

## **Distributed Manufacturing: A new form of localized production?**

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### **Abstract**

**Purpose:** The emergence of distributed manufacturing (DM) is examined as a new form of localised production, distinct from previous manifestations of multi-domestic and indigenous production.

**Methodology:** Supply network (SN) configuration and infrastructural provisioning perspectives were used to examine the literature on established localised production models as well as DM. A multiple case study was then undertaken to describe and explore the DM model further. A maximum variation sampling procedure was used to select five exemplar cases.

### **Findings:**

Three main contributions emerge from this study. First, the research uniquely brings together two bodies of literature, namely supply network configuration and infrastructure provisioning to explore the DM context. Second, the research applies these theoretical lenses to establish the distinctive nature of DM across seven dimensions of analysis. Third, emerging DM design rules are identified, and compared with the more established models of localised production, drawing on both literature and DM case-evidence.

**Practical implications:** Our study provides a rich SN configuration and infrastructural provisioning view on DM leading to a set of design rules for DM adoption, thus supporting practitioners in their efforts to develop viable DM implementation plans.

**Originality:** We contribute to the intra and inter-organisational requirements for the emerging DM context by providing new perspectives through the combined lenses of SN configuration and infrastructural provisioning approaches.

**Keywords:** Distributed Manufacturing, Digitalisation, Advanced Manufacturing Technologies  
**Paper Type:** Research Paper

## 1. Introduction

Distributed manufacturing (DM) can be understood to be: “technology, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location and scale.” (Durach *et al.*, 2017). Manufacturing components in different physical locations and then managing the supply chain to bring them together for final assembly of a product is also considered a form of DM (Srai *et al.* 2016). Early-stage studies and exemplars present the potential of DM to deliver on-demand personalised consumer goods, supplement shortfalls in local demand for pharmaceuticals, produce spares in remote locations such as oil and gas rigs and enable circularity through repairs and modifications (Roscoe and Blome, 2016; Ratnayake, 2019).

Laplume *et al.* (2016, 609) suggests that DM with its associated leverage of new technologies may disrupt established supply chains, and is in fact “a new localized form of production”. Unlike the industrial paradigm based on economies of scale, DM could develop a business model focused on economies of scope (Srai *et al.*, 2016). This work investigates whether this new model can function as a different type of localized production, by contrasting DM with two other localised production models, already well established in the literature. First, the so called *multi-domestic production model* is a nexus of interconnected functions, operations and transactions making and delivering manufactured products (DeToni, 1992). Here local manufacturing activity largely serves as the final assembly point for bringing globally scaled resources and manufactured products together for product adaptation to the segmented tastes of the local market. Second, the *indigenous production model* originates naturally in a region, with individual small and medium sized enterprises operating with a much smaller scale of capacity. Such manufacturers are embedded in the local economy, through their dependence on local resources and networks (Markusen, 1996).

For a rigorous comparison of localised production models, we adopt the configuration approach, a useful means for holistically examining dominant patterns in organizations regarding a set of multiple and interdependent characteristics (Miller, 1996). Configuration models represent multidimensional profiles of, for example, manufacturing strategies, process types, or indeed production models. They often suggest that there is parsimonious set of equifinal configurations of viable strategies (cf. Bozarth and McDermott, 1998). In more

detail, we use the supply network (SN) configuration concept by Srai and Gregory (2008) for holistically assessing the localised production models. The configuration approach is also driven with the idea of achieving organisational effectiveness through fit with particular environmental conditions and internal circumstances (Bozarth and McDermott, 1998; Sousa and Voss, 2008). In this vein, we additionally draw on the infrastructural provisioning perspective (Fine and Leopold, 1993), which emphasises the need for an appropriate provisioning system for localised production models in order to enable exploitation of technical and market opportunities.

Based on the above, the research question is framed as follows: How does DM compare with other localised production models from a SN configuration and infrastructural provisioning perspective? This research question allows us to explore the configurational and provisional factors underpinning sustainable DM models, and how DM differs from the more established models of localised production. Therefore, in order to explore the DM model from configurational and infrastructural provisioning perspectives, a multiple case study investigation research method was used.

## **2. Research framework and the localised production models**

### *2.1. Research framework*

#### 2.1.1 Supply network configuration perspective

The importance of the evolution of SN as the key element of industrial activity has been identified in many studies, linking for example SN structure to innovation capability (Choi and Krause, 2006), production dynamics (Kamath and Roy, 2007) and network configuration (Srai and Gregory, 2008). In this research supply network configuration provides a useful and critical lens in exploring the three different production systems. The SN as a unit of analysis encompasses the concept of an integrated network of key supply units, operating throughout the length of the supply chain, be they predominantly internal to a firm where there is a degree of vertical integration, or largely external supply partners where there is significant outsourcing of components, parts, technology or general supply. Indeed, in most instances a mixed approach is adopted across the integrated SN and represents its particular “configuration” (Srai and Gregory, 2008).

For practical purposes, the design boundaries of a SN are case dependent, and depend on the criticality of processes, materials and information flows rather than ownership or

network tier position, and the degree of influence any network node has on the firm, and what firms can exact on any element of the network. Thus the SN perspective of configuration considers both internal and external network members. Within strategic operations management, SN configuration has been shown to have a significant influence on production system capability (Srai and Gregory, 2008) and hence provides a useful perspective for analysing and comparing localised production models.

Drawing on the literature in the field, the work by Srai and Gregory (2008) provides a useful framework for configurational analysis due to its inclusion of (1) network structure, (2) production process flow dynamics, (3) product architecture and (4) network actor relationships. To provide clear dimensions of analysis for each of these four elements, each of these are developed further below.

