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Special Issue: Rethinking operations and supply chain management in light of the 3D printing revolution

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ABSTRACT

Predictions that 3D Printing will lead to an Additive Manufacturing revolution have been made for at least three decades. Although adoption of these technologies continues to increase, there is a disparity between companies and industries achieving success and those becoming disillusioned when the technologies fail to achieve unrealistic expectations. The articles in this Special Issue provide empirical evidence and contribute to theory, to help rethink assumptions about Operations and Supply Chain Management and take account of the opportunities that Additive Manufacturing offers. This introduction to the Special Issue proposes a model to explain the contribution of Additive Manufacturing to business and society, which may range from none at all to a systemic societal impact. The model identifies factors on three levels, i.e., operational, strategic and contextual, which should be aligned with an organisation's adoption of Additive Manufacturing, in order to reap the benefits of these technologies. We show how the studies reported in the Special Issue align with the proposed adoption model.

1. Introduction

Additive Manufacturing (AM) refers to a set of technologies that build parts in layers of material, directly from digital design drawings (e.g. Petrovic et al., 2011; Mellor et al., 2014). These technologies have been used by General Electric to produce over one hundred thousand aero-engine fuel nozzles,[1] by BMW to make over one million automotive components,[2] and by L'Oreal to produce all of its new product packaging prototypes.[3] Initially used only for rapid prototyping to assist design engineers, AM is now at the heart of many consumer goods, such as customisable Gillette razors,[4] and high-performance running shoes.[5] The flexibility of AM has enabled businesses to collaborate and repurpose their production lines to respond to COVID-19 (Boehme et al., 2021; Liu et al., 2021). AM-enabled maker communities, in collaboration with frontline health workers, were able to design and produce personal protective equipment (Corsini et al., 2021). And perhaps most significantly, producing such equipment provided evidence that AM can also be used for fast, high-volume, low-variety production (Huang et al., 2021).

It is almost 40 years since the first AM technologies reached the market. In that time, there have been regular predictions that a manufacturing revolution is just around the corner. In an interview in 1989, executives from 3D Systems claimed that these technologies would revolutionise manufacturing just as typewriters and computer had done for office work, within just another five years of development.[6] Decades later, claims that manufacturing will happen at the click of a

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1 https://news.auburnalabama.org/article/Economic%20Development/4228.
2 https://www.press.bmwgroup.com/global/article/detail/T0286895EN/a-million-printed-components-in-just-ten-years:-bmw-group-makes-increasing-use-of-3d-printing?language=en.
3 https://www.loreal-finance.com/en/annual-report-2017/operations/industry-4_0-agility-phototyping-distribution.
4 https://www.gillette.co.uk/razor-maker.list.
5 https://www.thomasnet.com/insights/nike-adidas-3d-printing/.
6 Interview with Good Morning America, available at https://www.youtube.com/watch?v=NpRDuJ5YgoQ, last accessed 5th September 2022.

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mouse (Waller and Fawcett, 2014), or by just pressing print (Eyers and Potter, 2017) remain unrealistic. The complexity of digital technologies (MacCarthy and Ivanov, 2022) and inflated expectations about their adoption may lead to digital disillusionment and the idea that AM is just a fad. Beyond the hype, however, and as the examples above show, AM has quietly moved from niche applications into the mainstream. The focus for AM vendors has steadily gone from developing innovative technologies to improving the range and consistency of materials, the speed and repeatability of processes and the efficiency of post-processing methods. The cost, quality and speed of AM continue to improve as higher volume, modular and more automated systems become increasingly available. While the short-term, revolutionary effects have been overestimated, the long-term evolution has arguably been underestimated as AM becomes a viable manufacturing technology.

