in local warehouses.	AM reduces time from production to shelf in retail stores, enhancing responsiveness to customer needs.	AM delivers immediate satisfaction by enabling at-home production or local pickup.
Supply chain design	AM facilitates decentralised production at factories, improving overall supply chain resilience and flexibility.	AM reduces dependency on international shipments, simplifying global supply chain design.	AM enables more responsive and adaptable regional distribution strategies.	AM supports agile warehousing strategies with lower local inventory requirements.	AM allows for dynamic store layouts and responsive inventory management in retail stores.	AM can shift part of the production closer to or directly at the consumer end, personalising the supply chain.
Environmental sustainability	AM reduces waste at factories through precise material usage and on-demand production.	AM decreases transport emissions by reducing the need for large, international shipments.	AM lowers environmental impact at distribution centres by minimising excess inventory and reducing waste.	AM supports sustainable practices at local warehouses with reduced storage needs and localised production.	AM reduces waste and emissions in retail stores from overstock and unsold inventory.	AM encourages sustainable consumption patterns by enabling made-to-order production.

operations could take place in global supply chains, creating further challenges. Finally, some dilemmas may also arise from an environmental standpoint. Academics and practitioners need to assess the carbon footprint related to alternative supply flows, as well as compare centralised manufacturing versus decentralised manufacturing in terms of GHG emissions. By producing parts close to the point of use, AM could allow for reducing the environmental impact of the transport phase. However, the AM production process is quite energy intensive. As a result, considering the entire product lifecycle may not result in a reduction in the overall environmental impact (Demiralay et al. 2023; Top et al. 2023) – making it unclear when it is truly convenient to adopt AM (Jarrar et al. 2023). Table 4 outlines the challenges concerning postponement implementation supported by AM across different supply chain tiers.

5. Moving the conversation forward: future research recommendations

As previous studies limitedly analysed the intersection between postponement and AM, this paper builds upon earlier studies (e.g. Liu and Xu 2017; Moradlou and Tate 2018; Ramón-Lumbierres et al. 2021) to deepen the understanding of this specific phenomenon. To this extent, we leveraged the opportunities and challenges discussed in Section 4 to identify research recommendations fostering future investigations for each of the postponement improvement dimensions we identified in our analytical framework (Figure 1). Moreover, our literature review highlights that postponement research (e.g. Boone, Craighead, and Hanna 2007; Pratavia et al. 2020; Van Hoek 2001) has been limited in its consideration of any grand theory to explain its working logic or predict its outcomes. As such, investigating the intersection between postponement and AM can create new opportunities for theorising to improve our understanding of the postponement phenomenon. Thus, we also propose several theoretical paths that could inform and strengthen future research in this area.

5.1. Uncertainties

Integrating AM into postponement strategies offers opportunities to digitalise inventories and create complex geometries during production, reducing demand uncertainties as manufacturing can happen only after certain demand is received (Heinen and Hoberg 2019; Moradlou and Tate 2018). Although there is a vast range of products that could be 3D printed, this does not entail that AM is

the best approach in all circumstances. AM seems appropriate for scenarios where the piece is unique and customised – and scholars agree that AM can be a key technology for the future of spare parts production (D'Aveni 2015; Eysers et al. 2022; Heinen and Hoberg 2019). However, AM implementation contexts could go beyond spare parts management and application boundaries may be blurrier than expected. Here, there is huge potential to develop hybrid postponement strategies involving different CODPs for various parts/products. Some parts can be standardised, while others are customised if not entirely unique (e.g. prostheses for surgery replacements). Standardised components might not be subject to any kind of postponement, while customised ones might be 3D printed at different tiers across the supply chain. Capabilities and competencies needed for a hybrid design may also change across different supply chain tiers (Conner et al. 2014). Despite the potential advantages of AM in this context (i.e. minimising inventories and forecasting risk for high-value and unique/critical items), the development of this type of hybrid supply chains might be hampered by a few major limitations, from amplified manufacturing costs to increased coordination complexity. Thus, to reap higher benefits from AM-enabled postponement, the level of customisation as opposed to complexity needs to be considered in the decision-making process (Conner et al. 2014). It seems great to have everyone producing what is needed, when is needed. However, scale economies, required capabilities, and materials supply requirements are valid reasons for companies to pursue centralised manufacturing. Therefore, it is essential to establish clear criteria for identifying which products can be subject to AM-enabled postponement in a hybrid supply chain design. Additionally, there is a need to explore the complementarities between AM technologies, standardisation, and customisation of parts and products in a hybrid design across supply chain tiers. Therefore, future research should consider these important aspects when exploring the potential for AM to design hybrid supply chains where standardised and customised parts and components co-exist.