Firstly, concepts of network tier structure are explored in the literature in terms of upstream and downstream complexity, levels of vertical and horizontal integration and geographical dispersion (Lambert and Cooper 2000, Lambert and Enz, 2017). In addition to network complexity, the degree of formalization and centralization have been discussed particularly in the servitization context (Tate and Ellram 2012).

Second, the dynamics of the replenishment process considers the push-pull decoupling point, component flows, and the impact of reconfigured manufacturing processes or unit operations on product and information flows, levels of modularity, necessary/unnecessary motion, optimal sequence of production steps/subassemblies, and production flexibility.

Third, the influence of product architecture (Choi and Hong 2002) and component attributes on network configuration choices (Rezk et al. 2016). This dimension influences levels of horizontal and vertical integration within the supply network and considers component and product SKU complexity and variety, product life-cycle management and any service aspects of the product offering.

Fourth, the nature of transactional buyer-supplier relationships (Alinaghian et al 2019), ranging from arm's length to ownership through vertical integration. The degree of network integration, particularly in the contemporary digital context, is highlighted at both the inbound procurement level (Srai and Lorentz 2019) and outbound e-commerce distribution level (Lim et al., 2018). This digital perspective provides for recent infrastructural and information technology advancements that may impact emerging as well as traditional production models.

### 2.1.2 Infrastructural provisioning perspective

In this work we take a system of provisioning approach to the role that infrastructure can play in supporting the development of DM. The system of provision approach takes as its units of analyses commodity-specific chains of provision, which are called ‘systems of provision’ or ‘sops’ (Fine and Leopold, 1993). It recognises the role played by social institutions and social-technical infrastructure, together with that of the market efforts of private organizations, in the delivery of goods and services (Brown and Robertson, 2014).

According to previous work on the “microeconomic capability” of local production systems (Lombardi, 2003), certain infrastructural provisioning attributes need to be in place, if manufacturing, is to be productive and competitive. The leading works on local production systems theory of Lombardi (2003) and Lazzarretti and Storai (2003) identify the following key provisioning conditions impacting on the manufacturing organization: (1) human resources; (2) physical infrastructure (i.e. transport, energy, utilities); (3) information infrastructure (i.e. local institutional regulation, IP, registration, permitting) and; (4) scientific and technological infrastructure (i.e. hardware, software). With the deployment of technology and science to improve physical infrastructural performance there has been recently a focus on the integration of physical, scientific and technological infrastructures together (i.e. intelligent transportation systems, smart energy, smart buildings).

We have developed the “information infrastructure” element, re-examined and re-termed it to encompass the more common term “local institutions”. We emphasise that this element focuses specifically on applied information aspects such as local laws, standards, financial incentives, investment support or regulations relating to products such as consumer protection or technical standards as well as tax and other administrative requirements. This paper will focus on a refined version of the original three key provisioning elements: (1) physical and technological infrastructure; (2) local institutions and; (3) human resources.

In terms of technical-physical infrastructure, evidence gleaned from many studies indicates the role played by local infrastructure (i.e. high-quality transport, energy, telecommunications) in supporting and accelerating the growth of local manufacturing (Koh et al., 2017). The role of technological infrastructure is to allow firms easier access to information sources and contact with markets, and it has been proven to have a strong positive influence on their economic effectiveness and profitability (National Infrastructural Commission, 2017). It has been recently acknowledged that government infrastructural support is instrumental for speeding up the development of new-generation digital technologies (Choi and Luo, 2019). Such developments over time may give rise to new value propositions related to manufacturing location/relocation choices. Infrastructural provisioning for instance is becoming central to the

circular economy, in particular, the design of waste, recycling and reuse infrastructure (Kalaitz et al., 2019).

Local institutions (North, 1990) can play an active role in the creation of regional and national information hubs or platforms to support the development of collaborative and community-oriented local manufacturing networks (Anderson et al., 2002; Shubbak, 2019). The literature on local manufacturing points to the need for strong and effective regulatory and intellectual property (IP) frameworks and local enforcement, which is cited as major issue in countries where current security, IP and legal systems are not appropriate for dealing with the rapid advancement in digital infrastructural networks (Baumers and Holweg 2019).

Regarding human resources, the structure and size of the labour supply in a local area may have a positive influence on a manufacturing firms' location decision. Skilled labour is of great importance, especially for the development of technical innovations in manufacturing. (Oakey, 1984). With respect to advanced manufacturing, the World Economic Forum (2019) identified an urgent need in developed economies, for either “upskilling the current workforce” or “training the next generation” of skilled engineers. For instance, there is a lack of science, technology, engineering and management (STEM) education in both the US and UK workforces (Despeisse and Minshall, 2017).

### 2.1.3 Integration of the two perspectives

The research framework presented in Figure 1 integrates together the above discussed SN configuration (Srai and Gregory, 2008) and infrastructural provisioning (Lombardi, 2003; Lazzeretti and Storai, 2003) perspectives for examining localised production models.