The aim of this Special Issue is to rethink assumptions about Operations and Supply Chain Management to account for the new possibilities that AM brings. It seeks to move beyond speculative ideas about what might be possible in the future, to develop theoretically informed empirical observations on the opportunities offered by AM now, as well as to highlight the challenges and barriers to be overcome. In particular, it seeks to address the question of what makes some companies successful in their AM adoption, while others fail to achieve benefits and become disenchanted with the technologies (Candi and Beltagui, 2019). The Guest Editors have been investigating this question over a number of years. Here we offer a model to explain the factors that influence the success of AM adoption. After outlining the model, we introduce the four articles comprising this Special Issue and highlight the insights they add to this model. Finally, we offer a set of themes for further research and suggestions for managerial practice, which we hope will stimulate further work.

1.1. *Understanding the contributions of Additive Manufacturing adoption*

As noted in the Introduction, AM has been expected to be revolutionary and disruptive for some time. Debates have ensued over whether it has already disrupted industries (D'Aveni, 2015; Sandström, 2016) or could disrupt supply chains (Beltagui et al., 2020). If the expectation is that established companies will be put out of business and traditional manufacturing processes made obsolete, this may never happen. Manufacturing processes such as casting and forging are as effective today as they have been for hundreds of years while injection moulding is unlikely to be replaced by AM for many high-volume, low-variety applications (Weller et al., 2015). Instead, we consider what makes adopting AM viable within a broader manufacturing system alongside other manufacturing processes.

The contribution that AM adoption makes can be considered at a strategic level, taking inspiration from Hayes and Wheelwright's (1984) seminal four-stage model of operations strategy. In the lowest stage of their model, operations are internally focused and have a neutral effect on strategy, whereas the highest stage sees operations leading the strategy and offering a competitive advantage that is externally focused. We adapt this model to the stages of contribution of AM relating to internal operations, supply chains, markets and societal impact.

- **Stage 1** shows AM adopted in a restricted manner that improves ***internal operations.*** For example, adoption could be considered successful if it leads to lower costs, faster new product development or reduced material waste. Improvements in efficiency, cost or performance would be positive, but overall contributions are limited.
- **Stage 2** describes AM adoption leading to changes beyond a single organisation, and affecting ***suppliers and supply networks.*** For instance, AM enables consolidation of multiple components into fewer parts (Knofius et al., 2019). This has the advantage of reducing complexity, since there will be a reduction in parts and suppliers. The effect is positive for the manufacturer where it reduces the number of supplier transactions, but has a noticeable negative impact on some suppliers, who face a loss of orders.
- **Stage 3** shows AM impacting on competition in ***the market*** by offering new value propositions to customers. In particular, AM can produce parts that are i) harder to make traditionally; ii) better suited to specific users or applications; iii) faster to iterate or innovate; and iv) nearer to where they will be needed in space and time. At this stage, AM contributes not only by improving current operations, but by enabling new business opportunities and competitive advantage.
- **Stage 4** describes wider impacts on ***society.*** In particular, the humanitarian, social and environmental credentials of AM have been recognised and are beginning to be exploited. There may be direct benefits, for example in reducing waste of raw materials in comparison to cutting and forming processes; supporting social innovations through crowdsourcing and the so-called 'maker movement' (Beltagui et al., 2021); or responding to humanitarian needs in the aftermath of a disaster in a tailored and ad-hoc manner. Benefits for people and the planet may also be indirect and situated beyond production processes; for example, enabling weight reductions in cars and aircraft may reduce fuel and emissions during the use phase and may facilitate recycling and re-use of material after end-of-life.

The scope of potential contributions ranges from internal in Stage 1 to societal in Stage 4. It is also possible and indeed common for new technology adoption to have no measurable contribution to performance (Stage 0) (Swink and Nair, 2007). Introducing digital technologies into manufacturing operations and supply chains requires "clear strategic thinking" (MacCarthy and Ivanov, 2022, p. 17). As shown in Fig. 1, we suggest this means the degree of alignment between an organisation's operations, strategy and its adoption of AM defines the stages of contribution. A low level of adoption, for example applying AM to some components, should lead to Stage 1 contribution, but only if this adoption aligns with the internal operations. We propose that Stage 4 contributions, at a societal level, require both a greater level of adoption and a sufficient strategic alignment. We explore this in more detail in the next section.

