# *Additive manufacturing: a framework for supply chain configuration*

Int. J. Production Economics 253 (2022) 108592

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe

# Additive manufacturing: A framework for supply chain configuration

Ajeseun Jimo [a,*], Christos Braziotis [a], Helen Rogers [b], Kulwant Pawar [a,c]

[a] Nottingham University Business School, Jubilee Campus, Nottingham, NG8 1BB, UK
[b] Technische Hochschule Nürnberg, Bahnhofstraβe 87, 90402, Nürnberg, Germany
[c] Department of Management Studies, Indian Institute of Technology Madras (IITM), India

ARTICLE INFO

*Keywords:*
Additive manufacturing
3D printing
Resource dependence
supply chain complexity
Supply chain configuration
Distributed manufacturing

ABSTRACT

Using Resource Dependence Theory (RDT), this paper explores the changing state of Supply Chain (SC) complexities and dependencies resulting from Additive Manufacturing (AM) adoption, analysing implications for competitiveness. We utilised an adapted SC configuration framework to develop embedded case studies across the Aerospace, Automotive and Power Generation industries. The sample included fifteen companies deploying metal AM across three SC tiers. Using an abductive logic, our findings reveal that the complexity and dependency-reduction potential of AM depends on economic, industry, geographical, organisational and technological factors. We developed a conceptual framework for AM SC configuration and four propositions, which provide further insights into the interplay between SC complexities, dependencies and competitiveness. By utilising RDT, we contribute to the AM SC configuration literature by highlighting the mediating role that dependencies play in achieving competitiveness, as well as strategies adopted by firms to mitigate uncertainty. We also highlight the interplay between 'relationship and governance' and three other SC configuration dimensions in relation to competitiveness. Insights into the changing state of complexities and dependencies identified in this study could also support managerial decisions in AM SC design.

## 1. Introduction

Due to Traditional Manufacturing (TM) limitations, organisations in various industries are now making end-use components with Additive Manufacturing (AM) to extend their product and process performance frontiers (Braziotis et al., 2019). AM is a disruptive paradigm that significantly reduces cost penalties associated with design complexity and variety (Eyers et al., 2018), creating scope for novel Supply Chain (SC) configurations (Kleer and Piller, 2019). The reduction in the minimum efficient scale for production is a radical departure from existing TM principles, which depend on scale economies. AM capabilities promise SC benefits in terms of responsiveness, efficiency (Holmström et al., 2010), environmental as well as social welfare (Kleer and Piller, 2019; Kohtala, 2015).

These benefits have attracted the attention of researchers, seeking to understand AM's potential to reduce SC complexity. Such studies typically highlight effects of AM adoption on different SC configuration aspects (Srai and Gregory, 2008) in a fragmented manner, raising contradictions. Due to parts-consolidation via AM, some studies suggest reduction in manufacturing complexities and supplier dependencies, relative to TM SCs (e.g. Holmström et al., 2016; Luomaranta and Martinsuo, 2020). Others propose introduction of complexities and dependencies due to the need for new supplier capabilities, especially for metal AM (Mellor et al., 2014; Strong et al., 2018). These contradictions create difficulties in understanding the characteristics of AM SC configurations. The changing state of complexities and dependencies in AM SCs are salient because they determine the boundaries of a focal firm's control on manufacturing processes (Flood, 1987) and therefore its ability to manage uncertainty and enhance competitiveness (Pfeffer, 2003, p. 37). Hence, our research seeks to address the following questions:

**RQ1**. How does AM adoption affect complexities and dependencies in metal component SCs?

**RQ2**. What is the role of dependencies in the competitiveness of metal AM SCs?

RQ1 aims to highlight pertinent contextual factors and their effects on SC configuration dimensions to explain the complexity and dependency-reduction potential of AM. RQ2 aims to understand the effect of dependencies on SC competitiveness and identify uncertainty

* Corresponding author.
*E-mail address:* ajeseun.jimo1@nottingham.ac.uk (A. Jimo).

https://doi.org/10.1016/j.ijpe.2022.108592
Received 31 May 2021; Received in revised form 7 July 2022; Accepted 27 July 2022
Available online 5 August 2022

mitigation strategies. We draw on Resource Dependence Theory (RDT) (Emerson, 1962) to shed light on the changing state of complexities and dependencies associated with AM adoption. RDT is selected due to its emphasis on the external perspective of organisations, proposing that organisational outcomes are accounted for by contexts in which they are embedded (Pfeffer, 2003, p. 39), as opposed to intra-organisational perspectives such as the Resource Based View (Barney, 1991). A configurational approach, considering four SC aspects (Srai and Gregory, 2008), is adopted to investigate complexities and dependencies due to the multidimensional nature of SC outcomes (Ketchen Jr. et al., 2021). We develop embedded case studies for metal AM SCs across the Aerospace, Power Generation and Automotive industries and apply an abductive logic to refine extant propositions. The research is conducted in the metal context due to the dearth of SC studies in this area and relative manufacturing complexities, compared to polymer SCs (Bourell et al., 2017).

Our study makes several contributions to the AM SC configuration literature. Firstly, we identify contextual factors (industry, economic, geographical, organisational and technological) that influence complexities and dependencies within and across metal AM SC tiers. Secondly, we apply RDT to better understand complexities and dependencies in AM SCs. Thirdly, we identify the mediating role dependencies play in SC competitiveness. Lastly, we highlight the interplay between 'relationship and governance' and three other SC configuration dimensions in relation to SC competitiveness. The remainder of this paper is divided as follows: Section 2 presents the literature on RDT, SC configurations and introduces the research framework. Section 3 explains the embedded case study methodology and section 4 presents the within and cross-industry analyses. Section 5 presents a framework for additive manufacturing SC configuration, leading to a discussion on four resulting research propositions. Section 6 presents theoretical, managerial contributions, limitations and future research recommendations.

## 2. Literature review

### 2.1. Traditional manufacturing supply chain configuration

Various structural shifts such as shortened product lifecycles and increasing demand for customisation etc., have heightened demand for low volumes and agility in TM SCs (Kovács and Sigala, 2021). The competitiveness of these SCs are hampered by the fine-slicing of production activities into distinct stages and geographical locations (Buckley and Strange, 2015), thereby creating interdependencies between buyers and suppliers (Pfeffer, 2003, p. 43). Activities are typically divided up between suppliers and buyers depending on product architecture, which influences complexity in other SC dimensions and hence determines a SC's configuration (Srai and Gregory, 2008). Interdependencies between buyers and suppliers could become asymmetric depending on the availability of suppliers and potential switching costs (Magnani et al., 2019). In such instances, the dependent party has less control on manufacturing activities, leading to uncertainties in achieving SC outcomes (Pfeffer, 2003, p. 42).

#### 2.1.1. Resource dependence theory and supply chain configuration

Researchers have relied on RDT to identify conditions which establish dependence between SC entities and strategies to reduce uncertainties. RDT is rooted in an open systems framework, based on the concept of dependencies that exist when organisations do not control all conditions required for competitiveness (Emerson, 1962). This concept is linked to *non-holonomic* constraints, whereby aspects of systems fall outside centralised control, the more complex they become (Flood, 1987). RDT provides a framework to explain how organisations deal with unpredictable supply environments and specifies three conditions which determine suppliers' dependence on buyers' or vice-versa: a) importance of resource; b) supplier substitutability; c) discretion over resource (i.e. capacity to determine the allocation of a resource) (Pfeffer, 2003, p. 451). RDT suggests that dependent firms would attempt to control their environments by applying a range of bridging and buffering strategies to reduce uncertainty (Hillman et al., 2009). Bridging strategies attempt to manage uncertainties by engaging in "boundary-spanning" and "boundary-shifting" actions with an exchange partner (Levina and Vaast, 2005). Buffering strategies attempt to gain stability by establishing safeguards from disturbances that a relationship confers, thereby reducing dependency and increasing autonomy (Bode et al., 2011; Pfeffer, 2003).

Studies applying RDT in the TM context have identified conditions which establish SC dependencies. For example, Kalaitzi et al. (2019) identified supplier scarcity, high switching costs, competition, political and geographical risk as conditions which created dependencies between an Electric Vehicle (EV) manufacturer and its suppliers for high value components. Genovese et al. (2020) demonstrated how the lack of SC management capabilities amongst some UK local authorities created dependence on contractors, thereby weakening their influence on SC decisions to generate local economic benefits. These studies typically specify bridging and buffering strategies adopted by dependent firms to manage uncertainty. Bridging strategies include closer co-ordination with suppliers, relationship-based pricing, monitoring systems, etc. Buffering strategies include building safety stocks, capacity expansion, fixed price agreements, insourcing etc. (Al-Balushi and Durugbo, 2020; Foerstl et al., 2021; Kalaitzi et al., 2019).

### 2.2. Additive manufacturing adoption and supply chain configuration

AM adoption for design and production of end-use components is expected to significantly influence complexities and dependencies in SC configurations and enhance competitiveness of low-volume SCs (Petrick and Simpson, 2013). A review of AM SC management articles, presented below, highlights expected effects of AM adoption on various SC configuration dimensions (i.e. product value structure, SC structure, material and information flow, relationship and governance) (Srai and Gregory, 2008) and implications for competitiveness. These dimensions are specified in terms of complexity and dependency. Definitions of these constructs are provided in Table A1 of the appendix.

#### 2.2.1. Product value structure

A product's value structure, which refers to key aspects of a product's architecture (e.g. modularity), has a significant effect on SC structures. An attractive feature of AM is the capability to combine multiple parts into a single component, referred to as parts-consolidation (Yang and Zhao, 2018). Huang et al. (2013), as well as Luomaranta and Martinsuo (2020) highlighted positive gains of parts-consolidation for assembly reduction, via design for AM (DFAM). However, the overall effect of consolidation depends on the level at which AM is deployed i.e. part, module or product (Jimo et al., 2019). Sandström (2016) demonstrated that this impact was not radical in hearing-aid production, due to the application of AM for a single component. Knofius et al. (2019) concluded that parts-consolidation may not always be beneficial for maintenance,repair and overhaul (MRO), as it could lead to higher total costs compared to repairing components by replacing specific parts.