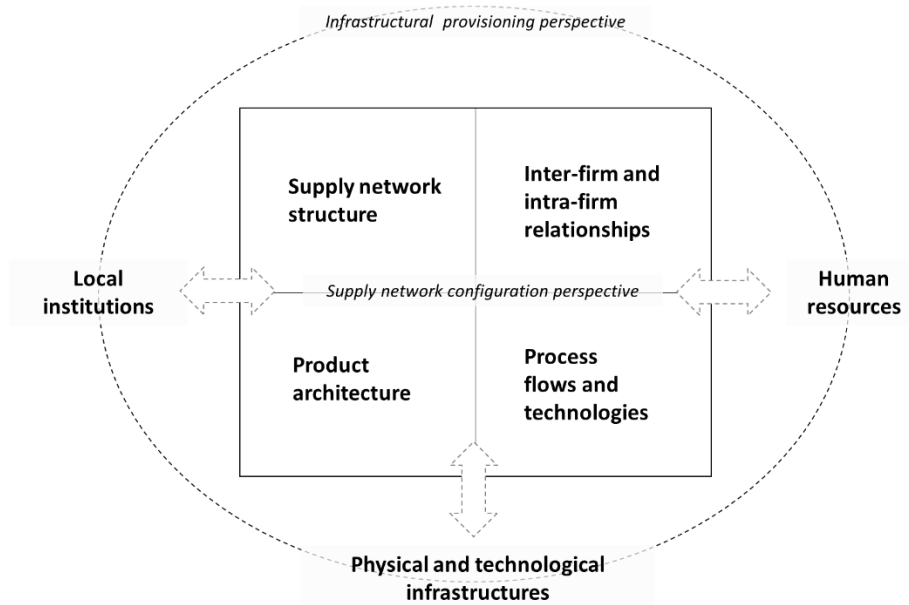


Figure 1 Research framework

Essentially, we suggest that for analytical purposes it is useful to conceptualise the SN configuration for localised production models as embedded in the infrastructural provisioning system. This embeddedness (e.g. Welch and Wilkinson, 2004) naturally implies interaction between the individual dimensions of the SN configuration and infrastructural provisioning constructs (see Figure 1). Indeed, the extant literature has discussed for example the influence of local institutions on manufacturing and SN structure (Srai and Ané, 2016; Lorentz *et al.*, 2013). The scope of this research is to examine the nature of these SN configuration and infrastructural provisioning dimensions independently in order to support theory building, recognising however, there will be interactions between dimensions that could form part of further research.

## 2.2 Multi-domestic production model

The concept of the local multi-domestic manufacturing configuration has been well established in the literature (Dunning, 1993; Gereffi *et al.*, 2005; Mudambi, 2008). Within a global footprint, dispersed manufacturing sites were generally considered as having often limited international strategic contribution. Ferdows (1997) refers to these as “server”, and in the more strategically elevated case, as “contributor” operations. In terms of the global – local tradeoffs, the integration-responsiveness (IR) framework (Prahalad and Doz, 1987) set out the competing needs for scale economies through integration and local responsiveness.

In this context, the multi-domestic model was essentially considered as a loosely coupled federation, of largely independent national sub-units (Bartlett and Ghoshal, 1987) offering operational and strategic flexibility (Mascarenhas, 1982) with limited economies of scale, whilst other global, or regional configurations leveraged scale investments in specialized and dedicated assets and systems that operated on a transnational basis. Others predicted that multi-domestic models might still benefit from some levels of centralized coordination; Gold (1982) for example, set out how the use of information and communication technologies may lead to flexible manufacturing systems offering both product variety and scale. In terms of the “multi-domestic” configuration option, where there is significant localization across all stages of the value chain, they all infer a limited strategic role. This multi-domestic configuration choice is thus explained in terms of limitations on economies of scale opportunities, resulting in a restricted headquarter coordination role with significant local autonomy.

Within the localized multi-domestic model, some consideration is given to contexts where a greater coordination role is played centrally. High levels of product modularity (McDermott *et al.*, 2013) for example, can lead to value-adding activities to be decoupled and dispersed (Cooper *et al.*, 1997; Ulrich, 1995). The physical characteristics of products and their implications for the flows of materials, components and knowledge that underpin the value-creation process can also impact levels of dispersion (Rezk *et al.*, 2016). Similarly, the current dispersion of activities and tasks (Baldwin and Evenett, 2015) have also been investigated in industry studies (Alcacer and Delgado, 2016; Gray *et al.*, 2015). In this paper we adopt the “multi-domestic” terminology to represent the highly dispersed and localized form of the multinational, with limited international coordination, particularly in the case of products customized to the home market context and with product architectures having limited component modularity. Our definition of multi-domestic production is therefore aligned with the “country-centered strategy” by Porter (1986), defined by low coordination and high dispersion, and therefore associated with the following states of the strategy implementation governing structural mechanisms (as hypothesized by Morrison and Roth, 1993): low centralization (lack of hierarchical decision making in the network), low formalization (lack of use of rules and official procedures in prescribing organizational behavior in the network) and low specialization (lack of the extent to which management tasks are developed into centers of excellence).

The multi-domestic production model may be described in terms of an archetypal configuration as follows. The *supply network structure* is likely to be complex, with many variety-flexible production locations near customers with regional distribution networks



(Ferdows, 1997; Prahalad and Doz, 1987), and with a limited level of central coordination (Bartlett and Ghoshal, 1987). Inbound supply chains may, however, be selectively extended beyond country borders for international sources, e.g. in the case of components with high value density (Rezk *et al.*, 2016). In terms of *process flows and technologies*, there is likely to be only some level of standardization of processes and technologies, as well as formalized standard operating procedures (Morrison and Roth, 1993), in order to allow for local flexibility. Codification of process knowledge may be possible, and expertise is found at the functional level and is typically geographically distributed. Enabling manufacturing technologies and IT systems vary across sites in a decentralized fashion (Bartlett and Ghoshal, 1987). Some are legacy technologies or adapted to local conditions, such as availability and serviceability (Lorentz *et al.*, 2013). Regarding *relationships*, there is likely to be variety in terms of how inter-organizational relationships are governed, as production unit roles vary from server to a more competent contributor type of profiles (Ferdows, 1997). Relational power towards global suppliers is likely to be relatively low due to uncoordinated procurement and spend pooling if there are no attempts towards synergies across the MNE (Trautmann *et al.*, 2009), and limited horizontal coupling (Rezk *et al.*, 2016). Nevertheless, power and influence on local suppliers and service providers is likely to be significant (Hong and Snell, 2013). Intra-organizational relations tend towards devolved true to the decentralized nature of the multi-domestic. *Product architecture* in the multi-domestic model is likely to be complex with broad product ranges produced in the variety-flexible sites, and the products may also be often characterized as having low value-density (Rezk *et al.*, 2016), making import substitution and alternative global strategies logistically uneconomical.