1.2. *Achieving potential contributions from Additive Manufacturing adoption*

Research on AM has repeatedly highlighted the need for a systems perspective. Considering AM in an organisation and its operations, Eyers and Potter (2017) argue that the whole manufacturing system must be taken into account, while Kim et al. (2015) highlight the importance of information systems and their architecture. Beyond the organisation, an ecosystem of actors, policies, and infrastructure contribute to the resources and technologies that make AM work (Piller et al., 2015). Finally, a supportive societal and institutional context is required for this technology to be available, adopted, and its benefits exploited.

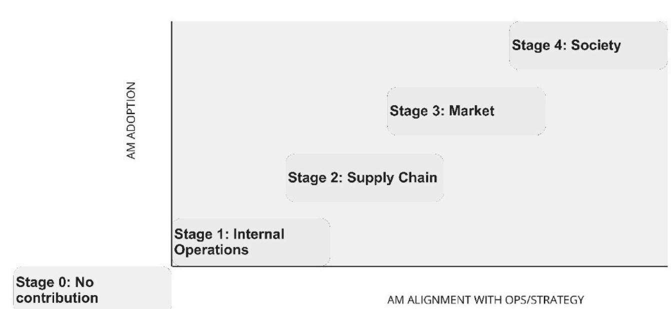

Fig. 1. Stages of contribution potentially made by AM adoption reflect fit with operations and strategy.

As shown in Fig. 2, we consider a system consisting of three levels. First, the *operations* level relates to manufacturing operations. Key decisions concern which products or parts AM should be applied to, which resources are required and the integration between AM and other internal processes. Decisions may depend on production volumes and cost implications (Baumers and Holweg, 2019; Weller et al., 2015) or on how design changes might affect internal processes. For example AM could allow parts consolidation (Knofius et al., 2019). This might mean faster assembly and reduced material usage. Or, if not well aligned, it may lead to lack of integration of AM with other manufacturing technologies.

Second, the *strategic* level relates to the role of AM within the organisation and its strategy. Decisions here relate to the business model and value proposition offered, as well as the related operations, supply chain and digital strategies. AM makes many previously impossible tasks technically possible, but unless it results in value creation, and unless the value can be captured through revenue generation or cost reduction, there may be limited rationale for adoption from a business perspective. For example, AM can offer operational advantages such as flexibility, or waste reduction, which could fit with a competitive strategy that focuses on these measures (Ghobadian et al., 2020). Alternatively, within an operations strategy built on speed and consistency AM may be inappropriate, and could create excessive costs or inefficiency (Eyers and Potter, 2017; Kim et al., 2015).

Thirdly, the contextual level relates to where (and when) AM is introduced. Here we highlight the societal and institutional contexts, which may determine whether AM fits in a particular industry or society for example. Societal megatrends that can make AM more appropriate include pressure for localised production, resource efficiency, servitization, or circular and socially responsible supply chains, all of which are potentially enabled by AM (Beltagui et al., 2020). Meanwhile the national and industrial context can determine whether the required infrastructure, legal frameworks, culture, and organisational support is in place to help adoption of AM.

1.3. Illustrative application to related articles published in the International Journal of Production Economics

To test the applicability of our model to existing research on AM, we identified and reviewed 33 articles published in International Journal of Production Economics (IJPE) up to March 2022 that included relevant terms (i.e., 3D print or Additive Manufactur*) in the title, keywords and abstract. An initial search yielded 54 articles, of which 21 (39%) were not strongly AM focused. We classified the remaining articles according to their focus on the operational (7 articles, 21%), strategic (19 articles, 58%) or contextual (7 articles, 21%) level factors. This review demonstrates that the levels of our model provides structured insights into existing AM literature. More specifically, we find that although all three level factors are represented in the existing literature, contextual and operational factors have received comparatively less attention. Operational concerns reflected in the research include measurement of the costs, and benefits in relation to challenges such as quality and uptime (e.g. Colosimo et al., 2020; Ding et al., 2021). These are clearly important for practice, and as the adoption of AM has increased, there have been more opportunities to measure and analyse operational data on costs and benefits. Meanwhile studies concerned with the contextual level have examined some of the barriers such as government policy, infrastructure readiness and legal frameworks. These studies provide comparisons across different national contexts such as China (Kai et al., 2018), Brazil (Frank et al., 2019) and New Zealand (Wang et al., 2022).