Utilising the Dynamic Capabilities View (Eisenhardt and Martin 2000; Teece, Pisano, and Shuen 1997) could provide a robust framework to investigate how AM can reduce uncertainties by enabling hybrid supply chains where standardised and customised parts co-exist. This theoretical lens can elucidate how organisations harness AM to swiftly reconfigure their resources and operations, fostering an environment where both standardised and customised parts enhance supply chain agility and responsiveness. The theory also emphasises the strategic management of resources to exploit emerging opportunities and address challenges presented by AM, such as

Table 4. Challenges of AM related to postponement dimensions at different supply chain tiers.

Postponement dimensions / supply chain tiers	Factories	International transport lags	Distribution centres	Local warehouses	Retail stores	End consumers' premises
Uncertainties	AM faces challenges in demand forecasting at factories, leading to potential overproduction or stockouts.	AM complicates predicting international shipment needs due to variable production times and the dependency on global supply chains for raw materials.	AM can lead to inconsistent supply at distribution centres, complicating inventory management.	AM's demand variability makes it hard to maintain optimal stock levels in local warehouses, due to the need to balance AM production with warehouse operations.	Retailers may struggle with rapid changes customer demands when integrating AM within traditional retail models and adapting retail spaces to accommodate AM processes.	AM's reliance on consumer input for production can lead to unpredictability and variability in usage. Also, ensuring consistent quality for AM materials can be challenging.
Volume	AM's small-batch production at factories may not achieve economies of scale, leading to higher costs.	AM's low volume production reduces bulk shipping efficiency.	AM requires careful coordination to handle variable volumes, risking inefficiencies. AM usage can inflate inventory volumes due to producing items closer to the demand point.	AM's usage can cause challenges in maintaining consistent stock levels, whereas the focus on raw materials can lead to changes in warehousing strategies.	AM's in-store production can lead to space constraints and operational inefficiencies. Retailers must manage new customer expectations for product availability.	AM's low volume, customised production can be costly and inefficient for consumers.
Lead time	AM's production speed constraints at factories can lead to longer lead times.	AM's reliance on local production can delay international supply chain processes.	AM may face challenges in maintaining quick restocking cycles due to production delays.	AM's slower production rates may lead to delays in local replenishment.	AM's in-store production might not meet immediate demand spikes, leading to customer dissatisfaction.	AM's production speed constraints can result in longer wait times for consumers.
Supply chain design	AM's integration into factory processes requires significant reconfiguration and investment.	AM reduces the need for international transport but complicates global supply chain coordination.	AM demands redesigning distribution strategies to accommodate on-demand, localised production.	AM's need for frequent, small deliveries can increase local logistical complexities.	AM requires changes in store layouts and operations to integrate production capabilities.	AM's integration into home environments requires user-friendly designs and substantial initial setup.
Environmental sustainability	AM's energy-intensive processes at factories can negate some environmental benefits.	AM reduces transport emissions but increases local energy consumption.	AM's potential for material waste due to frequent design changes and small-batch production.	AM's localised production can increase energy usage, offsetting some sustainability benefits.	AM's in-store production increases energy consumption and may result in material waste.	AM's home production can lead to higher energy usage and potential waste from trial-and-error production.

coordinating hybrid manufacturing processes and balancing scalability with customisation. Further, applying the theory in this context could offer insights into managing the intricate interdependencies and variability inherent in hybrid supply chains and help analyse how AM contributes to the complexity of supply chain structures and processes – particularly in integrating standardised and customised production. By applying the Dynamic Capabilities View, researchers could explore how companies navigate increased coordination demands and potential for system unpredictability, focusing on strategies to maintain efficiency and resilience in the face of manufacturing and supply chain complexity.

5.2. Volume

AM offers opportunities to address the trade-off between volume and variety, as companies can create bespoke products tailored to individual customer preferences (Sethuraman, Parlaktürk, and Swaminathan 2023). Whilst variety through permutations and combinations of options can be complex, the challenge facing today's manufacturers is the requirement to move beyond variety (Eyers et al. 2022). Unlike variety achieved through a catalogue of options or modularity of assemblies, customisation in AM can allow customers to individually shape their products in single volumes to meet their own requirements. The aerospace and automotive industries were the forerunners in AM pilot testing (Westerweel, Basten, and van Houtum 2018) and its use has now spread to other industries and applications (Akbari 2023; Durach, Kurpjuweit, and Wagner 2017). In the biomedical industry, using AM makes it possible to produce implants that match the needs of the human body more closely than traditional manufacturing, enabling bespoke products that perfectly suit an individual patient (Emelogu et al. 2016). Similarly, after-sales companies have been attracted by the opportunity that AM offers to digitalise their inventory since AM makes it possible to reduce stock levels by producing spare parts on demand (Heinen and Hoberg 2019). AM can be attractive for low volume spare parts production as it would potentially reduce the number of shipments across supply chain tiers, thereby reducing logistics costs (i.e. transport and warehousing) (Friedrich, Lange, and Elbert 2022; Li et al. 2017; Westerweel et al. 2021). In the context of spare parts production, AM could lead to lower setup costs and tooling investments (Frandsen et al. 2020). However, switching costs from conventional manufacturing techniques to AM can also be significant, preventing many firms from adopting AM (Akbari 2023; Heinen and Hoberg 2019). This paradox underlines both a research gap and an opportunity for further scholarly contributions and