In terms of provisioning *institutions*, infrastructure projects are handled at sub-national level involving capacity building within provincial and municipal government targeted specific industry development zones representing long-term capital investment (UNCTAD, 2008). In terms of *infrastructures* as well, this type of localized production model is not very demanding, as the model may indeed be the result of constraining international trade policy measures, and it could also be considered to be able to accommodate deficiencies in logistics and technology infrastructures (Arvis *et al.*, 2018), that inhibit global strategies and adoption of standardized practices and technologies across locations. The subsidiary units within the multi-domestic model seem to adapt well to location characteristics such as institutional or infrastructural constraints, e.g. lack of factory services (Lorentz *et al.*, 2013; Ashcroft and Ingham, 1979), with responsive strategies (Wei and Nguyen, 2017), and insourced-outsourced decision making adapted to local capabilities (Lorentz *et al.*, 2013).

Development of highly specialized *human resources* are also likely to be less salient due to the replication of general types of production competencies across locations (cf. Morrison and Roth, 1993), instead of centralized excellence serving the entire network. Nevertheless, each of the sites requires a set of specialized skills, functionally based and separated, due to the self-sufficient nature of the local operations (Bartlett and Ghoshal, 1987).

### *2.3 Indigenous production*

Indigenous production originates naturally in a region (e.g. leather production in Tuscany; wine production in the Côtes du Rhone; ceramics in Stoke on Trent). The indigenous manufacturing model is based on individual small enterprises operating with a much smaller scale of capacity for the production of products (i.e. food, crafts) and/or services to satisfy local demands. The manufacturer is likely to become rooted, or “embedded”, in the local economy, through their specialist dependence on local skills, materials, suppliers, partner companies, research etc. (Markusen, 1996).

The theoretical analysis of indigenous production network dynamics stressed the strategic importance and part played by geographical proximity to unique factors of production (i.e. workforce skills, innovation diffusion, etc.; Belussi and Caldari, 2008). Porter (1990) for example, underlines the part played by the indigenous Italian tile and ceramic industry in the building of the domestic and export competitiveness of Tuscany. Specific assets and resources (i.e. land, labour and capital stock) are likely to play an important part in building indigenous manufacturing capacity. For instance, Saxenian (2006) points to the growth and success of the highly specialised dyeing capability of Italian clothing suppliers.

For some economists, the distinctive feature of indigenous production model is not only firm dependency on local market demand, but also the weaving of economy and society into a “communitarian” market (del Ottati, 1994). The “communitarian” approach pictures economic behaviour (in contrast to neo-classical theory) to be socio-economic and embedded in local communities, who correspondingly have shared values in jointly developing local manufacturing activity. In particular, there is a shared inward logic of development, which focuses on factors of local competitive advantage (i.e. local trust and co-operation, local production complementarities and local skills based on tacit knowledge) and the production system is “design intensive”. In a design intensive production system, the firm is faced with the challenge of maintaining their competitive advantage through continually offering products that are different and new to that of the competition. Furthermore, indigenous production is characterised by a large number of small firms operating in specialised high value niche

markets (or industrial districts) of traditional consumer industries (i.e. shoes, apparel and furnishings) often characterised by volatile demand patterns.

The configuration of the indigenous production model, as a theoretical archetype, consists of a relatively simple *supply network structure* with a single or handful of small-scale sites within a compact geographical area, with little coordination required by owner-entrepreneurs. Both inbound and outbound supply chains are likely to be predominantly indigenous, as these naturally occurring production models draw on local materials, suppliers and partner companies (Markusen, 1996), and typically demonstrate low export propensity (Foley and Griffith, 1992). *Processes and technologies* are geared towards mass customization, and there is likely to be high level of localized tacit knowledge in the product design and bespoke production processes with low level of formalization, preventing decoupling (Rezk *et al.*, 2016). Process design emphasizes differentiation instead of scale. As the indigenous production model draws on local specialized and unique resources and assets, *relationships* tend to be long-term oriented and stable in nature, a network of indigenous supplier partners supporting the production model. Owner-managers often manage the supplier relationships in small firms, with trust and use of social factors as the fundamental elements in relationship management and governance (Morrissey and Pittaway, 2006). In terms of *product architecture*, the model is likely oriented towards local niche markets with a narrow and simple high-quality and branded product portfolio (Collins and Burt, 1999), although with some options for customized make-to-order variants, aligned with the resources and capacities of the small indigenous manufacturers.

The indigenous model is provisioned by foreign trade policy *institutions* protecting it from multinationals and global competition, as well as by a regulatory framework and business culture which support entrepreneurialism (Ribeiro-Soriano and Galindo-Martín, 2012). Requirements for local *infrastructures* are likely to vary, depending on the nature of production, nevertheless it may be assumed that unique infrastructures as factors of production (Porter, 1990) may also be required for supporting indigenous production. Similarly, unique and specialized *human resources* are required locally with the needed tacit knowledge regarding processes and products (Belussi and Caldari, 2008).

#### *2.4 Distributed manufacturing*

Current research on the configuration of DM *supply networks structure* suggests mixed network complexity characterised by a shift away from large-scale global supply networks towards small-scale flexible manufacturing networks (Kapletia *et al.*, 2019; Hennelly *et al.*,

2019). According to Luthra et al. (2019) DM consists of a distributed networks of operations serving a shared customer. An important characteristic of this new form of manufacturing is geographic dispersion and the decentralisation of operations and the supply chain close to the market (Hennelly et al., 2019; Srari et al., 2016; Rauch et al., 2015).