Over half of the articles related to AM that have been published in IJPE prior to this Special Issue have focused on the strategic level. This corresponds to our perspective, which highlight that strategic alignment is vital to realise the potential contributions of AM. These articles extend the scope of AM adoption decisions to consider the influence of markets and supply chains on AM adoption, or the impacts of AM throughout the supply chain and product lifecycle (Chekurov et al., 2018; Delic and Eyers, 2020). They consider value propositions, business models and particularly the pricing strategies that help to capture value from AM adoption (Chaudhuri et al., 2021; Sun et al., 2020). These studies demonstrate the need for a clear alignment between the adoption of AM at an operational level and strategic thinking related to digital infrastructure, business models, operations and supply chains. For example, research suggests AM can enable Manufacturing as a Service (MaaS) models, Mass Customization, and contribute to improved product maintenance, but only if used within a coherent operations strategy.

This non-exhaustive analysis is not necessarily representative of the entire body of AM literature, but has been used here to illustrate the applicability of our model.

1.4. Articles in the Special Issue

Despite the challenges that the COVID-19 pandemic brought to the research community, we received a number of very interesting submissions covering a broad range of topics. Following a rigorous review process, we accepted four articles for publication in this Special Issue. Each of them offers a valuable contribution to knowledge and practice through empirically evidenced and theoretically grounded research.

The pandemic offered a demonstration of how AM's flexibility could support resilience in supply chains. In their paper, Belhadi, Kamble, Venkatesh, Jabbour and Benkhati make a case that AM can also support efficiency, even though traditionally there may be a perceived trade-off between resilience and efficiency. Prior research has suggested that AM should reduce the length and complexity of global supply chains by enabling localised production with reduced transportation, or parts-consolidation requiring fewer processes. The implications of these assumptions are considered by Friedrich, Lange and Elbert, who focus on AM business models for logistics service providers, and Jimo, Braziotis, Rogers and Pawar who examine the changing complexity and

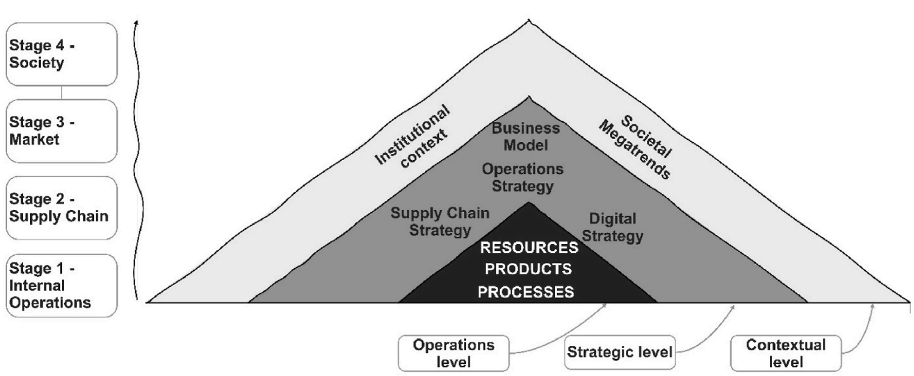

Fig. 2. Relating stages of AM contribution to levels of alignment.

dependencies in supply chains that are incorporating AM. The excitement over AM has often been uncritical, leading to unrealistic expectations that everything can or should be 3D printed. In their paper, Foshammer, Søberg, Helo and Ituarte focus on selecting the most suitable parts for AM. Below, we provide an overview of these articles as well as an indication of how they relate to the model described above.