#### 2.2.2. Supply chain structure

*2.2.2.1. Vertical complexity.* AM could enable insourcing of components, but this is subject to volume considerations (Hedenstierna et al., 2019). Ruffo et al. (2007) justifies insourcing based on cost efficiency, due to mark-ups applied by suppliers, which increases unit costs of components. However, cost efficiency could be achieved via outsourcing, above certain volume thresholds (Baldinger et al., 2016). For assemblies with several components initially sourced from multiple suppliers, the likely effect of insourcing AM is the collapse of supplier tiers or a reduction in vertical complexity (Choi and Hong, 2002). Ramón-Lumbierres et al. (2021) demonstrated AM's capability to substitute TM capacity at the supplier tier with AM at the OEM for toy production. To achieve this, however, investment in several AM machines is required due to slow throughput, which increases costs. Empirical studies (Corsini et al., 2020; Wagner and Walton, 2016) highlight shortening of intercontinental SCs with AM compared to TM, however Corsini et al. (2020) identified shifting burdens to the AM service SC. Collectively, these studies suggest that reduction in vertical complexity is dependent on several factors (e.g. production volume, AM throughput) and could lead to increased complexities in the same or complementary SCs.

*2.2.2.2. Horizontal complexity.* Through parts consolidation, AM is expected to rationalise the make-to-order supply base, potentially reducing horizontal complexity (Choi and Hong, 2002). Luomaranta and Martinsuo (2020) highlighted supply base rationalisation, referencing reduction of engine parts from 855 to 12, reducing logistics costs. Ramón-Lumbierres et al. (2021) demonstrated rationalisation in the toy industry, with the substitution of externally sourced injection-moulding from two suppliers with in-house AM. On the other hand, other studies mention the introduction of new SC members. Kunovjanek and Wankmüller (2020) highlighted the introduction of SC entities to facilitate distributed manufacturing. Strong et al. (2018) identified the potential for OEMs to utilise spare TM capacity for post-processing metal AM components. Overall, these studies highlight the need to take a holistic view of AM impacts on the number of entities to conclude on effects on SC configuration.

*2.2.2.3. Spatial complexity.* AM is expected to enable decentralised manufacturing (Holmström et al., 2010), whereby finished components are substituted with AM production capacity near consumption nodes, reducing spatial complexity (Choi and Hong, 2002). Most conceptual studies to date (Braziotis et al., 2019; Ghobadian et al., 2018; Huang et al., 2013; Rayna and Striukova, 2016; Tziantopoulos et al., 2019) agree on AM's potential to reduce spatial complexity and transportation costs, and increase responsiveness. However, Braziotis et al. (2019) and Khajavi et al. (2014) identified elimination of scale economies and increasing automation levels as necessary conditions for distributed manufacturing. Case studies that demonstrate the practicality of decentralised AM are mostly polymer-based applications associated with consumer, humanitarian and medical SCs (Corsini et al., 2020; Kunovjanek and Wankmüller, 2020; Rogers et al., 2016). For metal applications, empirical and analytical studies (Luomaranta and Martinsuo, 2020; Mellor et al., 2014; Strong et al., 2018) highlight the need for centralisation and proximity to post-processing suppliers to meet B2B demands for responsiveness. Collectively, these studies suggest that opportunities to reduce spatial SC complexity with AM lie on a spectrum; with decentralised manufacturing for non-critical polymer B2C applications at one end and centralised industrial metal B2B applications at the other.

### 2.2.3. Material and information flow

*2.2.3.1. Co-ordination.* AM is expected to reduce co-ordination burdens (Ballou et al., 2000) required for assembly. Holmström et al. (2016) and Bogers et al. (2016) identified AM's potential to reduce production planning and scheduling via distributed manufacturing. Co-ordination of multiple upstream suppliers for inbound inventory to focal firms could be reduced to one raw-material supplier, enhancing efficiency and responsiveness (Holmström et al., 2016). Khajavi et al. (2014) and Ghobadian et al. (2018) highlighted a reduction in co-ordination of inventories between centralised locations and demand points via distributed manufacturing. Kunovjanek and Wankmüller (2020) pointed out problems with managing quality assurance requirements in decentralised SCs during the production of medical device components. Collectively, these studies illustrate that AM may be beneficial in terms of reducing upstream co-ordination burdens but that co-ordination requirements may also emerge downstream.

*2.2.3.2. Manufacturing complexity.* AM can eliminate several value and non-value adding activities, reducing manufacturing complexity (Bozarth et al., 2009). Holmström et al. (2016) described opportunities to eliminate batching, kitting and assembly using an AM build. Huang et al. (2013) and Ghobadian et al. (2018) cited potential reductions in transportation and material distribution, especially in jobbing operations, which are typically beyond the domain of lean manufacturing. For metal applications, Mellor et al. (2014) and Eyers et al. (2018), demonstrated that several post-processing steps, accompany AM adoption, which necessitate production planning to increase efficiency (Thürer et al., 2021). Whilst some aspects of manufacturing complexity may be eliminated with AM adoption, other complexities arise due to post-processing.

### 2.2.4. Relationship and governance between supply chain entities

Governance refers to the level of control that SC entities exert on each other and is influenced by existing inter-dependencies for access to tangible and non-tangible resources (Gereffi et al., 2005). As highlighted in section 2.2.2.1, vertical integration by focal firms could reduce their dependence on large contract manufacturers (Holmström et al., 2016). Hohn and Durach (2021) identified the potential to reduce subcontracting and dependence on large accessory suppliers through insourcing via AM. Mellor et al. (2014) provided anecdotal evidence from an AM service provider, suggesting insourcing of AM by OEMs, due to decreasing orders. On the other hand, Kunovjanek and Wankmüller (2020) and Corsini et al. (2020) spotlighted the creation of new collaborative relationships via distributed AM. Whilst some studies draw attention to potential shifts in dependency away from largescale contract manufacturers, others highlight emerging dependencies. Overlooking emergent dependencies from design, all the way to post-processing would likely over-estimate a focal firm's ability to control its SC performance (Prajogo et al., 2020). A summary of the existing literature on effects of AM adoption on SC configurations is presented in Table 1 below.

## 2.3. Research framework

The preceding review highlights contradicting propositions on the effects of AM adoption on SC complexities and dependencies. This is likely due to AM's potential to reduce SC complexity and dependence (Holmström et al., 2016), as well as the existence of scale economies and post-processing (Eyers et al., 2018; Mellor et al., 2014; Strong et al., 2018). According to RDT, focal firms that reduce complexities and dependencies could reduce performance uncertainties, due to an increased sphere of SC control (Flood, 1987; Pfeffer, 2003). However, there appears to be a lack of understanding on the underlying mechanisms, that influence complexities and dependencies in AM SCs, as discussed in section 2.2. Therefore, RQ1 and RQ2 seek to shed light in this area and analyse implications for SC competitiveness. The research framework presented in Fig. 1 captures the aims of both RQs. The arrow on the right-hand side indicates the effect of AM adoption on complexities and dependencies that constitute a SC's configuration. The dotted arrows signify the uncertainties created by dependencies and the link with SC competitiveness.

# 3. Methodology

An exploratory approach was adopted because of the nascent state of AM SC configuration and buyer dependency studies and the need for theory development (Holmström et al., 2016; Kalaitzi et al., 2019).

**Table 1**
Effects of Additive Manufacturing on supply chain configuration from literature sources.

| Reference | Research Type | Material Type | Industry | Product Value Structure | Relationships and Gove mace | Supply Chain Structure | | | Material and Information flow | | Supply Chain Competitiveness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Stock Keeping units | Dependence | Vertical Complexity | Horizontal Complexity | Spatial Complexity | Coordination | Manufacturing Complexity | Efficiency | Responsiveness |
| Ramón-Lumbierre et al. (2021) | Analytic | Polymer | Consumer | | | × | × | × | × | × | × | |
| Thürer et al. (2021) | Analytic | Polymer | None | | | | | | | × | × | |
| *Knofius* et al. (2019) | Analytic | None | None | × | | × | | | | | × | × |
| Khajavi et al. (2014) | Analytic | Polymer | Aviation | | | | | × | × | | × | × |
| Strong et al. (2018) | Analytic | Metal | None | | | | | × | | | × | |
| Holmström et al. (2016) | Conceptual | None | None | | × | × | | | × | × | × | × |
| (Rayna and Struikova. 2016) | Conceptual | Polymer | Consumer | | | | × | × | | | | × |
| (Braziotis et al., 2019) | Conceptual | None | None | | | | | × | | | × | × |
| (Tziantopoulos et al., 2019) | | None | None | | | × | | × | | | | |
| Ghobadian et al. (2018) | Conceptual | None | None | | | × | | × | × | × | × | × |
| (Huang et al., 2013) | Conceptual | None | None | × | | × | | × | | × | × | × |
| (Hedenstierna et al., 2019) | Empirical | Polymer | Consumer | | × | | | | | | × | × |
| Hohn and Durach (2021) | Empirical | None | Apparel | | × | | | **X** | | × | | |
| *Eyers* et al. *(2018)* | Empirical | Both | Many | | | | | | | × | | |
| (Corsini at al.,2020) | Empirical | None | Humanitarian | | × | × | | × | | | | |
| (Kunovjanek and Wankmüller, 2020) | Empirical | Polymer | Medical | | × | | × | × | × | | | × |
| (*Bogers* et al.,2016) | Empirical | Polymer | Consumer | | | × | | | × | × | × | × |
| (*Rogers* et al.,2016) | Empirical | None | None | | × | | | × | | | | |
| Wagner and Walton (2016) | Empirical | None | Aviation | | | × | | × | | | | × |
| Mellor et al.. (2014) | Empirical | Metal | None | | × | × | | × | | **X** | | |
| (Ruffo et al., 2007) | Empirical | Polymer | None | | | × | | | | | | |
| Sandström (2016) | Empirical | Polymer | Medical | × | | | | | | | | |
| Luomaranta and Martinsuo (2020) | Empirical | Metal | None | × | | | × | × | | | | |