Yet, as this new form of distributed manufacturing develops, there is no consensus on what these supply networks will look like. Research by Kumar et al. (2020) and Roscoe and Blome (2019) both agree that organisations may need to uncouple manufacturing activities and much will depend on product and process characteristics of components. Roscoe and Blome (2019) propose organizations leverage the efficiency of centralized manufacturing and the flexibility of DM through what they term “ambidexterity capability” via the creation of different sub-units; one managing centralized production and another managing DM.

In terms of *processes and technologies*, an important component of a distributed manufacturing system is a focus on advanced technological developments (e.g. automation and robotics, additive manufacturing), that could potentially enable a much more integrated manufacturing system to be created. Various writers, have also considered how small-scale could bring environmental benefits leading to more sustainable forms of production (e.g. Phillips, 2018; Moreno et al., 2019; Luthra et al, 2019; Kohtala 2015; Rauch et al. 2015; DeVor et al. 2012; Kumar et al., 2016).

Much of the debate regarding processes and technologies appears to centre on the notion of “scale-out” versus “scale-up”, to what degree is it economically viable to support a business model centred on flexibility, localisations and a high degree of customisation? As yet, research suggests that, in the near future, technologies such as additive manufacturing will only be used in the production of some components of the final product due to efficiency and costs (Bessièrè et al, 2019).

With respect to *relationships* and, the move towards a more localised model of production supports the development of non-hierarchical relationships (Mourtzis and Doukas, 2012), allowing the consumer, or “prosumer” a greater role and participation of the in the local production model (Srari et al., 2016; Kohtala, 2015). Intra-firm integration of product design and manufacturing functions have been observed with the blurring of the traditional boundaries within the DM context (Srari et al., 2016). Mass customisation also drives integration of order placement and production (Eyers et al., 2018).

Currently there is no agreement in terms of *product architecture* Mourtzis and Doukas (2012) and Srari et al. envisage DM will give rise to greater modularity whereas, although not

entirely disagreeing with this view, Kohtala (2015) presents four different ‘prosumption’ networks that vary in terms of consumer input and scale of production. The most extreme form of prosumption supports peer-to-peer relationships which, at a small and local level, supports the ‘personal fabrication’ of goods. More conventional approaches to DM would align with ‘mass customisation’, where the producer has control over the degree of consumer involvement and production is large-scale with a tendency towards modular or batch production. At a smaller scale, Kohtala presents the concept of ‘bespoke fabrication’ where products can be personalised but overall control remains with the producer.

There is a growing body of literature reviewing the *physical/technological infrastructural* barriers and enablers for DM adoption and exploitation (Ben-Ner and Siemensen, 2017). DM does not require the same investment in supporting physical infrastructure as previous forms of advanced manufacturing. It requires a much lighter physical or what might be termed cyber-physical infrastructure, with an emerging prototype being that of a Smart City (Öberg et al., 2017; see also Kumar et al., 2016).

The *human resource* demands will also change with DM (Ben-Ner and Siemensen, 2017). The relatively menial jobs of assembly, retail sales, packaging, shipping, transportation, are anticipated to change with the need for more: “analytical, integrative, creative, and autonomous occupations of designers, consultants, engineers, product developers and so on” (p. 21). Despeisse and Minshall (2017) suggest the need for government and industry to come together to provide easy access to training programs for workers and students.

Despeisse and Minshall (2017) outline the need for *local institutions* to ensure that there is sufficient commercial protection and patent enforcement to allow firms “... to capture value from their local investments in DM and IP rights. As current security, IP and legal systems are not appropriate for digital networks, such cyber security concerns, if not confronted will prevent rapid DM adoption” (p. 4). Ben-Ner and Siemensen (2017) believe that whilst DM start-ups will require much less capital than in other production systems due to them not needing complex distribution chains, and through their ability to shorten design and product testing lead time, they do however, pose substantial legal and regulatory challenges.

#### **4. Methods**

We undertake a multiple case study approach (Yin, 2003) for describing and exploring DM network configurations and infrastructural provisioning. Using multiple observations increases the confidence in the results being able to fully capture the phenomenon of interest, namely nature and form of the DM production model, which serves as our unit of analysis.

It is noted that case studies on supply networks face major challenges in terms of for example defining the boundaries of the study (Halinen and Törnroos, 2005). Indeed, our analyses of the DM models also covers the broader network-oriented boundary conditions, and further, includes the provisioning context. Addressing this challenge, we draw on the concept of network horizon, i.e. based on the perception of the decision maker or informant regarding the relevant actors and phenomena within the visible horizon, we delimit the analysis accordingly (Halinen and Törnroos, 2005; also Carter *et al.*, 2015).

#### *4.1 Data collection*

In selecting cases for the study, a purposive maximum variation sampling procedure was used for identifying information rich cases, from which much can be learned about the phenomenon (Patton, 2002). DM is not an established concept and the levels and types of adoption in industry is currently unclear. On this basis, an academic expert international panel was assembled, with 11 participants, to help identify specific gaps in DM knowledge, the major implementation issues, and potential case studies to explore configuration choices design and infrastructural provisioning. Case studies were selected, covering a range of maturity levels and adoption from partial (process) through to full (production) model deployment. The five cases selected thus represent variation within roll-out or new product introduction through to first production at scale where respondents have insights on supply network configuration choices and value provisioning requirements. The cases thus reflect different levels of complexity on product design, production technology and supply network. Eisenhardt (1989) points out that in the context of limited cases, it is helpful to select extreme situations and polar types to better illuminate the scope of the phenomenon, therefore, cases in this study range from the simple to complex applications across product design production technology/assembly and supply network (Table 1a). The set of selected cases also demonstrate a degree of variation in terms of the complexity of production technology and implementation, and with the nature of firms ranging from large to small and entrepreneurial (i.e. R&D, start-up and new organizational activity). This diversity in terms of cases (Eisenhardt, 1989) allows us to better explore the nature of the DM model through empirical

observations and to support future scholarly efforts leading to greater understanding and generalisation.