exploration in this area, aiming to investigate products and industries suitable for AM-enhanced postponement but also analyse how the benefits gained from AM-enhanced postponement differ by industry-specific characteristics.

Incorporating Contingency Theory (Stonebraker and Afifi 2004) into the exploration of AM-enhanced postponement strategies can elucidate the nuanced interplay between a firm's internal capabilities and its external environment, in line with the original premise of the theory (Van de Ven and Drazin 1984). By employing the theory, scholars can address the trade-off between volume and variety by analysing how the variations in the effectiveness of AM across different product types and industries are contingent upon the alignment between strategic choices and contextual demands (Sousa and Voss 2008). As such, it prompts an examination of the ways in which product characteristics such as complexity, variability, and demand uncertainty are aligned with AM-enhanced postponement strategies. This inquiry could not only identify where AM fits best but also construct a strategic fit analysis between AM capabilities and the varied requirements of market environments through the lens of the theory, thus providing comprehensive insights into effective AM-enhanced postponement strategies.

5.3. Lead time

Using AM within postponement strategies can shorten lead times and improve responsiveness and efficiency (Hohn and Durach 2021; Knofius, van der Heijden, and Sleptchenko 2021). For example, on-site printing for spare parts production at remote geographic locations can guarantee supplies even when facing upstream disruptions and constraints in replenishment (Bogers, Hadar, and Bilberg 2016; Westerweel et al. 2021). In global supply chains, which involve international transport lags, AM could be implemented through 3D printing on board vessels during lengthy sea transport delays. This could contribute to both producing spare parts for maintenance or customising parts or products before arriving in destination countries. However, in global supply chains, important implications relate to where operations take place (Prataviera et al. 2020) as changing the location of such operations can affect the trade-off between supply chain costs and responsiveness. Therefore, AM has the potential to significantly influence reshoring and nearshoring initiatives. Here, reshoring (i.e. the return of manufacturing operations to domestic markets) may be facilitated by AM's ability to reduce production costs and lead times, making local production more competitive (Moradlou and Tate 2018). In turn, nearshoring (i.e. the relocation of production facilities closer to end

markets) could benefit from AM by enabling agile and decentralised manufacturing networks (Durach, Kurpjuweit, and Wagner 2017). This would enable both quick responses to changing customer demands in local markets and the shrinking of supply chain distances (Sasson and Johnson 2016). However, challenges such as the need for skilled labour and the development of robust AM ecosystems (Friedrich, Lange, and Elbert 2022) must be addressed to fully capitalise on these opportunities. Therefore, scholars could examine AM-related implications for global supply chains to specifically understand the influence of AM adoption on reshoring and nearshoring initiatives.

In this context, applying Complexity Theory (Byrne 2002; Lewin 1999) and Network Theory could disclose relevant research opportunities. Complexity Theory could help analyse how AM's impact on reshoring and nearshoring depends on how well these strategies align with organisations' external environment and internal capabilities. On the other hand, Network Theory can scrutinise the relationships and interactions within and across organisations that constitute the global supply network. Thus, it could shed light on how AM fosters the development of agile and decentralised manufacturing networks, further elucidating the reshoring or nearshoring phenomena.