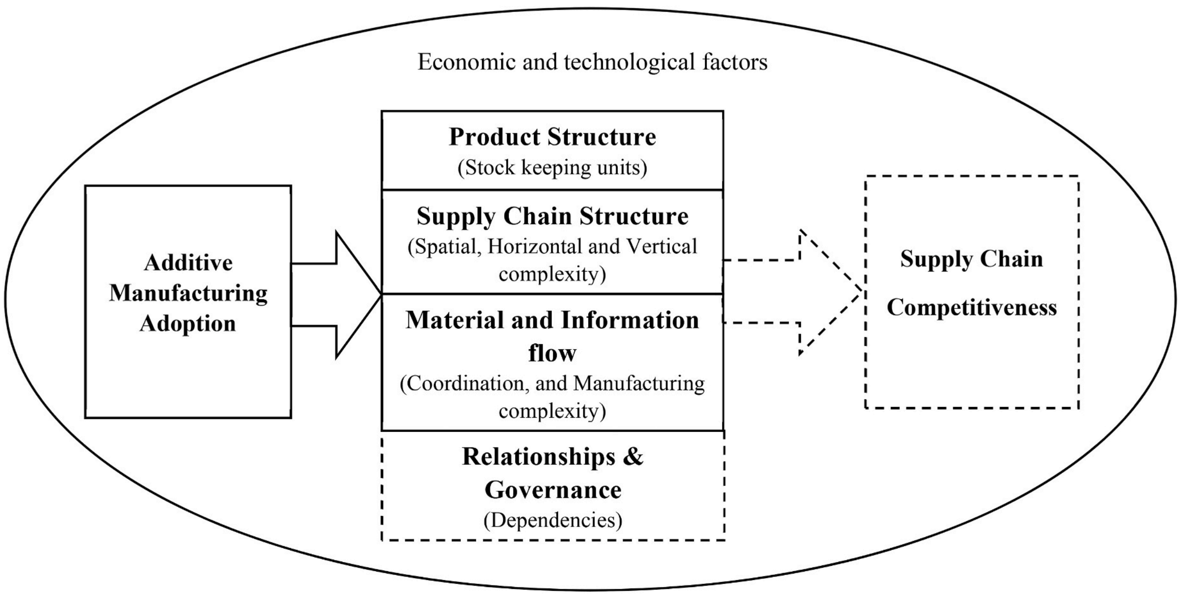


**Fig. 1.** Research framework adapted from Srai and Gregory (2008).

Qualitative case studies are applied owing to their suitability in investigating phenomena surrounding emerging contexts (Meredith, 1998), as well as being suited to "how" questions which fits well with the nature of our study. An embedded case study design is adopted, whereby the unit of analysis is the metal AM SC of three industries: Aerospace, Automotive and Power Generation consisting of a raw-material supplier, AM specialist, post-processing sub-contractors, Tier-1 and OEM customers in a B2B context. We analyse the configuration of metal AM SCs as a general phenomenon, while considering influential industry factors (Miller and Lehoux, 2020). The embedded units consist of low-volume metal AM applications for components produced via powder-bed fusion processes (Selective Laser melting (SLM)[1] and Electron Beam Melting (EBM)[1]). These units belong to15 companies that utilise SLM and EBM to manufacture metal components. This approach has been widely adopted in studying SC configurations in different contexts because of its flexibility in dealing with associated complexities (Eisenhardt et al., 2016).

### 3.1. Case study sample

Our sample was selected to include high-value manufacturing applications in industries that have attained considerable AM adoption levels (Altıparmak and Xiao, 2021). It consists of Tier-2, Tier-1 and OEMs deploying metal AM to investigate dependencies between buyer (Tier 1, OEM) and supplier positions (Tier 2, AM service provider, Research Centres), in compliance with established SC definitions (Mena et al., 2013). This multi-tier design was necessary to overcome the criticism of utilising dyads to contribute to SCM research, with some explicit linkages identified between firms where possible, due to confidential practices. Participating firms were able to provide information about relationships with their suppliers and customers, further enhancing insights into the extended SC, thus improving the internal validity and quality of our research. Our sample includes three world-class research centres in the UK at the frontiers of AM development, operating extensively in the AM engineer-to-order SC. To provide further granularity to the SC definition, the AM applications focused on specific parts and modules at various maturity levels ranging from R&D to full production. Most of the firms in the sample are situated in nations that are at the forefront of AM developments namely UK, USA and Germany. Two firms are located in India, which provided a developing economy perspective. Pseudonyms have been used to protect firm anonymity. RC stands for Research Centres, T2S -Tier-2 suppliers, AMS – AM service providers, T1S -Tier-1 suppliers and OEM - Original Equipment Manufacturers.

### 3.2. Data collection

Semi-structured interviews provided the primary sources of evidence. This was complemented with other sources including: factory floor observations, company websites, brochures and product papers to enhance construct validity (Table 2). Interviews and site observations were conducted between August 2018 and January 2020. The semi-structured interviews were developed from a case study protocol, underpinned by SC configuration framework presented in section 2 (Bryman, 2015). This protocol was piloted between August 2018 and January 2019 in organisations that were in early AM implementation stages. In total, 22 interviews were carried out (12 face-to-face and 10 via Skype and phone calls). Respondents were asked to: 1. Give a general overview of AM applications in their organisations, 2. Identify a specific part/module and explain why AM was adopted, 3. Describe challenges encountered during AM implementation 4. Describe the operation of respective SCs in terms of manufacturing processes, material and information flows, relationship between external SC entities and product value structure. All interviews were voice recorded with the consent of respondents. Seven companies granted factory floor tours, providing the opportunity to observe manufacturing processes in operation. Due to commercial sensitivity, T1S4 and AMS3 disclosed SC information, avoiding references to specific components, which was useful in triangulating SC practices on an industry level. For example, AMS3 confirmed the experience of AMS4 with respect to an immature post-processing supply base in India. Field notes were maintained to document observations and triangulate descriptions of in-house manufacturing processes for construct validity (Voss et al., 2002). Secondary sources of data (company websites, brochures and online case studies) were also analysed to triangulate interview data, especially in terms of manufacturing capabilities and practices, SC structure and

[1] Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are metal Additive Manufacturing Processes in the Powder Bed Fusion class. The main distinction between both processes is the energy source used in melting the powder based raw material. SLM uses a laser energy source, whilst EBM uses an Electron Beam

**Table 2**
Case study sample information. RC- research centre, T2S – tier 2 supplier, T1S – tier 1 supplier and OEM – original equipment manufacturer.

| Company | Employees | Industry | Location | Interview duration & observation | No. of interviewee(s) | Complementary sources |
|---|---|---|---|---|---|---|
| **RC1** | <500 | Aerospace | U.K. | 2 h + 1 plant tour | 2 (Head of strategy (HS), Project Engineer (PE)) | Company website, online case study |
| **RC2** | <500 | Aerospace | U.K. | 2 h 11 m + 1 plant tour | 2 (Principal Research Engineer (PRE), Lead Transformation Advisor (LTA)) | Company website, online case study |
| **RC3** | <10,000 | Motorsport | U.K. | 1 h 20 m + 1 plant tour | 1 (Principal Engineer (PE)) | Company website |
| **T2S1** | <200 | Aerospace | U.K. | 1 h 40 m + 1 plant tour | 1 (Additive Manufacturing lead (AML)) | Company website, government project directory |
| **AMS1** | <100 | Motorsport | U.K. | 2 h 40 m + 1 plant tour | 2 (Technology Director (TD), Manufacturing Development Lead (MDL)) | Company website |
| **AMS2** | <11 | Motorsport | U.K. | 1 h 20 m | 1 (Managing Director (MD)) | Company website, manufacturing process brochure |
| **AMS3** | <50 | Aerospace | INDIA | 1 h 22 m + 1 plant tour | 1 (Head of Post-Processing (HPP)) | Company website, online case study |
| **AMS4** | <50 | Aerospace | INDIA | 1 h 20 m | 2 (CEO, Partner) | Company website, online case study |
| **T1S1** | <12,000 | Aerospace | U.S. | 2 h 45 m | 3 (Additive Manufacturing Manager (AMM), Director of Advanced Manufacturing (DAM), Senior Engineer (SE)) | Company website |
| **T1S2** | <300,000 | Aerospace | U.K. | 1 h 20 m | 1 (Lead Materials and Process Engineer (LM&PE)) | Company brochure |
| **T1S3** | <10,000 | Automotive | Germany | 1 h 35 m | 1 (Program Manager, Additive Manufacturing (PMAM)) | Company website |
| **T1S4** | <10,000 | Aerospace | U.S. | 1 h | 2 (Research and Tech Manager (RTM), Engineering Director (ED)) | Company website |
| **OEM1** | 14,000 | Power-Generation | Germany | 1 h 26 m | 1 (R&D Engineer (RDE)) | Company website |
| **OEM2** | <400,000 | Power-Generation | Germany | 1 h 56 m | 2 (VP Additive Manufacturing (VPAM), Business Development Officer (BDO)) | Company website |
| **OEM3** | <10,000 | Aerospace | U.K. | 1 h 37 m | 1 (Materials and Process Engineer (M&PE)) | Company website |

component characteristics. Furthermore, process maps were generated for the first three cases and sent to respondents for member-checking and to gain deeper understanding of EBM and SLM SCs (Creswell and Miller, 2000). All these measures were taken to develop a chain of triangulated evidence to enhance construct and internal validity of the research. A case study database was maintained on NVivo Pro-12 to store audio recordings, transcripts, and secondary data sources for reliability (Yin, 2014).

### *3.3. Data analysis*

An abductive logic was adopted, whereby an initial coding structure, developed from the theoretical framework (see section 2.3) was used as a basis for analysis, permitting the emergence of new constructs to refine theory (Klag and Langley, 2013). All interviews were transcribed verbatim using QSR NVivo Pro-12, providing an initial opportunity to engage in preliminary analysis and generation of tentative themes (Fereday and Muir-Cochrane, 2006). The first coding round was conducted during within-case analysis resulting in the generation of semantic themes on 2 levels mapped to nodes on NVivo Pro-12 (Braun and Clarke, 2006). A second coding round was conducted to check for duplications and regrouping of sub-nodes. To capture nuances of dependencies and SC configuration across three industries, we adopted a non-traditional three-phase approach to case study analysis (Bhakoo and Choi, 2013). In phase 1, the SC for a specific application and organisation was the unit of analysis. This within-firm analysis was conducted for each application in all industries and SC tiers. In phase 2, queries in NVivo were used to conduct cross-firm analysis between SCs in the same industry following a literal replication logic to enhance internal validity of identified relationships, shifting the unit of analysis to the industry (within-industry analysis). Subsequently, we carried out a cross-industry analysis following a theoretical replication logic that configurations will differ based on industry characteristics, to enhance external validity through analytical generalisation (Eisenhardt, 1989).

