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Distributed manufacturing: a new form of localised production?

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Received 21 August 2019
Revised 3 February 2020
Accepted 21 April 2020

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.

Design/methodology/approach – 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 SN 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 – This 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/value – The authors 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 as: "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

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Support from the Advanced Manufacturing Supply Chain Initiative (Grant No. 35708-233529, ReMediES – Reconfiguring Medicines End-to-end Supply), and the EPSRC grants Future Continuous Manufacturing and Advanced Crystallisation (CMAC) Research Hub (Grant No. EP/P006965/1), and Redistributed Manufacturing in Healthcare Network (Grant No. EP/M017559/1) is gratefully acknowledged.

International Journal of Operations & Production Management
Emerald Publishing Limited
0144-3577
DOI 10.1108/IJOPM-08-2019-0600

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, p. 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 focussed on economies of scope (Srai *et al.*, 2016). This work investigates whether this new model can function as a different type of localised 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 organisations 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 aforementioned, the research question is framed as follows: How does DM compare with other localised production models from an 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, SN 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 an SN are case-dependent and depend on the criticality of processes, materials and information flows rather than ownership or network tier position, 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 is developed further.

First, 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 degrees of formalisation and centralisation have been discussed particularly in the servitisation 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 SN and considers component and product stock keeping unit (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 organisations, 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 Lazzeretti and Storai (2003) identify the following key provisioning conditions impacting on the manufacturing organisation:

(1) human resources;

(2) physical infrastructure (i.e. transport, energy, utilities)

(3) information infrastructure (i.e. local institutional regulation, intellectual property (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 focusses 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 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 earlier discussed SN configuration (Srai and Gregory, 2008) and

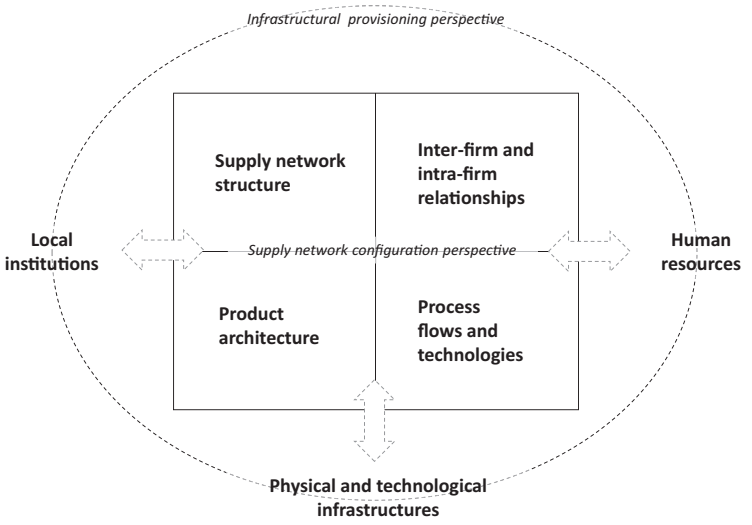

Figure 1.
Research framework

infrastructural provisioning (Lombardi, 2003; Lazzeretti and Storai, 2003) perspectives for examining localised production models.

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 that, 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 trade-offs, 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 specialised and dedicated assets and systems that operated on a transnational basis. Others predicted that multi-domestic models might still benefit from some levels of centralised 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 localisation 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 localised 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) has 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 localised form of the multinational, with limited international coordination, particularly in the case of products customised 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 hypothesised by Morrison and Roth, 1993): low centralisation (lack of hierarchical decision-making in the network), low formalisation (lack of use of rules and official procedures in prescribing organisational behaviour in the network) and low specialisation (lack of the extent to which management tasks are developed into centres of excellence).

The multi-domestic production model may be described in terms of an archetypal configuration as follows. The *SN 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, for example, 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 standardisation of processes and technologies, as well as formalised 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 decentralised 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-organisational 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 are likely to be significant (Hong and Snell, 2013). Intra-organisational relations tends towards a devolved structure, consistent with the decentralised nature of multi-domestic operations. *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 characterised 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 localised 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 standardised 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, for example, 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 specialised *human resources* is 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 centralised excellence serving the entire network. Nevertheless, each of the sites requires a set of specialised 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 and so on (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 focusses on factors of local competitive advantage (i.e. local trust and cooperation, 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 *SN 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 customisation, and there is likely to be high level of localised tacit knowledge in the product design and bespoke production processes with low level of formalisation, preventing decoupling (Rezk *et al.*, 2016). Process design emphasises

differentiation instead of scale. As the indigenous production model draws on local specialised 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 customised make-to-order (MTO) 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 specialised *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 *SN 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 network 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; Srai *et al.*, 2016; Rauch *et al.*, 2015).