5.4. Supply chain design

Introducing AM might challenge the existing relationships with suppliers and sub-suppliers, further creating the need for new materials supply (Ramón-Lumbierres et al. 2021). Integrating AM with postponement could redefine make-or-buy decisions (Jimo et al. 2022) and sourcing strategies (Akbari 2023). Companies might want to make critical components in-house to maintain better control over the supply chain (Friedrich, Lange, and Elbert 2022). Recent developments in this area suggest further exploration of the rent or buy of 3D printers (Li et al. 2024), as printers become part of the value creation (Bogers, Hadar, and Bilberg 2016). This can be particularly interesting for performing postponement activities at different supply chain tiers, as the limited number of 3D printers' manufacturers in the market creates power asymmetries. Printers' manufacturers might want to maintain existing power dynamics that potentially affect printers' availability on the market, thus creating scalability problems (Bogers, Hadar, and Bilberg 2016). Scholars might also explore the dynamics between printers' manufacturers and material suppliers in the 3D printing industry, emphasising the importance of collaborative relationships in advancing technology. This is also true for material used for 3D printing, which is

considered to be scarce and expensive, creating an opportunity for further investigation of buyer-supplier relationships in this context. An interesting area that needs further exploration is the emergence of rental manufacturing infrastructure, where one company with 3D printing capabilities offers on-demand printing for other businesses in the same geographical area (Sasson and Johnson 2016). Moreover, scholars could explore how local manufacturing would change logistics needs; AM could disrupt business relationships with logistics service providers, as manufacturing decentralisation could reduce transport needs. However, a counterargument suggests that logistics service providers will have a greater role in 3D printing services (Durach, Kurpjuweit, and Wagner 2017). This suggests that a deeper understanding of ownership over the design process is needed. For example, companies need to understand how to manage digital designs and the sharing of digital models with customers, yet the loss of intellectual property becomes a concern for supply chain actors involved in information and knowledge exchange. Thus, exploring interorganisational relationships is an interesting venue for future researchers, as AM and other emerging technologies have failed to protect intellectual properties rights in AM, which could inhibit the development of decentralised or 'glocalised' AM manufacturing networks (Kurpjuweit et al. 2021).

In global supply chains, important implications relate to where operations are executed, not only in terms of supply chain tiers but also concerning the involved countries and jurisdictions – due to the legal and fiscal challenges that emerge when conducting operations in different jurisdictions (Ballardini, Flores Ituarte, and Pei 2018; PrataViera et al. 2020). Different countries have different regulations, standards, and compliance requirements which could create challenges for the implementation of AM-enabled postponement operations (Akbari 2023). First, the location where operations take place, as well as the place and form in which stock is held, can have major legal and fiscal implications (Cohen and Lee 2020). It can influence where and how much a company pays in duties and other taxes, but such impact could extend to individual consumers if they are accountable for such operations due to AM implementation. As regulatory frameworks often differ across jurisdictions, legal and fiscal issues might create compliance problems that open new challenges deserving further examination (Norrman and PrataViera 2023). Second, there might be concerns about intellectual property rights associated with AM-enabled postponement (Bogers, Hadar, and Bilberg 2016; Friedrich, Lange, and Elbert 2022), especially in the case of unbranded and unpatented products that require minimal standardisation (Savolainen and Collan 2020). The increased consumer involvement through AM-enabled

postponement at the consumer premises, or when parts are not centrally produced, would also raise legal liability questions that call for further research exploration (Ballardini, Flores Ituarte, and Pei 2018; Bogers, Hadar, and Bilberg 2016). The changes in the CODP across the different tiers of the supply chain will also have legal liabilities depending on whether the official manufacturer keeps control of the designs or source code (Ballardini, Flores Ituarte, and Pei 2018; Bogers, Hadar, and Bilberg 2016). Thus, these challenges highlight the opportunity for significant contributions by both scholars and practitioners to enhance understanding AM-related implications for global supply chains, particularly in terms of legal and fiscal implications across multiple jurisdictions.

Here, applying Transaction-cost Economics (Williamson 1981) could strengthen the understanding of how integrating AM with postponement strategies can influence make-or-buy decisions and reshape buyer-supplier relationships. The theory could help analyse the cost implications of in-house production versus outsourcing in the context of AM, considering the costs of coordination, contracting, and adjusting supply chain structures. Another relevant theoretical perspective to unveil AM-enhanced postponement opportunities could be the Resource Orchestration Theory (Sirmon et al. 2011). Focal companies orchestrate their own knowledge with the knowledge and resources of other supply chain actors, influencing supply chain relationship and their dynamics (Gong et al. 2018). Therefore, Resource Orchestration Theory can help understand how to effectively deploy and utilise resources in an AM-enhanced postponement context, emphasising that what matters is not postponement or AM but the alignment of these two interdependent concepts. If firms adapt and reconfigure their resources and capabilities to exploit AM opportunities, scholars could explore how these capabilities support strategic decision-making in make-or-buy scenarios and the management of evolving buyer-supplier relationships to generate synergistic effects (Hitt, Xu, and Carnes 2016). Lastly, Contingency Theory (Stonebraker and Afifi 2004) could also be relevant to explain how the specific contexts of global supply chains (including geographical, legal, and market conditions) affect the adoption and effectiveness of AM. This theoretical perspective could further help examine how variations in regulatory frameworks, labour skills availability, and technological infrastructure across different regions influence the strategic use of AM in global supply chains.