Process maps were instrumental as a visualisation strategy in conducting cross-case comparisons (as shown in Fig. 2). This enabled representation of large amounts of data across several dimensions to effectively highlight patterns (Miles, 2019). These stages involved several rounds of coding, data analysis and literature appraisal to develop theoretically and empirically grounded arguments about future developments of AM SC configuration through abduction (Klag and Langley, 2013).

## 4. Analysis

We analyse the case studies in three industries from within and cross-industry perspectives. Two illustrative examples of SCs in three industries are provided in Fig. 2 and explanations given in the following sections.

### *4.1. Within-industry analysis*

#### *4.1.1. Aerospace metal AM supply chain*

The metal AM SCs for seven Aerospace firms were explored. Interview and observational data facilitated the verification of generic operational principles for SLM and EBM as provided on websites and process brochures, as well as providing application specific details. Design and AM production capability was derived predominantly by focal firms via dependencies on AM specialists, except for T1S1 and OEM customer of T2S1 that invested significantly in in-house capability. Vertical complexity differs with respect to the positioning of AM capacity from consumption nodes. The lowest vertical complexity was achieved by T1S1 in deploying AM capacity in-house for assembly operations, as verified from interview accounts and website information. All other SCs included supply nodes for production and distribution to consumption nodes. Raw material was sourced mostly locally, except AMS4 and RC2, which had international suppliers. Generic metal powder was held at AM production sites to fulfil demand.

Horizontal complexity also varied according to insourcing levels, based on an organisation's size; T1S1, RC1 and RC2 having the most integrated operations. This resulted in differing levels of co-ordination required for post-processing. Spatial complexity varied with respect to the location of raw-material suppliers and post-processing subcontractors relative to the AM specialist. The supply bases of UK and

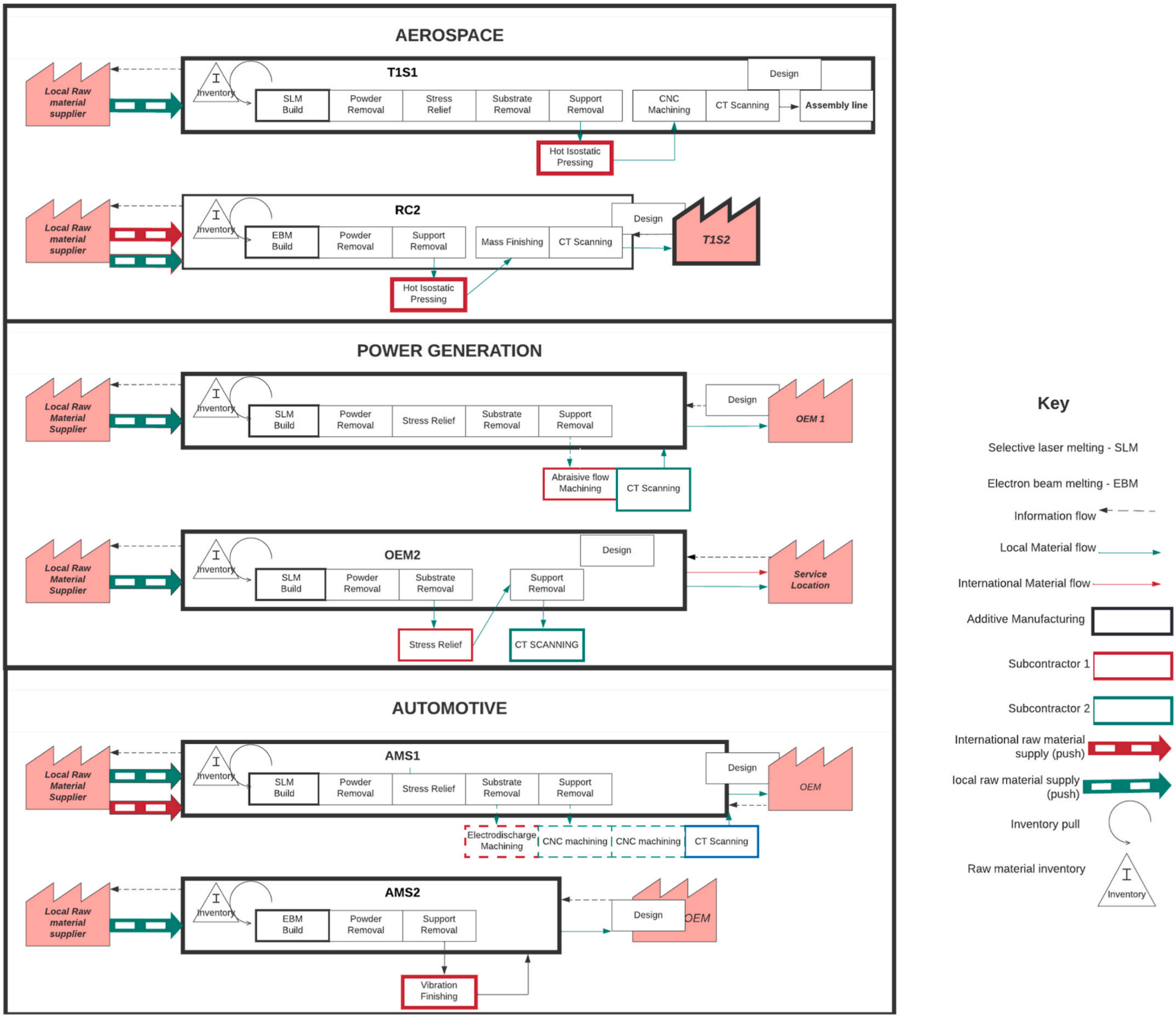


**Fig. 2.** Illustrative examples of metal AM supply chains for Aerospace, Power Generation and Automotive industries.

USA were mature in terms of providing local raw-material and post-processing capabilities to buyers. However, India has a less mature supply base both for raw-materials and post-processing, as confirmed by respondents from AMS4 and AMS3, who stated their dependence on foreign European and Asian suppliers. The SCs of safety critical components (T2S1 AMS4, RC2, T1S1, T1S2) consisted of capital-intensive processes such as Hot Isostatic Pressing (HIP), 5-axis CNC machining and CT-scanning, to guarantee the integrity of components for flights. SCs of non-safety-critical components (OEM3) did not contain such specialised processes.

### 4.1.2. *Power generation metal AM supply chain*

The metal AM SCs for Power Generation based on 2 applications were explored. Design and AM production capability is developed through in-house investments in R&D and manufacturing capacity (OEM2) and dependencies on AM specialists (OEM1). Despite AM being in-house, OEM2 serves local and international customer service locations for MRO, as described by the VP of AM and corroborated by website information. Spatial complexity was low for both SCs in terms of raw material and post-processing, due to the maturity of respective local supply bases. Safety criticality and geometric complexity of power generation components influenced the use of outsourced abrasive flow machining and CT scanning to guarantee integrity of components. Horizontal and vertical complexity was comparable for both SCs.

### 4.1.3. *Automotive metal AM supply chain*

AM SCs for four automotive applications were explored. General operational principles of SLM were consistent across the firms, however a respondent from T1S3 revealed an unconventional design practice, which resulted in the elimination of a mandatory post-process. Outsourcing to AM specialists was the dominant mechanism for acquiring design and manufacturing capabilities amongst the automotive companies. Vertical complexity was similar for pairs of cases (AMS1 and AMS2; RC3 and T1S3) as production capacities were located in 2nd and 3rd tiers respectively from the OEM. Spatial complexity for raw-material supplier and post-processing was low because of the maturity of local supply bases in Germany and the UK, providing the opportunity for AM specialists to dual source from international supply bases (AMS1). Non-safety critical components (RC3, T1S3 and AMS2) required cheaper post-processing methods such as bead-blasting, sandblastingand vibration finishing. Horizontal complexity varied according to the degrees of insourcing, the most capital-intensive processes being CT-scanning and 5-axis CNC-machining, which were subcontracted by AMS1 and noticeably absent during the plant tour.

## 4.2. Cross-industry analysis

We analyse the metal AM SCs across the three industries to identify distinctive characteristics and contextual factors that influence complexities and dependencies in the SC configuration. We also analyse the implication of these complexities and dependencies for SC competitiveness. These characteristics are summarised in Table 3. A scale comprising three values: “high”, “medium” and “low” is used to describe sub-dimensions. For example, manufacturing complexity is high, low and medium based on the number of processes in the SC. Based on the refined coding structure that emerged from the analysis, Table 4 presents illustrative quotes that describe effects of contextual factors on SC configuration dimensions.

### 4.2.1. Product value structure

Table 3 shows that most components exploited DFAM to reduce part count in modules down to 1, the highest reduction being heat-exchangers (AMS1, RC3), where individual TM parts run into hundreds. DFAM was applied to create complex external and internal geometries to deliver superior function and reduced weight across applications. Complex internal geometries were important to enhance fluid flow in modules (T1S1, RC1, OEM3; OEM1, T1S2; AMS1, RC3). In Power Generation applications (OEM1, OEM2) module function takes precedence over weight-reduction. The other end of the spectrum consists of parts with low complexity (1:1 ratio) (T2S1, TIS3, AMS2), where DFAM was applied for weight-reduction in Aerospace and Automotive industries respectively.

All industry applications demonstrated the importance of DFAM in optimising AM build performance and reducing manufacturing complexity. Aerospace and Automotive respondents (T2S1, T1S1, RC1, RC3, T1S3, AMS2) highlighted DFAM’s function in developing optimal orientations for components in the build envelope to reduce failures and lead-time. Respondents provided support for application of DFAM to reduce post-processing and component costs. However, the application of other post-processes such as HIP, CNC-machining and CT-scanning are influenced by safety criticality levels of components and were not eliminated with DFAM. These AM capabilities to extend product and process performance frontiers, makes metal AM an important resource to focal firms, thereby fulfilling the first condition of RDT in creating dependencies. Most focal firms referenced in this study depended on the AM service provider for DFAM expertise (see Fig. 2 for examples), except (T1S1, OEM customer of T2S1, OEM2 and AMS2), which had in-house capacity.