A key informant/gatekeeper for each case organization was identified by the experts at the panel. These gatekeepers identified participants who were actively involved at a project level, for introducing and scaling up DM within their organization. Their roles were any or a combination of the following: (1) testing the performance impact of an intervention; (2) adjusting operational guidelines; (3) early implementation; (4) refining delivery strategies and materials and (5) scaling-up within the organization. The selected cases are listed in Table 1a along with the involvement of multiple case respondents or informants, the used data collection methods, as well as data triangulation approaches used. A more complete description is available in Table 1b

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----- Insert Table 1b approximately here -----

#### *4.2 Data analysis*

The case study data from interviews, workshops, modelling etc. (Table 1a) were used to write up within-case narratives, structured along the dimensions specified in the research framework (see Table 1b, with reduced-form data; Miles and Huberman, 1994). This process of within-case analysis involved, first, the coding of the data according to the codes derived from the seven dimension framework (Miles and Huberman, 1994), and second, iteration in the narrative write-up phase, as minimum two researchers scrutinized and triangulated coding and each of the within-case narratives in terms of accuracy. In order to support the analysis and uniform coding procedures by multiple researchers, the dimensions of the research framework were defined and operationalised with literature-derived descriptions and keywords (coding structure; for operationalisations, see protocol in Appendix A). The within-case analysis was important from the point of view of making sense of the data and the empirically observed five DM production models.

As the next step, a cross-case analysis was conducted with the help of a data display, with the five DM production models cross-tabulated with the seven dimensions. The display was populated with reduced-form data from the case narratives (Miles and Huberman, 1994). The analysis process in this phase was again iterative as a minimum of two researchers were involved in order to ensure consistency of interpretation for data reduction and full coverage

of the within-case narratives. By observing the data display, first-order thematic observations, regarding key characteristics of each of the DM production models, were made and discussed by two researchers. These first-order observations were then clustered together into second order themes, based on thematic affinity. The outcome of this phase was a set of emergent discriminators for defining a generic DM production model. In order to qualify as a discriminator, it was necessary for a second order theme to appear in minimum three empirically observed and analysed DM production models. The data display supported the examination of the data across the units of analysis, in addition to providing transparency and a chain of evidence regarding our conclusions.

## 5. Cross-case analysis and results

Cross-case analysis summarised in Table 2 involved analysis of the cases across the seven dimensions for coding purposes. For each case, the first-order thematic observations, as presented in Table 2, capture the salient points on both configuration and provisioning. The cross-case analysis involved further coding to identify second order themes as set of emerging constructs. The process of moving from an *a priori* framework, enriched from the literature and leading to set of first-order thematic observations from the case studies provided a basis for the identification of these second-order themes (last column, Table 2). Each of the second-order themes are evidence by at least three observation across the five case studies, the relevant observation highlighted in bold and cross-referenced by a case number in the final column (Table 2).

----- Insert Table 2 approximately here -----

*Supply network structure:* Starting with the SN configuration perspective, and observing the data display (Table 2), the dominant feature of the DM model appears to be the increased complexity of the manufacturing footprint, as production takes place in many small units or even in micro-factories at customer sites (CATBT case), close to demand (field ready rescue case), or within short delivery lead times (diagnostic devices and lighting fixtures cases). Therefore, the outbound tier structure is typically simple in nature with relatively more direct distribution models (e.g. diagnostic devices). In contrast, there appears to be variation in terms of the inbound supply chain, as sourcing for components may be entirely localised (field ready rescue case), the supply base may be rationalised (lighting fixtures cases), or components and raw materials sourced globally (e.g. customised insoles case, medical devices). The emerging



constructs in terms of the second order themes for supply network structure in distributed manufacturing across the five case studies can be summarised as follows: close proximity to end-use or consumption (as evidenced in cases 1, 2, 3, 4, 5; see Table 2), proliferation in manufacturing sites (cases 1, 2, 3, 4, 5), rationalised upstream supply network (cases 1, 3, 4), and the critical role of the central actor in a hub-spoke network (cases 3, 4, 5).

*Process flows and technologies:* Based on the cross-case observations, the DM model may typically be characterised with highly modular and flexible make-to-order (MTO) processes, facilitating late customisation or full personalisation, for example with 3DP technology (e.g. lighting fixtures and diagnostic devices cases). Speed appears to be of essence in the DM model as significant lead time reductions have been achieved with for example reduced number of process steps, enabling JIT manufacturing and fast response (e.g. field ready rescue, CATBT, customised insoles cases). Novel technologies of digitalization are used to automate and control processes and to achieve more effective planning and scheduling, the latter with for example predictive analytics (e.g. lighting fixtures and CATBT cases). However, there appears to be a broad range of uses of technology, as at the other end of the range there is basic assembly with low technology characteristics (field ready rescue case). Nevertheless, even in this case, digital technologies are used to share product design and assembly instructions. Some of the DM cases also suggest potential for circular economy models and more sustainable operations (e.g. diagnostic devices and lighting fixtures cases). Similarly, the emerging constructs for *process flows and technology* in distributed manufacturing across the five case studies can be summarised as follows: short lead time (cases 1, 2, 3, 5), production to order rather to forecast/stock (cases 1, 3, 4), modular-build process for simpler assembly (cases 1, 3, 4)

*Inter-firm and intra-firm relationships:* Across the cases, the DM model appears to imply integration, first, within the firm, in terms of product design and manufacturing (e.g. the lighting fixtures case). Second, integration may take place between firms and actors (e.g. patients in the diagnostic device case), as digital platforms are used for integrating e.g. order placement, production and distribution (e.g. CATBT and lighting fixtures cases). At the extreme, the DM model may also imply the prosumer model, in which the roles of producer and consumer overlap (e.g. the field ready rescue case). Competitive partnership types of 3PL relationships become crucial for executing last mile logistics (e.g. lighting fixtures case). Furthermore, the DM model may also draw on trust-based relationships with for example universities and the prosumer partners with open IP (customised insoles and field ready rescue cases). Thus we propose that the emerging constructs for inter-firm and intra-firm relationships in distributed manufacturing across the five case studies can be summarised as follows:

consumer co-creation (cases 1, 2, 4), integration of product design and manufacture (cases 1, 4, 5), IP-driven lock-in partnerships upstream and open partnerships downstream (cases 3, 4, 5).