5.5. Environmental sustainability

As the planet is becoming dangerously unstable, supply chains need to deliver greater value with less input

and use resources sustainably and efficiently to minimise environmental impacts (Budiman and Rau 2021). Reducing supply chains' environmental impacts while optimising cost-effectiveness presents a delicate equilibrium to achieve, and postponement strategies can help address it (Jabbarzadeh, Haughton, and Pourmehdi 2019). Postponement strategies can minimise inventory-related waste, save valuable resources, and lessen carbon emissions (Yang, Yang, and Wijngaard 2005), and their combination with AM could potentially revolutionise the carbon footprint associated with product flows. However, we need contextualised analyses of the impact on GHG emissions driven by centralised vs. decentralised manufacturing (Budiman and Rau 2019). AM could reduce transport intensity, affecting both costs and GHG emissions, but this could be different across different transport lags and for different positioning of the CODP (Simão, Gonçalves, and Rodriguez 2016). Scholars could explore the trade-offs between economic and environmental outcomes, as they might offer win-win scenarios as well as conflicting perspectives. For example, AM could minimise material waste (Chen, Cui, and Lee 2021; Sasson and Johnson 2016) but the environmental impact driven by redesigning supply chains might encompass an increase in the overall emissions related to transporting materials to the new manufacturing locations and to conducting AM-enabled manufacturing operations. Moreover, implications could differ if CODP positioning varies, creating new trade-offs (Budiman and Rau 2019). Empirical investigations about these trade-offs could encourage the development of a new set of measures, indicators, and methodologies to compute the GHG emissions generated across various supply chain tiers for different CODPs. Scholars could also develop analytical research to investigate different postponement strategies along with their enablers and the resulting environmental impacts.

Applying Resource-Based View (Barney 1991) and Stakeholder Theory (Freeman et al. 2010) could offer a comprehensive perspective on understanding the environmental implications of integrating AM into postponement strategies. Resource-Based View can highlight how firms leverage their unique resources and capabilities, such as AM technology, to achieve sustainable competitive advantages while minimising their environmental impact. This viewpoint encourages exploring how AM can serve as a strategic asset to reduce GHG emissions through more efficient production/logistics processes, emphasising the firm's internal strengths in driving environmental sustainability. In turn, Stakeholder Theory could broaden the inquiry's scope by considering the expectations and influences of various stakeholders on a firm's environmental strategies. It may also underscore

Table 5. Research agenda for AM-enhanced postponement strategies.

Postponement dimensions	Research recommendations	Example research questions	Suggested theoretical perspectives
Uncertainties	Explore the potential for AM to design hybrid supply chains where standardised and customised parts and components co-exist	How could AM enable hybrid supply chains of standardised and customised parts and components? How can companies balance the trade-offs between economies of scale associated with standardised production and the flexibility offered by additive manufacturing for customised parts in hybrid supply chains?	<ul style="list-style-type: none"> • Dynamic Capabilities View
Volume	Investigate products and industries suitable for AM-enhanced postponement when trading-off volume and variety	How can AM influence postponement strategies for different types of products and industries? How do benefits gained from AM-enhanced postponement differ by industry specific characteristics?	<ul style="list-style-type: none"> • Contingency Theory
Lead time	Analyse how AM adoption can influence sourcing decisions (i.e. reshoring, near-shoring) to shorten lead times	How does AM impact postponement strategies across different regions and countries to reduce delivery lead times? How does AM adoption influence the strategic decisions of companies regarding reshoring or nearshoring production activities, and what are the key factors driving these decisions?	<ul style="list-style-type: none"> • Complexity Theory • Network Theory
Supply chain design	Examine changes in buyer-supplier relationships and potential challenges related to legal compliance when intersecting AM and postponement strategies	How can AM reshape buyer-supplier relationships for postponement strategies? How does AM influence make-or-buy decisions across supply chain tiers when implementing postponement? How to manage intellectual property rights and legal compliance when developing AM-enhanced postponement strategies?	<ul style="list-style-type: none"> • Transaction-cost Economics • Resource Orchestration Theory • Contingency Theory
Environmental sustainability	Explore the environmental implications linked to embedding AM into postponement strategies	How does AM impact energy consumption, waste generation, and GHG emissions for different postponement strategies? How does CODP positioning determine the environmental implications of AM-enabled postponement strategies?	<ul style="list-style-type: none"> • Resource-Based View • Stakeholder Theory

the importance of aligning AM-enhanced postponement strategies with the broader goals of environmental stewardship, as perceived by customers, regulators, and the community at large. Ultimately, the theory advocates for a holistic approach that recognises the interdependencies between firms and their stakeholders in achieving environmental objectives, suggesting that successful implementation of AM in postponement strategies not only requires technological innovation but also stakeholder engagement and collaboration to effectively address environmental concerns.