Belhadi et al. (2022) combine the perspectives of ambidexterity and dynamic capabilities to examine how resilience and efficiency are both being supported by AM in a number of industries in an African context. A combination of focus groups and case studies based on interviews supports identification of capabilities and a framework for achieving resilience and efficiency. This is one of a very small number of studies in an African context. The study helps to elaborate the **contextual level** factors of our model. For example, skills and infrastructure are among the factors explored. The article also expands the strategic layer by considering how achievement of strategic goals such as resilience and efficiency is related to other factors, such as a digital strategy concerned with data architecture and analysis.

Friedrich et al. (2022) develop a taxonomy for AM business models, which is then elaborated and validated through analysis of secondary data from 47 logistics service providers (LSPs) and a series of additional interviews. They identify activities and a timeline of their implementation, to derive six profiles, and show a clear contrast between path-dependent or path-breaking strategies. The former sees LSPs taking a cautious approach, seeking to build on their existing business activities or waiting for clear demand signals from customers. The latter is more pro-active, involves new partnerships and can create distance from the LSP's existing activities. This study elaborates the **strategic level** factors of our model, with a focus on business models. The success of AM adoption could vary greatly not only due to the differing strategies adopted, but how the business model fits with operational activities and the wider context in which the logistics service provider operates.

Jimo et al. (2022) consider how the potential of AM to alter a product architecture affects the interconnections between supply chain partners. Using a resource dependence perspective and building on a review of complexity in prior AM research, they examine the competitiveness of supply chains where AM is adopted. Their case studies include examples from the Aerospace, Motorsport and Power-Generation supply chains based on data from multiple tiers, and help to create process maps to demonstrate AM application. Their findings show the buffering and bridging strategies used to support supply chain competitiveness, and highlight a number of factors influencing complexity and resource dependence. This study investigates a number of the **contextual level** factors in the outer level of our model, including industry and geography as well as demonstrating the importance of aligning the strategic level to operational level AM activities.

Foshammer et al. (2022) use a knowledge management perspective, suggesting that a combination of bottom-up and top-down approaches should be used to identify parts suitable for AM, particularly in the critically important context of aftermarket and legacy parts. The bottom-up approach uses tacit knowledge of experts, while top-down relies on a data-driven approach. They test the proposed approach in the context of aftermarket spare parts for aerospace applications. This study explores the **operational level** factors of our model, by taking a practical approach to look at suitability of parts and products for AM.

In combination, the four studies outlined in Table 1 shed light on the three levels of our model, and offer a first step to connecting these levels in theoretical development and practical decision-making.

1.5. Suggested research themes for AM in Operations and Supply Chain Management

We have proposed a model to explain the success of AM adoption, which has the potential to guide decision-making in practice. The studies presented in the Special Issue expand our understanding of AM adoption and its effect on Operations and Supply Chain Management. They also inform many aspects of the model we present. However, there is a need to test and to elaborate this model further, by refining the processes and decisions in each of the operational, strategic and contextual levels. . We identify several areas for further investigation, to build on their work.

- **What drives success?** We proposed several stages of contribution that AM adoption may make. It may affect internal operations (1), suppliers and supply networks (2), markets (3) or society (4). We suggest the higher stages are related to both greater levels of adoption and to better alignment of AM with operations and strategy. Without such alignment, however, there is also the possibility of no likely? contribution (0) in some contexts. The Special Issue papers suggest some of the factors that can contribute to achieving desired contributions, but more research is needed to test and elaborate the adoption model further, in order to support decision-makers in defining success and how to achieve it.
- **What is the value proposition of AM?** The technical characteristics of AM represent four main sources of value, in terms of producing parts that may be *harder* to make by other means, *better* suited to specific applications or users, *faster* to develop, test and scale, or *nearer* to the place and time they are needed. Alternatively, AM may

Table 1
Overview of articles in the special issue.