*Product architecture:* Here the cross-case analysis suggests opportunities for component reduction and therefore less work-in-process (WIP) inventory (e.g. lighting fixtures and field ready rescue cases). The achievement of relatively simplified component base appears to be contrasted with more variety in terms of final products, and at the extreme, products are unique and customised for customer's physical characteristics (e.g. the customized insoles case). However, typically the significant increase in product variety is constrained with limited customisation options (e.g. diagnostic devices case). There appear to be also through-life management opportunities based on use-profiles. Concluding the cross-case analysis from the SN configuration perspective, we suggest that the emerging constructs for product architecture in distributed manufacturing across the five case studies can be summarised as follows: component rationalisation (cases 1, 4, 5), mass customisation involving end-users in product design (cases 2, 3, 4), service/repair offering (cases 1, 3, 4).

*Local institutions:* Turning to the infrastructural provisioning perspective, the cross-case observations suggests that the DM models are flexibly adaptable to local regulation (e.g. lighting fixtures and diagnostic devices), although this is managed centrally albeit requiring local knowledge. Regulation may lag behind and needs to catch up with innovative production processes and DM facilities (e.g. CATBT case). In the cases of relatively more local inbound supply chains, the DM model appears to be resistant to the negative effects of restrictive trade policies (e.g. lighting fixtures case). The emerging constructs in terms of the second order themes for local institutions in distributed manufacturing across the five case studies can be summarised as follows: agile regulation supporting innovation (cases 1, 2, 3), adaptation to, or development of new quality standards on production and product (cases 1, 4, 5).

*Physical and technological infrastructures:* In terms of infrastructural requirements of the DM model, the cross-case analysis suggests some variation, as the level of requirement appears to depend on the nature of production. High technology operations naturally require more advanced levels of supporting services and utility provision (part externally provisioned e.g. co-location with institutional or SN partner) for product conformance (e.g. lighting fixtures and CATBT cases), whereas basic assembly may be designed to be robust enough to thrive in demanding conditions (field ready rescue case) and enable production by consumers (diagnostic device case). In the cases where fast response and short delivery times are important, the DM distribution model demands high quality infrastructure for last-mile

logistics (e.g. lighting fixtures case). Thus we propose that the emerging constructs for physical and technological infrastructures in distributed manufacturing across the five case studies can be summarised as follows: investment in data/digital infrastructures (cases 1, 3, 4), requirement for distributed physical infrastructure (cases 2, 3, 4).

*Human resources:* In the cases where the DM model involves high technology manufacturing or design, the cross-case analysis seems to suggest that advanced multi-skill expertise may be required co-located and centrally, whereas distributed facilities may typically require differentiated manufacturing skills although adapted to for example the 3DP context (e.g. lighting fixtures and customised insoles cases). The digital theme seems to permeate the DM model, as from the perspective of this dimension, digital platforms provide mechanisms for knowledge transfer to front-line production (e.g. field ready rescue case). Furthermore, with the novel DM model, traditional staff roles may change (e.g. lighting fixtures case), and with the prosumer role evident in some cases, the users may also require increased levels of guidance and training (e.g. diagnostic devices and field ready rescue cases). Concluding the cross-case analysis from the infrastructural provisioning perspective, we propose that the emerging constructs for human resources in distributed manufacturing across the five case studies can be summarised as follows: product and process design expertise centralised (cases 2, 3, 4, 5), production expertise less critical and distributed (cases 1, 3, 4, 5).

## **6. Discussion and conclusions**

In this research we set out to explore whether DM is a distinctive form of local production system, different from the established multi-domestic and indigenous localised production models, taking an inter- and intra-organisational network perspective. Unlike the more established multi-domestic and indigenous production models that have considered the broader production system, existing literature on the more emergent DM context has largely focused on enabling technologies that support production at lower scale, volume/variety product flexibility and the ability to adapt to local consumer requirements. By adopting a network configuration and infrastructural provisioning perspective, the research extends current DM research.

Building on the cross-case analysis in Table 2, we now examine how DM compares with the more established multi-domestic and indigenous production models. Table 3 sets out, using the conceptual contrasting approach, how each of the three production models compare against our seven dimensions of analysis from the literature and empirical case study perspectives.

----- Insert Table 3 approximately here -----

Initial analysis examines evidence from the literature, and for the more emergent DM context, cross-case empirical evidence is used to build repeat observations against the seven dimensions of analysis, providing discriminating constructs of DM when compared with other local production systems. This leads to a set of emerging constructs (through second order thematic coding) that provide ‘network’ level insights on the necessary supply network configurations and infrastructure requirements for successful DM adoption.

Three contributions have therefore emerged from this study. First, the research uniquely brings together two bodies of literature, namely supply network configuration and infrastructure provisioning. This extends the work of Rezk et al. (2016) on vertical and horizontal network effects within production systems at the component and product level. Here, the research examines enabling supply network configurations (that consider ‘vertical’ supply network collaborations either side of the production activity) and at the local-site level in terms of infrastructural provisioning (or ‘horizontal’ linkages with local institutions, as well as in terms of cultural and regulatory norms). The interplay between network and infrastructural provisioning elements introduces new requirements for successful DM adoption.