In sum, our investigation into the intersection of postponement and AM has uncovered new research opportunities to enhance our understanding of the postponement phenomenon. This also prompted us to propose several theoretical perspectives that can guide and strengthen

future research in this area. Table 5 provides an overview of the research agenda proposed in this section.

6. Concluding remarks

In the dynamic landscape of supply chain management, the confluence of postponement strategies and AM suggests promising synergies (Minguella-Canela et al. 2017; Zinn 2019). AM can help improve supply chain responsiveness and strengthen postponement applications for product customisation, yet the existing literature has been overlooking the nuanced opportunities and challenges that arise when AM intersects with postponement (Chen, Cui, and Lee 2021; Ramón-Lumbierres et al. 2021). We merged these two bodies of literature, building upon empirical contributions offered by previous

studies and reviewing them to explore their intersection through analytical conceptual research. We depicted several scenarios related to combining AM with postponement strategies according to different alternatives for CODP positioning and to different supply chain tiers that could incorporate AM. This enabled us to formulate a research agenda for scholars to explore how AM could enhance or hinder the application of postponement strategies. This agenda is outlined with a focus on exploring when and where to postpone AM-related operations, as well as examining which products and industries are best suited for AM-enhanced postponement.

6.1. Research implications

In this study, we synthesise the current state of knowledge by integrating discussions from diverse research areas, consistent with Cronin and George (2023). Recognising that scholars from different fields often overlook shared intersections, we merge two distinct bodies of literature – postponement and AM – to facilitate a reciprocal engagement, thereby generating new insights within each domain. Further, we organise and categorise the reviewed materials using a newly developed analytical framework based on extant AM-postponement literature (Figure 1), thus identifying how each field can inform the other and highlighting ongoing challenges and opportunities. This approach promotes knowledge development by shaping emergent themes and streams related to when and where AM intersect with postponement – problematising the literature to establish solid departure points for future theorising.

This study also unveils a portfolio of theoretical opportunities for scholars across five core dimensions of postponement improvement: uncertainty, volume, lead time, supply chain design, and environmental sustainability. As the primary goal is to provide guidance for those interested in conducting further research on the AM-postponement intersection, the proposed agenda clarifies how research should proceed, including recommendations for new questions to be asked, theories to be utilised, and efforts to be channelled (Cronin and George 2023). By combining knowledge about postponement and AM, we not only direct researchers toward new landscapes but also offer them new perspectives on existing ones. To this end, we view this study as an ‘opening up exercise’ that could enable researchers to critically interrogate and reimagine extant literature to generate new ways of thinking (Alvesson and Sandberg 2020). This exercise offers novel ideas that lie at the boundaries of AM and postponement domains, highlighting areas in need of more frontline empirical work.

6.2. Managerial implications

Despite the study’s conceptual nature, it also offers practitioners a set of managerial insights that could pragmatically inform the combination of postponement and AM in practice. Previous studies suggest that AM-postponement combinations could be fruitful when demand is unpredictable and customers require a high degree of customisation (Mellor, Hao, and Zhang 2014; Minguella-Canela et al. 2017). We thus propose a novel 2×2 matrix framework to guide the strategic adoption of AM in postponement strategies (Figure 2). The matrix is structured along two critical dimensions: production volume (low to high) and customisation level (low to high). Each quadrant presents a distinct strategic approach to AM adoption – Pilot, Scale, Evaluate, or Integrate – accompanied by nuanced conditions that signal the appropriateness of each. These conditions are derived from our comprehensive analysis of AM opportunities and challenges across various postponement strategies and supply chain tiers – i.e. Section 4.

Figure 2 supports practitioners’ decision-making by offering insights into when and how to leverage AM technologies within different supply chain contexts. For example, managers could pilot AM to enhance responsiveness in manufacturing and minimise lead times for unique customer orders, including bespoke components subject to highly variable demand patterns (Ramón-Lumbierres et al. 2021). Yet, before scaling AM adoption when production volumes increase, managers should ensure the timely supply of materials for AM and guarantee the availability and reliability of the resources required at different supply chain tiers. Demand volume is a key driver, making AM suitable for localised MTS production of consumer goods (e.g. Chen, Cui, and Lee 2021) – though AM may not be appropriate for every type of products. AM might appear as an easy-to-go technology to enable the production of complex geometries and respond to rapidly evolving consumer preferences and market demands, yet managers should carefully evaluate whether AM adoption is aligned with postponement strategies and the corresponding CODP positioning when demand is sporadic.