### 4.2.2. Supply chain structure

*4.2.2.1. Vertical complexity.* For most industry applications, the position of AM capacity was one node away from respective consumption nodes, which was usually not in the same geographical location. Most industry applications (OEM3, AMS4, RC2, T1S2, AMS1, OEM1, RC1 and RC3) depended on an AM service provider for manufacturing (see Fig. 2 for examples). T1S1, OEM customer of T2S1 and OEM2 were the exceptions with insourcing of the AM process to make modules for in-house assembly and distributed MRO locations respectively. Therefore, based on the position of AM capacity relative to focal companies, vertical complexity was judged to be high across the majority of industry applications, highlighting dependencies between focal firms and AM

**Table 3**
SC configuration dimensions for Aerospace, Automotive and Power Generation applications.

| | AEROSPACE | | | | | | | POWER GENERATION | | AUTOMOTIVE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T2S1 | AMS4 | TISI | RC1 | OEM3 | RC2 | TIS2 | OEM1 | OEM2 | AMS1 | RC3 | T1S3 | AMS2 |
| **Supply Chain Configuration Dimension** | SLM | SLM | SLM | SLM | SLM | EBM | EBM | SLM | SLM | SLM | SLM | SLM | EBM |
| **Product Value Structure** | | | | | | | | | | | | | |
| Ratio of TM to AM parts | 1:1 | 5:1 | 30:1 | 4:1 | 4:1 | 9:1 | 9:1 | 70:1 | 13:1 | 100 - 1000: 1 | 105:1 | 1:1 | 1:1 |
| Geometric complexity | | | | | | | | | | | | | |
| Safety criticality | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| **SC Structure** | | | | | | | | | | | | | |
| Spatial complexity (raw material) | | | | | | | | | | | | | |
| Spatial complexity (Post processing) | | | | | | | | | | | | | |
| Horizontal complexity | 3 | 2 | 1 | 0 | 2 | 1 | 1 | 1 | 2 | 3 | 1 | 1 | 1 |
| | | | | | | | | | | | | | |
| **Material and Information flow** | | | | | | | | | | | | | |
| Manufacturing complexity | 8 | 8 | 8 | 7 | 7 | 6 | 6 | 6 | 6 | 7 | 5 | 4 | 4 |
| Post-processing co-ordination | | | | n/a | | | | | | | | | |
| | | | | | | | | | | | | | |
| **Relationship and Governance** | | | | | | | | | | | | | |
| Dependence factors (AM specialist) | | | | A, B, C | A,C | A,B,C | | A, B | | A,B,C | A, B | A, B | A,B,C |
| Dependence factors (post-processing) | A,B,C | A, B, C | A, B, C | | A, C | A,C | A, C | A,C | | A,C | | | A,C |
| Uncertainty management strategy | Bridging | Bridging | Buffering | | Bridging | | Buffering and bridging | Bridging | | Buffering and bridging | | | Buffering |

**Dependency Factors**
Importance of Resource – A
Supplier Substitutability – B
Discretion Over Resource – C

SLM – Selective laser melting, EBM – Electron beam melting
Manufacturing complexity (1,2,3…) – Number of processes
Horizontal Complexity (1,2,3….) – Number of subcontractors

High Medium Low

**Table 4**
Illustrative quotes.

| SC configuration dimension | Effects of contextual factors on SC configuration | Illustrative quotes |
|---|---|---|
| **Product value structure** | Design for AM affects manufacturing complexity, which affects cost efficiency | "The traditional manufacturing version is an assembly made of sheet metals that are bent and cut out and then combined again with brazing. It's at least 70 components." (R&DE, OEM1)<br>"If I want to make it low cost then minimise supports. That compromises performance and mass but brings the cost right down." (PRE, RC3) |
| **SC structure** | | |
| Vertical complexity | Economies of scale affects vertical complexity | "We need to make the suppliers realise that's half of the story. Because they haven't thought about how you economically appropriate environmental and powder health and safety controls." (LTA, RC2)<br>"In the end, it comes down to a company's make or buy decision. It's not worth us buying technology in-house, because there are external suppliers." (M&PE, OEM3) |
| Horizontal complexity | Safety criticality and geometric complexity affects horizontal complexity | "If a part requires CT scanning, it's not because it is additive, it because it is in a critical application." (AMM, T1S1)<br>"The part was not critical, so you don't need to post-process. Just down from the base plate directly into the assembly." (PMAM, T1S3) |
| Spatial complexity | Supply base maturity affects spatial complexity | "There is no service bureau for hipping in India. We have to get that outsourced from abroad, which is a bottleneck for us. The logistics is very expensive." (CEO, AMS4)<br>"Some of the complex Electrostatic Discharge Machining operations are not available in India. The contract manufacturing service has to take it in Germany or in Japan." (HPP, AMS3) |
| **Material and information flow** | | |
| Manufacturing complexity | AM machine and design for AM capabilities affect manufacturing complexity | "On the laser side, it is a necessity to stress relieve definitely on ti64. Not a constraint on the EBM, they don't have to stress relieve." (SE, RC2)<br>"For motorsport, we rely completely on the build being correct. During the build, the machine records many parameters and can give an indication of layer quality. But it is actually post-processing." (CEO, AMS2) |
| Co-ordination | Horizontal complexity and dependencies increase co-ordination burdens | "The outside processes added way too much time to. We make the part quite quickly in the additive machine, then we have to go out for quite specialised heat treatment." (SE, T1S1)<br>"A lot of companies just buy a 3D machine without all post-processes, and say they can deliver serial parts, but they don't have the process chain inhouse. This can be problematic if they must bring it to a sub-supplier." (PMAM, T1S3) |
| **Relationship and governance** | | |
| Dependence factor (AM service provider) | | **Supplier substitutability**<br>"This company doesn't have its own AM capability. They are now struggling a little bit to find someone who can manufacture these components on their behalf." (AML, RC1)<br>**Discretion over resource**<br>"Guaranteed income vs capital expenditure is difficult, but not too bad with us because we are a very focused 3 d printing company. But others will struggle to justify buying AM machines because they won't have enough business to guarantee financial profitability." (MDL, AMS2) |
| Dependence factor (post-processing) | | **Supplier substitutability**<br>"Specialised EDM post-processes are challenging to source, especially considering that these are smaller quantities. Trying to find a vendor who would work on a single piece and align his process and set up for that is challenging." (Partner, AMS4)<br>**Discretion over resource**<br>"The only inspection that is not done in-house is the X-RAY, CT SCAN because they are both big, expensive." (TD, AMS1) |
| Buffering strategies | | "It comes down to the most cost-effective way to produce repeatable quality parts. If demand is low, we subcontract. If demand is high then we need a bigger supply chain, or we bring it in-house." (M&PE, OEM3)<br>"We are about to get vibration finishing in-house. Right now, we have to subcontract it. Because all the components need surface finishing." (CEO, AMS2) |
| Bridging strategies | | "It is about relationship building, making them aware that this service would be required and its as slowly overtime you can evolve where businesses start to look at offering it as a service." (AML, T2S1)<br>"We are working towards building some contingency, in our supply chain. Effectively, working with other people around us that are running machines so that we can go "can we use your machines in the event of needing some contingency." (MDL, AMS1) |

service providers.

*4.2.2.2. Horizontal complexity.* Horizontal complexity of respective SCs varied with the level of outsourced post-processes at the SC tier where AM capacity is installed. Table 3 shows the decreasing trend of horizontal complexities across industries from left to right. AM components (shown towards the left) are characterised by high safety-criticality and geometric complexity, which require capital intensive post-processes such as H.I.P, 5-axis CNC machining, abrasive flow machining and CT-scanning to meet quality requirements. These processes were outsourced to specialist suppliers in majority of instances (except RC1, RC2 and AMS4), thereby creating supplier dependencies. AM components towards the right-hand side of Table 3 were less complex and non-safety critical, therefore post-processing was not significant, resulting in lower horizontal complexity and supplier dependence.

*4.2.2.3. Spatial complexity.* Fig. 2 and Table 3 shows how spatial complexity for raw material supply was mostly low for developed economies (Germany, U.K. and U.S.A.), due to the maturity of local supply bases. Organisations with medium spatial complexities (RC2, AMS1), maintain both local and international sources in Europe and North America. Counterparts in India (AMS3 and AMS4) had high spatial complexities due to raw material importation from Europe and U.S.A. A similar situation exists for post-processing, where India lacks specialised processes such as HIP and complex electrostatic discharge machining, therefore dependence is created on post-processing suppliers in Europe and Asia, which increases logistics costs and delays.

#### 4.2.3. Material and information flow

*4.2.3.1. Manufacturing complexity.* Three Aerospace SCs (T2S1, AMS4 and T1S1) had the highest manufacturing complexities owing to safety-critical applications that require extensive post-processing with HIP and CT scanning. Notably, (T2S1, RC2 and T1S2) had similar application requirements in terms of structural loads, however respective SCs are shorter due to EBM capabilities, which eliminate two post-processes. Power Generation applications had the mean manufacturing complexity with OEM1 requiring an Abrasive Flow machining process due to complex internal channels. The Automotive SCs (T1S3, AMS2) had the lowest manufacturing complexities, due to advanced DFAM and machine capabilities that eliminated some post-processes. Notably, AMS2 exploits EBM's 'in-process monitoring' capability to eliminate separate inspection activities for Motorsport applications. Fig. 2 and Table 3 show that the number of batch processes in respective SCs varied, with Aerospace having the highest concentration (T2S1, AMS4, T1S1). Power Generation and Automotive SCs contained a lower number of batch-processes (CNC machining). In most of the cases, these batch-processes are controlled by specialist suppliers, who apply lean management practices to maximise capacity. These supplier dependencies create bottlenecks and reduce responsiveness, as highlighted by respondents from T2S1 and T1S1.

*4.2.3.2. Co-ordination.* All SCs required one raw material, regardless of component complexity, therefore co-ordination efforts with multiple suppliers for inbound parts was not required. A common trend across cases was insourcing of core AM post-processes (powder, support and substrate removal and stress-relief heat treatment) and subcontracting of capital-intensive and specialist processes. RC1 has a fully integrated SC. AMS2 subcontracts one process; the CEO expressed his desire to bring it in-house due to its low cost. As shown in Table 3, the level of co-ordination for post-processing differs with horizontal and spatial complexity, due to dependence on local and international post-processing subcontractors. This is complicated by the presence shared batch processes, such as H.I.P, which require co-ordination of orders from different customers to maximise capacity, creating trade-offs between efficiency and responsiveness.