Second, the research applies the supply network and value provisioning perspective to establish the distinctive nature of DM across the seven dimensions of analysis. These are derived from the literature and first order case observations, identifying the critical differences that exist between these three forms of local production system. Whilst establishing the uniqueness of DM as a new form of local production system, it is particularly relevant to firms that seek to deploy DM by extending from existing forms of local production. This scenario of DM adoption, referred to as ambidexterity capability (Roscoe and Blome, 2019), findings suggests firms should consider the wider network requirements of DM beyond technology development and demand side factors. More specifically, from a SN configuration perspective DM is uniquely characterised by (1) (high) Density of manufacturing sites (on full commercialisation), (low) Inbound to Outbound supplier-ratio, and a (high) Degree of centrality around the lead site requiring significant coordination, (2) (short) Production lead times, (high) Modularity, with fewer and standardised production stages, digitally controlled to ensure conformance across sites, with Product and production process design fully integrated supporting a production-to-order rather supply model, (3) Consumer involvement in product design and use, (extensive) deployment of design-for-manufacture (DFM) principles,

(significant) IP-driven closed partnerships upstream and open partnerships downstream (e.g. 3PL partnership become crucial), and (4) Rationalisation of components, with (high) Levels of product customisation, integrated with a Service/repair offering. From an infrastructural provisioning perspective DM uniquely enables (5) Agile regulation supporting innovation, Adaptation to, or development of new quality standards on production and product conformance, and requires (6) Investment in data/digital infrastructures, Requiring distributed physical infrastructure for both manufacturing and distribution, with part externally provisioned facilities and services leveraging resources from collaborating/co-located partners and institutions and (7) Centralised product and process design expertise centralised, Production expertise less critical and distributed, with Digital platforms providing mechanisms for knowledge transfer. This set of more granular observations provide rich areas for future research.

Third, emerging and discriminating DM design rules are identified drawing on both literature and DM case-evidence. These second order emerging constructs (last column Table 3) set out the requirements for DM models, defined as a set of binary dimensions required to support adoption at the local level. These extend current research on supply network configuration design (Srai and Gregory 2008), and value provisioning (Saxenian, 2006), and more importantly how these two perspectives can be operationalised in combination for the implementation of DM models. Using the context of DM we contribute to local production system theory (Saxenian, 2006) by introducing the role that infrastructural provisioning plays in the development of manufacturing activity. Previous studies have solely focused on factors of production such as land, labour and capital in determining supply network configuration (Srai and Gregory, 2008). We suggest that it is the interface between infrastructural provisioning and network configuration, which determines the development and performance of localised production models.

In conclusion, we propose that DM is indeed a new form of localised production model. By contrasting the DM model with the multi-domestic and indigenous production models, we provide discriminating network design and provisioning constructs for the emerging DM model. These findings contribute to the emerging theoretical knowledge on DM by providing new perspectives through the combined lenses of SN configuration and infrastructural provisioning approaches. The novel analytical framework supports future replication studies and accumulation of further evidence regarding the archetype and variety of configurations and provisioning contexts for DM.

In terms of managerial implications, our study provides a set of binary design rules on the nature and requirements of the DM model, relevant for independent or co-located facilities, demonstrating discriminating features with other forms of local production models. This provides support to practitioners in their efforts to assess and develop plans for DM, and also demonstrating viable commercial opportunities for location decisions and manufacturing footprint design (Ferdows 1997). With this improved understanding of the DM model from the SN configuration and infrastructural provisioning perspectives, future research may also seek to integrate more mature aspects of DM, together with advances in production and digitalisation technologies with intra and inter-organisational requirements. The societal benefits of DM have been discussed in the literature, particularly in education and maker-spaces, treatment at the point-of-need in healthcare, and early stage industrial development, and this research provides system design insights for both industrial and institutional players.

The authors recognise the exploratory nature of this research and the limitations of a relatively small sample of case studies, limiting generalisability, despite the case study protocols used and multiple respondents for each case.

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Appendix A Interview and workshop protocol for all cases

|   | <i>Case Dimensions</i>                            | <i>Questions for research participants - investigating the nature and form of the DM production model (unit of analysis)</i>   |
|---|---|--|
| <b>How are the supply networks of DM models configured?</b>       | <i>Supply network structure</i>                   | How would you describe the value chain of DM product(s) from materials to final use? ( <i>Illustrate the journey if possible</i> )   |
|   | <i>Process flows and technology</i>               | How would you describe the key process steps and flows involved in DM, including activities of end-users (if relevant)? ( <i>levels of responsiveness, complexity, cost, waste, etc.</i> ) |
|   | <i>Inter-firm &amp; intra-firm relationships</i>  | How would you describe the nature of key supply relationships at different stages of the value chain? ( <i>Integrated, transactional, etc.</i> )   |
|   | <i>Product architecture</i>                       | How would you describe the structure of DM product(s)? ( <i>Components, systems, digital, mechanical – benefits and limitations</i> )  |
| <b>How are the DM models provisioned in their given contexts?</b> | <i>Institutions</i>                               | Who are the institutional players and secondary stakeholders and how would you describe responsibilities and governance in the DM system? ( <i>QC, standards, compliance, etc.</i> )       |
|   | <i>Physical and technological infrastructures</i> | How would you describe the investments and assets needed for the operation and performance of the DM system? ( <i>critical, enabling, ICT, output, location decisions, etc.</i> )          |
|   | <i>Human resources</i>                            | What are the required human resources capabilities needed for DM execution and how available are they? ( <i>Skills, expertise - established or to be developed</i> )                       |