Building on the matrix offered in Figure 2, we also suggest broader issues that should capture managers’ attention across the four identified approaches. First, managers need to carefully examine both investment and operational costs associated with AM-enhanced postponement. While AM enables reduced material costs, the initial investment in AM equipment remains substantial, potentially restricting cost-effectiveness to a limited number of scenarios that allow on-site AM machinery. Here, introducing AM for postponement purposes varies

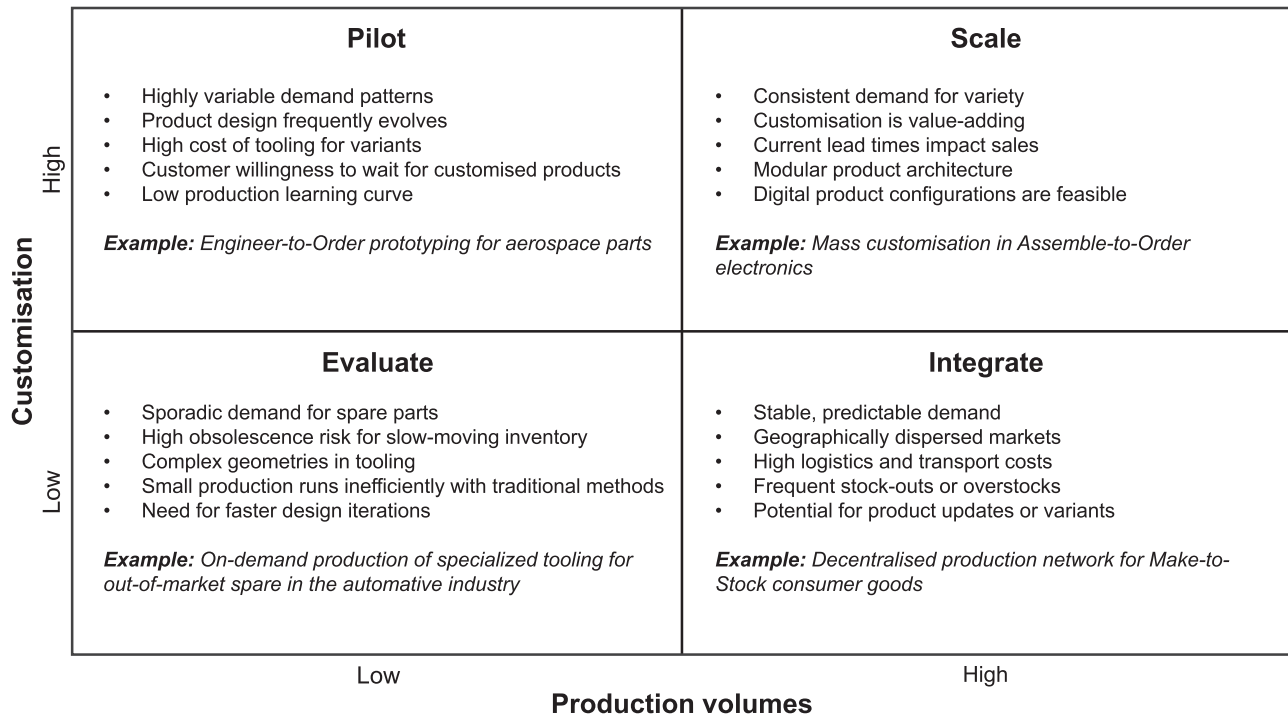


Figure 2. Strategic approaches to AM adoption for postponement.

across different supply chain tiers (e.g. for OEMs, B2B customers, or B2C customers), since scale economies may not justify dispersed manufacturing. This also highlights the critical impact of sourcing the right materials and tools. Managers need to assess the availability and scalability of the new tools and machinery required for AM, further examining the capabilities and functions required to offer variety. We also highlight the need to understand what new materials might be the most appropriate for AM; as postponement strategies differ, different resources might be required at distinct stages of product development across various supply chain tiers. Furthermore, managers must assess how the decentralisation of operations affects the trade-off between supply chain costs and responsiveness. This study also emphasises that regulatory frameworks differ across jurisdictions, stressing that legal and fiscal issues might create serious compliance problems. Combining postponement strategies with AM can change where and how much companies pay in duties and taxes, and such impact could extend to individual consumers if they become accountable for such operations due to AM implementation. Lastly, we offer guidance concerning the stricter environmental regulations that compel managers to carefully examine the environmental implications of their supply chains. To this end, combining postponement strategies with AM can reduce inventory and encompass waste reduction opportunities, while decentralised manufacturing could

reduce transport costs and minimise the environmental impact associated with long-distance shipping. Nevertheless, we advise managers to conduct in-depth environmental assessments that consider all supply chain tiers, from manufacturing to distribution until consumption.