#### 4.2.4. Relationship and governance between supply chain entities

AM manifests superior design capabilities, through the product value structure, making it an important resource to focal firms (section 4.2.1), thereby fulfilling the first condition for dependence according to RDT. Dependencies were identified along vertical, horizontal and spatial dimensions in sections 4.2.2 and 4.2.3. Table 3 shows the other complementary factors (denoted as 'B' and 'C'), which reinforce dependencies on suppliers according to RDT and discussed as follows.

*4.2.4.1. Discretion over resource.* The high cost of metal AM adoption was cited by Aerospace and Automotive respondents (OEM3, RC1, RC2, AMS1, AMS2) as a major barrier to insourcing for focal firms, creating dependencies on AM service providers. Other factors influencing dependency include lack of specialisation amongst traditional focal firms in managing quality, health and safety requirements of metal AM (RC1, RC2, AMS1), restricted capacity availability created by existing production contracts with other customers (RC1, AMS1, AMS2) and lack of DFAM expertise (AMS1, AMS2, RC2). Dependencies were also created between AM adopters and subcontractors for processes such as HIP, 5-axis CNC-machining, CT-scanning, due to scale and specialisation considerations (T2S1, AMS4, T1S1, RC2, T1S2, AMS2) as highlighted in section 4.2.2. Discretion of OEMs over batch processes such as H.I.P and CNC-machining in Aerospace and Automotive industries is limited due to low volumes and subcontractor business models, which are based on scale economies as highlighted by respondents from T2S1, T1S1, OEM3, AMS3, AMS2 and OEM1.

*4.2.4.2. Supplier substitutability.* Dependencies on suppliers are compounded by the limited scope for supplier substitution. Respondents across industries (RC1, AMS1, RC3, AMS2, OEM1), highlighted the relative scarcity of metal AM suppliers. Scarcity is heightened by the fact that specific capabilities are required for different applications. Respondents across industries (RC2, T1S3, OEM1) mentioned they had difficulties in finding suppliers with the right quality philosophies to meet Aerospace, Automotive and Power-Generation industry requirements. For post-processing, supplier substitutability is also challenging due to limited number of suppliers for CT scanning, finish machining (T2S1, T1S1, AMS2) and absence of specialised post-processes in developing regions (AMS3, AMS4).

*4.2.4.3. Bridging and buffering strategies.* Given identified dependencies from sections 4.2.1–4.2.4, Table 3 shows the application of bridging and buffering strategies by firms to mitigate performance uncertainties in terms of cost efficiency and responsiveness. Despite the large capital outlays associated with metal AM and HIP, T1S1 and T1S2 created in-house capacity to serve as a buffer from dependence on external suppliers, which creates delays. In a similar manner, AMS2 also highlighted plans to insource a relatively inexpensive finishing process, due to the high volume of orders. AMS1 highlighted the development of buffers (access to production capacity) through relationships with machine manufacturers, in peak seasons where in-house capacity is fully utilised.

On the other hand, the capital intensity of metal AM and associated post-processes prevented insourcing amongst firms with high dependencies (OEM1, OEM3, AMS1, AMS3, AMS4), leading to the application of bridging strategies on existing supplier relationships to enhance competitiveness. AMS1 highlighted the importance of bridging, via transparent communications with focal firms for capacity availability. Low volume AM orders are particularly problematic for batch post-processes, thereby creating the need to deepen relationships and co-ordination with existing subcontractors (AMS3, T2S1, OEM1) to achieve a balance between cost-efficiency and responsiveness.

## 5. Discussion

Our study demonstrated that AM's potential to reduce complexity and dependency is contingent on economic (AM infrastructure costs), industry (safety criticality, supplier scarcity), geographical (supply base maturity), organisational (size, DFAM, specialisation, component geometry) and technological (AM machine capability) factors (RQ1). Our study also demonstrated that dependencies create uncertainties, which require application of bridging and buffering strategies to enhance SC competitiveness (RQ2). Hence, we refined our conceptual framework to capture these findings (see Fig. 3). The framework reveals the mediating role that 'relationship and governance' plays between the other three SC configuration dimensions and strategic bridging and buffering decisions required for SC competitiveness. The bi-directional arrows show that dependencies in component design (product value structure) and production (SC structure and material and information flow) require bridging and buffering strategies to enhance SC competitiveness (left to right direction of bridging and buffering arrows). SC managers also need to understand the requirements for competitiveness in respective markets to devise appropriate bridging and buffering strategies (right to left direction of bridging and buffering arrows). These bridging and buffering strategies feed into existing dependencies to modify the SC's configuration. For example, the buffering strategies applied in cases of TIS1, T1S2 and AMS2 reduces vertical and horizontal complexity in the SC structure, whilst bridging strategies applied by OEM1, OEM3, AMS1 and ASM3 affect information flow.

We now discuss our findings considering propositions about complexity and dependency changes from the extant management literature (section 2.2) and develop four propositions to shed further light on RQs.

In TM SCs, focal firms manipulate the product value structure by exploiting commonalities in parts across different products to reduce SC complexity (Choi and Hong, 2002). This reduces the portion of supply dependencies outside their direct control and performance uncertainties (Flood, 1987; Pfeffer, 2003). Whilst rationalising supply bases at the component level with TM is difficult (Hendry et al., 1999), our analysis demonstrates AM's potential to enhance competitiveness of metal components and their SCs, making it an important resource to focal firms (Pfeffer, 2003). Uncertainties in achieving these benefits are likely to be reduced when AM is insourced by focal firms. However, outsourcing levels reflected across our cases suggest that generally, vertical dependence on AM service providers is created when AM is adopted in metal SCs, as opposed to the view of dependence reduction (Holmström et al., 2016). Given the importance of AM in high value manufacturing industries, AM service providers possess considerable control over the tangible and intangible resources to create dependencies from focal firms in design and manufacturing (Pfeffer, 2003). They possess scale advantages in serving a wide customer base as their core competence, to recoup huge investment costs associated with AM adoption. Although these dependencies are necessary to maximise returns on AM in terms of product performance and process efficiency, they reduce the level of control that focal firms have on the competitiveness of their SCs. As AM is still an emerging technology, focal firms do not appear to have sufficient volumes to make insourcing worthwhile. These conditions are comparable to the nascent EV SC, where OEMs depend on suppliers due to small volumes (Kalaitzi et al., 2019). These dependencies are compounded by the relative scarcity of AM specialists and specific competencies required for particular applications.

Studies discussed earlier recognised AM's potential to reduce manufacturing complexity, however complexities created by post-processing were also emphasized (Section 2.2.3). Our analysis shows that manufacturing complexity could be reduced through machine and DFAM capabilities. However, some complexities are influenced by safety criticality levels and/or geometric complexity of components, which create dependencies on post-processing specialists (Pfeffer, 2003). These horizontal dependencies, constitute an additional source of uncertainties for firms adopting AM as co-ordination burdens are introduced for post-processing, which affects SC responsiveness (Choi and Hong, 2002). Whilst extant research highlights reductions in co-ordination burdens from multiple input suppliers in TM SCs (Bogers et al., 2016; Ghobadian et al., 2018; Holmström et al., 2016; Khajavi et al., 2014; Ramón-Lumbierres et al., 2021), our analysis highlights co-ordination burdens that emerge through dependencies on post-processing subcontractors. Therefore, we propose that:

P1: In instances where vertical complexity is reduced through insourcing of AM by focal firms, dependencies on subcontractors are likely to persist for critical metal AM applications, which require specialisation.

Responsiveness is further compromised by the presence of outsourced batch-manufacturing processes such as heat-treatment and CNC-machining, which require lean management principles for cost efficiency. This creates conflicting performance objectives between additive manufacturers and post-processing sub-contractors, introducing additional uncertainty for SC competitiveness (Wontner et al., 2020). These batch processes represent bottlenecks in metal AM SCs and require effective co-ordination to enhance efficiency (Sun and Yu, 2015). The low volume of AM components reduces the additive manufacturer's discretion over control of subcontractor processes (Pfeffer, 2003). Shared processes such as HIP depend on combined discretionary control from different customers to maximise capacity, which introduces uncertainties in responsiveness as demonstrated by our analysis. Therefore, we propose that:

P2: Supplier dependencies are exacerbated by the presence of batch processes in metal AM SCs, which introduce trade-offs between cost-efficiency and responsiveness.

Extant literature has emphasized AM's scope to enable decentralised manufacturing, and hence reduce spatial complexity (Corsini et al., 2020; Tziantopoulos et al., 2019), however metal AM is likely suited to centralisation due to dependence on post-processing specialists (Mellor et al., 2014; Strong et al., 2018). Our analysis favours the latter view, with most metal AM production capacities located in centralised facilities near respective post-processing supply bases. However, co-ordination burdens are exacerbated when local post-processing supply bases lack specialised sub-contractors. This introduces international supply dependencies and uncertainties for competitiveness of additive manufacturers located in underdeveloped regions. Therefore, we propose that:

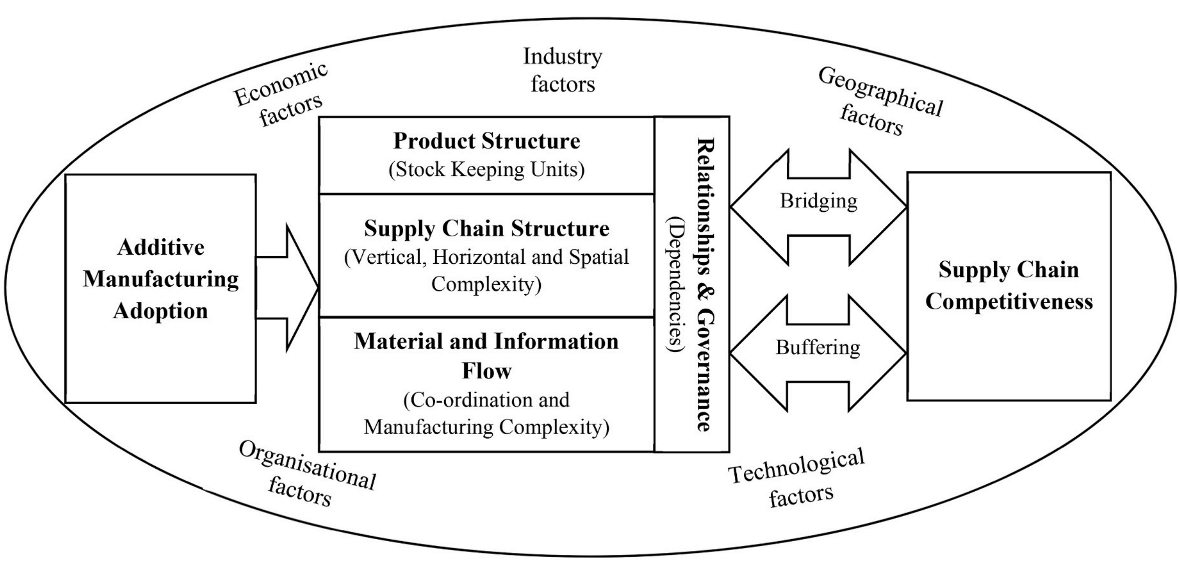


**Fig. 3.** Additive manufacturing supply chain Configuration framework.

P3: Industrial metal AM applications with high dependencies on specialist processes, are unlikely to scale up in regions where the post-processing supply base maturity is low.