	Title	Research context	Theoretical framework	Methods	Key findings	Level in model
Belhadi et al. (2022)	Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view	Manufacturing supply chains in Africa	Ambidexterity and Dynamic Capabilities	Focus Groups and Interview based Case Studies	Suggests that AM can reconcile resilience and efficiency, helping supply chains to achieve both.	Contextual level
Friedrich et al. (2022)	How additive manufacturing drives business model change: The perspective of Logistics Service Providers (LSP)	Responses of LSPs to opportunities and threats of AM	Business Model Dynamics	Taxonomy development, qualitative coding and clustering.	Identifies six clusters, representing proactive or reactive business models of LSPs adopting AM.	Strategic level
Jimo et al. (2022)	Configuring additive manufacturing supply chains: A resource dependency perspective	Metal AM in aerospace, power generation and automotive supply chains.	Resource Dependence Theory	Case studies, using interviews to study 3 tiers of each supply chain.	Proposes dependencies between supply chain partners as a mediating factor in competitive benefit of AM adoption.	Strategic/ Contextual levels
Foshammer et al. (2022)	Identification of parts suitable for additive manufacturing: A knowledge management-based approach	Spare parts in aerospace aftermarket.	Knowledge Management	Abductive case study using Analytical Hierarchy Process (AHP) and workshops	Develops an assessment method to support decision-making and focus expert attention on the most suitable spare parts for AM.	Operational level

be slower, more expensive or wasteful of energy and resources if not used appropriately. Research is needed to help establish the value propositions that AM can offer to customers, as the basis for novel business and supply chain models.

- **How do we know when the time is right for adopting AM?** By comparing contexts, researchers might identify the influence of societal and institutional factors in shaping successful outcomes of AM adoption. For example, which combination of technological, regulatory and demand forces can be associated with higher levels of success? How does the possible democratisation or decentralisation of manufacturing affect the value propositions? Answering such questions supports managerial decisions on the timing, degree and nature of AM adoption.
- **How can AM address societal challenges?** Research has considered and demonstrated, albeit at small scale, how AM could contribute to sustainability and circularity, or support humanitarian and social benefits. Further research could establish how the benefits can be scaled up in order to tackle global societal challenges and sustainable development goals. In particular, there is a need to demonstrate both the feasibility and profitability of proposed benefits to society and to the organisations that could scale and deliver these benefits.
- **Can AM be a leap-frog technology?** While levels of industrial development vary across the globe, there are hopes that the flexibility and relative affordability of AM might help companies, industries and countries to catch up or to move ahead of those considered more developed. Thus far, the concept of leap-frogging has been suggested but not demonstrated, and research might seek to document or stimulate industrial development driven by AM.

2. Conclusion

"Historically, we have tended to overestimate what we could do on a short-term basis and to grossly underestimate what we could do on a long-term basis" (Schriever, 1961).

While this quote was made in relation to space exploration, it is apt in describing the development of AM technology. What was initially a prototyping technology with great value in New Product Development has gradually evolved into a useful tool for niche applications and increasingly a viable option for mainstream manufacturing. This is not to say that AM will become the only option, but that it should be taken seriously within a set of other options in a manufacturing system. This Special Issue provides empirical evidence and theoretical development to guide thinking on where and how AM can be utilised. While AM can expand the way manufacturers think about their production methods toolbox, care should be taken to ensure alignment. This paper has proposed a model showing the different levels of AM adoption, and argued that to achieve desired contributions of AM within organisations, supply chains, markets and societies, alignment should be ensured at each level, i.e. operational, strategic, and contextual.

Finally, we would like to extend our thanks to the authors who submitted their work to this Special Issue, to all reviewers who helped us assessing each manuscript we received and provided unvaluable feedback to the authors, and to the IJPE editorial team for giving us this opportunity to advance our understanding of AM in Operations and Supply Chain Management through this Special Issue. We hope readers will benefit from the articles in this Special Issue and believe it offers useful insights to help shape future research by academics and decision-making by managers.

Data availability

No data was used for the research described in the article.

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