6.3. Research limitations and future developments

While this study makes significant contributions, it also has limitations. The main one is that our analysis is purely conceptual, lacking empirical support from primary data sources. Although this broad ‘bird’s-eye’ perspective (Ivanov and Dolgui 2020) is justified by the current scarcity of AM applications for postponement in real-world settings (Ahmed, Heese, and Kay 2023; Li et al. 2024), we expect the situation to change soon as manufacturers increasingly consider AM technologies to enhance their supply chains’ efficiency, flexibility, and response to fluctuating market demands. Given this context, conceptual studies like ours are important, as they provide a foundation for future empirical research, particularly in fields where direct evidence is still emerging (e.g. Dolgui and Ivanov 2024; Psarommatitis et al. 2022; Youngdahl and Ramaswamy 2008). Another limitation of this study is the lack of differentiation between specific AM technologies, which may lead to an oversimplification of their impacts across various postponement contexts. To address this, we recommend that future studies

expand our analytical framework to incorporate a range of AM technologies (e.g. Fused Deposition Modelling, Selective Laser Sintering, Direct Metal Laser Sintering), thereby providing a more nuanced understanding of how each technology can specifically improve (or hamper) postponement strategies across the five dimensions identified in this research. Moreover, future research could build upon our analytical framework to investigate challenges such as decentralised manufacturing and material sourcing complexities, with a focus on how product complexity influences the adoption of AM within postponement strategies across different supply chain tiers. Given the complexity of these issues, we first recommend utilising exploratory qualitative research (e.g. case studies, action research) to extract in-depth insights into the interplay between AM and postponement. Quantitative studies, including surveys and mathematical models, could then provide generalised insights to support decision-making in AM-enhanced postponement at a more advanced stage. Ultimately, we hope that the insights from this research will serve as a foundation for future researchers interested in AM-postponement intersections, helping them build their empirical studies on solid theoretical grounds to advance our understanding of this intriguing phenomenon.

Data availability statement

Data sharing is not applicable to this article as no new data was created in this study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors



Dr. Lorenzo Pratavia is Assistant Professor of Logistics and Supply Chain Management at University of Verona. He holds a Ph.D. in Management, Economics, and Industrial Engineering from Politecnico di Milano (Italy). Previously, he was Senior Lecturer in Logistics and Supply Chain Management at Cranfield School of Management, where he also served as Deputy Course Director for the FT MSc in Logistics and Supply Chain Management. His main research interests concern global distribution network design, supply chain collaboration, supply chain resilience, and logistics environmental sustainability. His research has been published in leading academic journals, including *Journal of Business Logistics*, *Supply Chain Management: An International Journal*, and *International Journal of Physical Distribution and Logistics Management*.



Dr. Amer Jazairy is an Assistant Professor of Logistics & Supply Chain Management at Texas A&M University. He holds a Ph.D. in Industrial Economics and Management from KTH Royal Institute of Technology in Sweden. His current research focuses on greening logistics networks and examining the implications of disruptive technologies on modern supply chains. Dr. Jazairy's work has been recognised with several awards, including Nofoma's Best Paper Award and Emerald's Highly Commended Outstanding Doctoral Research Award. His research has been published in leading academic journals such as the *International Journal of Production Economics*, *International Journal of Physical Distribution & Logistics Management*, *Business Strategy and the Environment*, and *Transportation Research Part D*.



Dr. Ismail Abushaikh is a Senior Lecturer in Logistics & Supply Chain Management at Cranfield School of Management and Director of the Executive MSc in Logistics and Supply Chain Management. His research revolves around supply network design, supply chain integration, and the managerial aspects of warehouse design and operations. Dr. Abushaikh's research has appeared in many reputed international journals such as the *Journal of Operations Management*, *Supply Chain Management: An International Journal*, and *Human Resource Management* (US). Dr. Abushaikh acquired his practical managerial skills in logistics through roles at multinational companies, specifically within the Operations and CRM divisions at Aramex and the Commercial division at Goodyear.

ORCID

Lorenzo Bruno Pratavia <http://orcid.org/0000-0001-8821-7498>

Amer Jazairy <http://orcid.org/0000-0003-0582-8942>

Ismail Abushaikh <http://orcid.org/0000-0001-5011-2578>

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