To mitigate uncertainties created by these dependencies, our study suggests that firms apply bridging and/or buffering strategies to enhance SC competitiveness (Bode et al., 2011). To manage vertical dependencies for AM capacity, production volumes appear to be crucial in differentiating the application of bridging strategies with existing suppliers and buffering (insourcing in this instance). We show that AM service providers are not immune to capacity shortages and may apply bridging strategies with existing machine manufacturers to access AM capacity. For dependencies on post-processing specialists, majority of firms (focal firms and suppliers) relied on bridging strategies to enhance competitiveness of their SCs. The exceptions were T1S1 and T1S2 who built buffers by insourcing capital-intensive processes. Smaller organisations were unable to insource expensive post-processes that were critical to their operations (AMS2, AMS3, AMS4) due to financial constraints and had cope with inefficiencies created by external dependencies. So, in addition to volume considerations, our study suggests that organisational size and cost are important factors in examining uncertainty mitigation strategies adopted by SC entities. This provides nuance to earlier propositions, which suggest that bridging strategies are adopted when dependencies are high (Kalaitzi et al., 2019). Therefore, we propose that:

P4: To mitigate uncertainties in metal AM SCs, large OEMs/Tier1s are more likely to adopt buffering strategies, as opposed to smaller firms who are likely to adopt bridging strategies.

## 6. Conclusions and implications

For low-volume, high-value manufacturing applications in engineering-oriented industries, organisations are gradually moving towards AM to capitalise on its benefits. Due to fragmented treatment of AM SC configurations, we adopted a holistic approach, applying SC configuration and RDT to analyse metal applications across three industries. Using an abductive logic, we developed a framework to refine extant propositions about the changing state of complexities and dependencies in SC configurations, resulting in four propositions.

### *6.1. Theoretical contributions*

Our research offers a new perspective on SC configurations in the AM context. This is one of the first empirical studies, which takes a cross-industry perspective in providing insights about the changing state of complexities and dependencies in the AM context through the RDT lens. Firstly, we contribute to AM SC configuration literature by applying a holistic framework to identify the underlying mechanisms that influence complexities and dependencies in vertical and horizontal SC configuration dimensions. Our cross-industry/tier/regional case study design enabled us to detect economic, industry, geographical, organisational and technological factors that shape AM SC configurations. Secondly, we applied the RDT lens to understand complexities and dependencies in a nascent SC. Through our conceptual framework and 4 propositions, we provide further insights into the interplay between complexities and dependencies in a SC's configuration, with implications for performance. Thirdly, we contribute to AM SC configuration literature by utilising RDT to highlight the meditating role dependencies play in SC competitiveness, as well as buffering and bridging strategies deployed by organisations to mitigate uncertainties in metal AM SCs. Lastly, we contribute to SC configuration literature by highlighting the interplay between 'relationship and governance' and the other three SC configuration dimensions in relation to SC competitiveness.

### *6.2. Managerial implications*

Our paper develops a SC configuration framework, which identifies economic, industry, technological, organisational and geographical factors that require careful consideration during AM implementation. These factors are particularly important in the pre-installation phase of technology implementation (Mellor et al., 2014). During AM business case evaluation, consideration should be given to the SC configuration shaping factors identified in this study. We also identify how complexities and dependencies change in composition and magnitude, depending on industrial applications. These insights could support managerial decisions when designing SCs. This is crucial in highly regulated industries such as Aerospace, healthcare and pharmaceuticals, which require innovative and specialist capabilities for responsive and efficient SCs. Lastly, an awareness of bridging and buffering strategies available to SC designers could help mitigate uncertainties associated with supplier dependence and manage potential bottlenecks associated with the intersection of economies-of-one and economies-of-scale.

### *6.3. Limitations and future research*

Our study is subject to the common limitations of case study research. Whilst we cannot claim statistical generalisability, analytical generalisability is achieved to a reasonable degree by constant reflection between analysis, the conceptual framework, propositions and theory (Yin, 2014). Future quantitative studies are required to test the strength of identified contextual factors on the configuration of AM SCs in different industries to deepen our understanding of their relative importance. To enhance external validity, future research could test the four propositions to deepen understanding of the key complexities and dependencies in AM SCs, especially in under-explored areas (e.g. medical, marine and construction sectors). As described in section 3.1, our approach during data collection with suppliers and focal firms aimed to better understand the complexities and dependencies within and across SC tiers. Although these steps enhance internal validity of the SC phenomena (Giunipero et al., 2008), future research could attempt focusing on a single complex component from raw-material supplier to the finished product, to shed further light on the effect of resources and buyer/supplier power on dependencies and competitiveness. Our study used a cross-sectional case study approach to develop propositions. Future research could apply longitudinal case studies to study changes in complexities and dependencies in SCs before and after AM adoption. This would extend insights on the effects of AM adoption on SC evolution, especially in terms of the lifecycle of TM and AM SCs for reference components (MacCarthy et al., 2016). Finally, as this study was limited to powder bed fusion AM processes, future research could focus on other AM processes such as Directed Energy Deposition and Fused Deposition Modelling.

## Acknowledgements

The authors acknowledge that majority of this research was carried out as part of a PhD programme sponsored by The University of Nottingham through the Vice Chancellors Research Excellence Scholarship and Nottingham University Business School Scholarship. The authors also wish to acknowledge that some aspects this research was carried out as part of the UKIERI SPARC Support Programme (code P730) funded by the MHRD, India. We also wish to thank all organisations and individuals that provided data, which was used in the development of this paper.

## APPENDIX

**Table A1**
Definition of constructs applied in study

| Construct | Definition | Authors' Definition |
|---|---|---|
| Vertical complexity | Refer to the number of levels in the system (Choi and Hong, 2002) | Number of SC tiers |
| Horizontal complexity | Number of Suppliers in each tier (Choi and Hong, 2002) | Number of subcontractors |
| Spatial Complexity | The average distance between firms engaged in buying and supplying (Choi and Hong, 2002) | |
| Manufacturing complexity | The level of detail and dynamic complexity found within the manufacturing facility's processes. (Bozarth et al., 2009) | Number of manufacturing processes in a supply chain |
| Supply Chain Coordination | Ability of a logistics manager to integrate interrelated supply chain activities across different lines of organisational authority and responsibility (Ballou et al., 2000). | |

## References


Al-Balushi, Z., Durugbo, C.M., 2020. Management strategies for supply risk dependencies: empirical evidence from the gulf region. Int. J. Phys. Distrib. Logist. Manag. 50 (4), 457–481.

Altıparmak, S.C., Xiao, B., 2021. A market assessment of additive manufacturing potential for the aerospace industry. J. Manuf. Process. 68, 728–738.

Baldinger, M., Levy, G., Schönsleben, P., Wandfluh, M., 2016. Additive manufacturing cost estimation for buy scenarios. Rapid Prototyp. J. 22 (6), 871–877.

Ballou, R.H., Gilbert, S.M., Mukherjee, A., 2000. New managerial challenges from supply chain opportunities. Ind. Market. Manag. 29 (1), 7–18.

Barney, J., 1991. Firm resources and sustained competitive advantage. J. Manag. 17 (1), 99.

Bhakoo, V., Choi, T., 2013. The iron cage exposed: institutional pressures and heterogeneity across the healthcare supply chain. J. Oper. Manag. 31 (6), 432–449.

Bode, C., Wagner, S.M., Petersen, K.J., Ellram, L.M., 2011. Understanding responses to supply chain disruptions: insights from information processing and resource dependence perspectives. Acad. Manag. J. 54 (4), 833–856.

Bogers, M., Hadar, R., Bilberg, A., 2016. Additive manufacturing for consumer-centric business models: implications for supply chains in consumer goods manufacturing. Technol. Forecast. Soc. Change 102, 225–239.

Bourell, D., Kruth, J.P., Leu, M., Levy, G., Rosen, D., Beese, A.M., Clare, A., 2017. Materials for additive manufacturing. CIRP Annals 66 (2), 659–681.

Bozarth, C.C., Warsing, D.P., Flynn, B.B., Flynn, E.J., 2009. The impact of supply chain complexity on manufacturing plant performance. J. Oper. Manag. 27 (1), 78–93.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3 (2), 77–101.

Braziotis, C., Rogers, H., Jimo, A., 2019. 3D printing strategic deployment: the supply chain perspective. Supply Chain Manag.: Int. J. 24 (3), 397–404.

Bryman, A., 2015. Social Research Methods. Oxford university press.

Buckley, P.J., Strange, R., 2015. The governance of the global factory: location and control of world economic activity. Acad. Manag. Perspect. 29 (2), 237–249.

Choi, T.Y., Hong, Y., 2002. Unveiling the structure of supply networks: case studies in Honda, Acura, and DaimlerChrysler. J. Oper. Manag. 20 (5), 469–493.

Corsini, L., Aranda-Jan, C.B., Moultrie, J., 2020. The impact of 3D printing on the humanitarian supply chain", *Production Planning & Control*. Taylor & Francis 33 (6–7), 692–704.

Creswell, J.W., Miller, D.L., 2000. Determining validity in qualitative inquiry. Theory Into Pract. 39 (3), 124–130.

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14 (4), 532–550.

Eisenhardt, K.M., Graebner, M.E., Sonenshein, S., 2016. Grand challenges and inductive methods: rigor without rigor mortis. Acad. Manag. J. 59 (4), 1113–1123.

Emerson, R.M., 1962. Power-dependence Relations". American Sociological Review, JSTOR, pp. 31–41.

Eyers, D.R., Potter, A.T., Gosling, J., Naim, M.M., 2018. The flexibility of industrial additive manufacturing systems. Int. J. Oper. Prod. Manag. 38 (12), 2313–2343.

Fereday, J., Muir-Cochrane, E., 2006. Demonstrating rigor using thematic analysis: a hybrid approach of inductive and deductive coding and theme development. Int. J. Qual. Methods 5 (1), 80–92.

Flood, R.L., 1987. Complexity: a definition by construction of a conceptual framework. Syst. Res. 4 (3), 177–185.

Foerstl, K., Franke, H., Cataldo, Z., 2021. What drives managers to insource production? Evidence from a behavioural experiment. J. Purch. Supply Manag. 27 (4), 100715.

Genovese, A., Morris, J., Koh, S.C.L., Acquaye, A., 2020. An investigation into design and performance of supply chains for public procurement projects. Prod. Plann. Control 33 (9–10), 811–830.

Gereffi, G., Humphrey, J., Sturgeon, T., 2005. The governance of global value chains. Rev. Int. Polit. Econ. 12 (1), 78–104.

Ghobadian, A., Talavera, I., Bhattacharya, A., Kumar, V., Garza-Reyes, J.A., O'Regan, N., 2018. Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability. Int. J. Prod. Econ. 219, 457–468.

Giunipero, L.C., Hooker, R.E., Joseph-Matthews, S., Yoon, T.E., Brudvig, S., 2008. A decade of scm literature: past, present and future implications. J. Supply Chain Manag. 44 (4), 66–86.

Hedenstierna, C.P.T., Disney, S.M., Eyers, D.R., Holmström, J., Syntetos, A.A., Wang, X., 2019. Economies of collaboration in build-to-model operations. J. Oper. Manag. 65 (8), 753–773.

Hendry, L., Kingsman, B., Amaro, G., 1999. Competitive advantage, customisation and a new taxonomy for non make-to-stock companies. Int. J. Oper. Prod. Manag. 19 (4), 349–371.

Hillman, A.J., Withers, M.C., Collins, B.J., 2009. Resource dependence theory: a review. J. Manag. 35 (6), 1404–1427.

Hohn, M.M., Durach, C.F., 2021. Additive manufacturing in the apparel supply chain — impact on supply chain governance and social sustainability. Int. J. Oper. Prod. Manag. 41 (7), 1035–1059.

Holmström, J., Holweg, M., Khajavi, S.H., Partanen, J., 2016. The direct digital manufacturing (r) evolution: definition of a research agenda. Operations Management Research 9 (1–2), 1–10.

Holmström, J., Partanen, J., Tuomi, J., Walter, M., 2010. Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment. J. Manuf. Technol. Manag. 21 (6), 687–697.

Huang, S.H., Liu, P., Mokasdar, A., Hou, L., 2013. Additive manufacturing and its societal impact: a literature review. Int. J. Adv. Manuf. Technol. 67 (5–8), 1191–1203.

Jimo, A., Braziotis, C., Rogers, H., Pawar, K., 2019. Traditional vs additive manufacturing supply chain configurations: a comparative case study. Procedia Manuf. 39, 765–774.

Kalaitzi, D., Matopoulos, A., Clegg, B., 2019. Managing resource dependencies in electric vehicle supply chains: a multi-tier case study. Supply Chain Manag.: Int. J. 24 (2), 256–270.

Ketchen Jr., D.J., Kaufmann, L., Carter, C.R., 2021. Configurational approaches to theory development in supply chain management: leveraging underexplored opportunities. Journal of Supply Chain Management 58, 71–88.

Khajavi, S.H., Partanen, J., Holmström, J., 2014. Additive manufacturing in the spare parts supply chain. Comput. Ind. 65 (1), 50–63.

Klag, M., Langley, A., 2013. Approaching the conceptual leap in qualitative research. Int. J. Manag. Rev. 15 (2), 149–166.

Kleer, R., Piller, F.T., 2019. Local manufacturing and structural shifts in competition: market dynamics of additive manufacturing. Int. J. Prod. Econ. 216, 23–34.

Knofius, N., van der Heijden, M.C., Zijm, W.H.M., 2019. Consolidating spare parts for asset maintenance with additive manufacturing. Int. J. Prod. Econ. 208, 269–280.

Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. J. Clean. Prod. 106, 654–668.

Kovács, G., Sigala, I.F., 2021. Lessons learned from humanitarian logistics to manage supply chain disruptions. J. Supply Chain Manag. 57 (1), 41–49.

Kunovjanek, M., Wankmüller, C., 2020. An analysis of the global additive manufacturing response to the COVID-19 pandemic. J. Manuf. Technol. Manag. 32 (9), 75–100.

Levina, N., Vaast, E., 2005. The emergence of boundary spanning competence in practice: implications for implementation and use of information systems. MIS Q. 29 (2), 335–363.

Luomaranta, T., Martinsuo, M., 2020. Supply chain innovations for additive manufacturing. Int. J. Phys. Distrib. Logist. Manag. 50 (1), 54–79.

Magnani, G., Zucchella, A., Strange, R., 2019. The dynamics of outsourcing relationships in global value chains: perspectives from MNEs and their suppliers. J. Bus. Res. 103, 581–595.

MacCarthy, B.L., Blome, C., Olhager, J., Srai, J.S., Zhao, X., 2016. Supply chain evolution – theory, concepts and science. Int. J. Oper. Prod. Manag. 36 (12), 1696–1718.

Mellor, S., Hao, L., Zhang, D., 2014. Additive manufacturing: a framework for implementation. Int. J. Prod. Econ. 149, 194–201.

Mena, C., Humphries, A., Choi, T.Y., 2013. Toward a theory of multi-tier supply chain management. J. Supply Chain Manag. 49 (2), 58–77.

Meredith, J., 1998. Building operations management theory through case and field research. J. Oper. Manag. 16 (4), 441–454.

Miles, M.B., 2019. Qualitative Data Analysis: A Methods Sourcebook, fourth ed. SAGE, Los Angeles.

Miller, F.A., Lehoux, P., 2020. The innovation impacts of public procurement offices: the case of healthcare procurement. Res. Pol. 49 (7), 104075.

Petrick, I.J., Simpson, T.W., 2013. 3D printing disrupts manufacturing: how economies of one create new rules of competition. Res. Technol. Manag. 56 (6), 12–16.

Pfeffer, J., 2003. The External Control of Organizations: A Resource Dependence Perspective. Stanford Business Books, Stanford, California.

Prajogo, D., Chowdhury, M., Nair, A., Cheng, T.C.E., 2020. Mitigating the performance implications of buyer's dependence on supplier: the role of absorptive capacity and long-term relationship. Supply Chain Manag.: Int. J. 25 (6), 693–707.

Ramón-Lumbierres, D., Heredia Cervera, F.J., Minguella-Canela, J., Muguruza-Blanco, A., 2021. Optimal postponement in supply chain network design under uncertainty: an application for additive manufacturing. Int. J. Prod. Res. 59 (17), 5198–5215.

Rayna, T., Striukova, L., 2016. From rapid prototyping to home fabrication: how 3D printing is changing business model innovation. Technol. Forecast. Soc. Change 102, 214–224.

Rogers, H., Baricz, N., Pawar, K.S., 2016. 3D printing services: classification, supply chain implications and research agenda. Int. J. Phys. Distrib. Logist. Manag. 46 (10), 886–907.

Ruffo, M., Tuck, C., Hague, R., 2007. Make or buy analysis for rapid manufacturing. Rapid Prototyp. J. 13 (1), 23–29.

Sandström, C.G., 2016. The non-disruptive emergence of an ecosystem for 3D Printing — insights from the hearing aid industry's transition 1989–2008. Technol. Forecast. Soc. Change 102, 160–168.

Srai, J.S., Gregory, M., 2008. A supply network configuration perspective on international supply chain development. Int. J. Oper. Prod. Manag. 28 (5), 386–411.

Strong, D., Kay, M., Conner, B., Wakefield, T., Manogharan, G., 2018. Hybrid manufacturing – integrating traditional manufacturers with additive manufacturing (AM) supply chain. Addit. Manuf. 21, 159–173.

Sun, L., Yu, S., 2015. Scheduling a real-world hybrid flow shop with variable processing times using Lagrangian relaxation. Int. J. Adv. Manuf. Technol. 78 (9–12), 1961–1970.

Thürer, M., Huang, Y., Stevenson, M., 2021. Workload control in additive manufacturing shops where post-processing is a constraint: an assessment by simulation. Int. J. Prod. Res. 59 (14), 4268–4286.

Tziantopoulos, K., Tsolakis, N., Vlachos, D., Tsironis, L., 2019. Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era. Prod. Plann. Control 30 (7), 510–521.

Voss, C., Tsikriktsis, N., Frohlich, M., 2002. Case research in operations management. Int. J. Oper. Prod. Manag. 22 (2), 195–219.

Wagner, S.M., Walton, R.O., 2016. Additive manufacturing's impact and future in the aviation industry. Prod. Plann. Control 27 (13), 1124–1130.

Wontner, K.L., Walker, H., Harris, I., Lynch, J., 2020. Maximising 'Community Benefits' in public procurement: tensions and trade-offs. Int. J. Oper. Prod. Manag. 40 (12), 1909–1939.

Yang, S., Zhao, Y.F., 2018. Additive manufacturing-enabled Part Count reduction: a lifecycle perspective. J. Mech. Des. 140 (3), 031702-031702–12.

Yin, R.K., 2014. Case Study Research: Design and Methods, fifth ed. SAGE, Thousand Oaks, California.