Yet, as this new form of DM develops, there is no consensus on what these supply networks will look like. Research by both Kumar *et al.* (2020) and Roscoe and Blome (2109) agrees that organisations may need to uncouple manufacturing activities and much will depend on product and process characteristics of components. Roscoe and Blome (2019) propose that organisations leverage the efficiency of centralised manufacturing and the flexibility of DM through what they term "ambidexterity capability" via the creation of different sub-units; one managing centralised production and another managing DM.

In terms of *processes and technologies*, an important component of a DM 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 manufacturing closer to the point of consumption 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 (Bessière *et al.*, 2019).

With respect to *relationships*, 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 local production model (Srai *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 (Srai *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 Srai *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, support 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 programmes 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.

3. 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 SNs 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 cover the broader network-oriented boundary conditions and further, include the provisioning context. Addressing this challenge, we draw on the concept of network horizon, that is, 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).

3.1 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 are 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 SN configuration choices and value provisioning requirements. The cases thus reflect different levels of complexity on product design, production technology and SN. 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 SN (Table 1). 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 organisational 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 organisation 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 organisation. 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 organisation. The selected cases are listed in Table 1 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 2.

3.2 Data analysis

The case study data from interviews, workshops, modelling and so on (Table 1) were used to write up within-case narratives, structured along the dimensions specified in the research framework (see Table 2, 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 a minimum of two researchers scrutinised 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 1). 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).

Table 1. Details on case study data collection and protocols

	Context	Respondents (and position)	Data collection method	Interview length and process	Data triangulation approaches	Case selection rationale (maturity/ complexity)
Case 1: medical diagnostic devices	Involves a single-patient-use automated urine flowmeter, designed to help diagnose medical urinary problems	Medical Research Scientists and Mechanical Engineers (x6)	Focus group, engineering design, production and test, cost modelling	One-day workshop involving formal presentation and data collection on SN configuration parameters and institutional relationships. SN mapping exercises captured and transcribed for further analysis	Manufacturer's product and supply data Fused deposition modelling (3DP) Promodel v15 (supply chain)	Final prototype roll-out and testing Complex R&D and production technology
Case 2: personalised cell and tissue-based therapies	Represents mid-value range remedies, using mesenchymal stem cells (MSCs)	Medical Research Scientists and Biological Engineers (x11)	Interview, workshop engineering test, cost and operations modelling	One-day workshop involving formal presentation and data collection on SN configuration parameters and institutional relationships. SN mapping exercises captured and transcribed for further analysis	Regulatory reports, product data CompacT SelecT cell culture platform SADT models to IDEF0 standard	Final prototype roll-out and testing Complex product design and production technology
Case 3: fully customised insoles through 3DP	Describes use of mechatronics and biomechanics to scan a user's foot and create customised 3D printed insoles and sandals via a customer's smartphone	Senior Engineer Head of Partnership Engineering Research and Development VP Footwear	Interview, follow-up interview and case validation, validation from external source	Duration 1 h and 1 h 30 min interview Follow-up 1-h interview, case validation with email correspondence for case validation	Company reports, product data, company website	Early commercialisation at scale Simple product design and complex production
Case 4: advanced 3DP lighting fixtures and LUX supply	Involves a world leader in lighting, serving professional and consumer markets, a "pop-up" factory could be deployed, either in the customer's facility or distributors warehouse	Head of Global Manufacturing, Head of Supply Chain, Venture Manager, Operations strategy specialist, Financial and Industrial Specialist	Workshop, interviews, modelling and data visualisation	One-day workshop, involving five expert respondents. Data collection involving expert presentation and extensive SN configuration analysis. Data summarised, reviewed in 1 h interview with respondents for accuracy	Site visit, sales data, product data, process design data, company reports	Early commercialisation at scale Complex product design and production
Case 5: field-ready rescue basic assembly	"Rescue lifting air bags" first designed and manufactured in Syria to extract civilians trapped under the rubble of collapsed buildings	Director Operations staff Innovation advisor	Interviews, follow-up interview and case validation, validation from external source	1 h interview 1 h, 30min interview 30 min interview – validation Email correspondence for case validation	Product data, company website, company report, operations data	Early commercialisation at scale Simple product design and simple assembly

Table 2. Within-case descriptions structured with the SN configuration coding dimensions

	Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field-ready rescue basic assembly
Supply network structure	Components are sourced, assembled, tested and packaged in China, shipped to the Netherlands to undergo further assembly, testing and packaging before proceeding to distributors in North America and Europe. A DM approach involves a greater number of components produced closer to production at close proximity, i.e. at the point of need and use (clinic or home use)	The drivers for DM are primarily related to cost, capital and capacity – large centralised facilities for CATBTs risk sunk costs and complex, high cost cell preservation logistical arrangements. Shift from mass production and complex global SNs, towards smaller, more agile decentralised units, allowing local production of smaller batches of personalised products. DM provides opportunities for a range of final manufacturing points, from regional hubs to small units in close proximity to patients. Network co-ordination takes place through integrated product-service system	The materials for the sandals are sourced from a certified partner in Asia. Currently, 95% of sales are in the USA, which makes their single assembly and customisation facility the best solution environmentally, serving 39 countries so far. Customisation and final assembly are completed in California, due to CO2 emissions for electricity being around 35% lower than in China. With growth of sales volume, expansion and setting up of small and agile decentralised manufacturing units in Europe, to be close to the point of product delivery reducing LTs, carbon footprint and business costs	Most of the components are 3D printed in the same facility whilst the remaining components that are currently not viable to 3DP are manufactured and supplied from Asia. The company is looking to expand their operations in to local markets both in Europe and developing countries, in order to reduce lead times. With the DM network, the information on design, quantity required, quantity produced and delivery status becomes significantly more complex and distributed so whilst production is local, the supply chain becomes more complex and involving a hub and spoke relationship	Using locally available technology and an approach that enables local capacity not only provides means to significantly reduce costs, but also an increased ability to save lives. By being locally manufactured with local, readily available resources and tools, it was possible to reduce the cost to 1/10th of the imported alternative, increase accessibility and significantly reduce lead time, as a result saving more lives. The initiation of research, design and production of dozens of additional search and rescue tools, telecommunications and medical equipment are being explored and fielded

(*continued*)

Table 2.

	Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field-ready rescue basic assembly
Process flows and technology	A DM approach involves local production for home use by the patient enabled by 3D printing of the device, which takes only 2 h, and a single-step assembly. Devices can be reprocessed rather than disposed. The device can be returned to the hospital for data retrieval, alternatively, data could potentially be uploaded by the patient from home. Through DM, the production process becomes leaner, more agile and flexible enabling a near real-time MTO rather than a MTS approach. Localised manufacturing close to the point of need and use leads to time and cost reduction and more sustainable supply chains	CATBTs have expensive and time-sensitive supply chains; responsive manufacture coordinated with clinical use is preferred, especially if cryopreservation is required. Recently attention has focussed on automated CMF platforms that enable CATBTs to be made at a higher degree of reproducibility than via manual operation. Products are more sustainable through efficient use of resources and reduced logistical tails. The mining of [big] data is required to closely monitor regulatory conformance and product quality, safety and efficacy improvements	Product manufacture involves an SLS additive manufacturing process with a HP multijet fusion printer. This has removed their reliance on powder suppliers, as the HP process can recycle 80% of the material used in printing. The delivery of customised products enables the reduction of inventory, moving from a cash up-front model to an on-demand model that reduces waste. Production is JIT as cannot store much inventory so they initiate partnerships to increase capacity, manage over flow and access new markets. Delivery LT is five days compared to a traditional orthotic (42 days) which is costlier and typically manufactured in Asia	Using automation and 3DP enables printing and assembling products during the day and component printing during the second shift. 3DP and automation enable the company to deploy flexible lines that typically changeover every 30 units. There are production capacity constraints due to long LTs of some materials. Currently 95% of orders come from Europe which have a 3 wk LT, markets further away have a 26 wk LT. Technical capabilities in the new automated 3DP process enables new product features, print-to-order, customisation and a much improved carbon footprint	Locally made tools, equipment, and locally led process improve community resilience through building local capacity. Significant reduction in lead time compared to traditional imported product. Open source data moved in and out of Syria from UK, USA and Turkey

(*continued*)

Table 2.

	Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field-ready rescue basic assembly
Inter- and intra-firm relationships	The redistributed manufacturing supply chain removes a number of product (from China) and distributor (Netherlands and UK) relationships from the conventional approach. At the point of a test being prescribed, the device could be produced by a Health Service provider or an on-site/local manufacturer as part of a service agreement	Performance may be managed through an integrated product-service system, and will depend on the effective configuration of operational responsibilities (product management, asset ownership and maintenance, risk/rewards) shared between manufacturer innovators, infrastructure owners and end-user operators	The company is looking for partners who can offer capital and supporting infrastructure for their expanding operations. An example is a partnership with one of their main powder suppliers and now investor – this is providing them with support for their European expansion and reducing material costs. They also have pilot projects with two 3DP companies, however, there are issues around the IP of the production process they are currently trying to patent	The DM model requires partnering with local 3PLs in order to support the make/supply-to-order business models. The digital platform enables engagement directly with end-users and holds potential for achieving long lasting customer relationships and even lock-in opportunities. Internally, the platform facilitates the integration of design and production functions essential for the mass customisation business model	Relationships are established on the ground with local communities who are trained, once the delivery team arrive at the disaster zone. This approach will increase resilience to future disasters by enabling more people to respond to crisis and to fill gaps in the supply chain in the early stages of a response

(*continued*)

Table 2.

	Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field-ready rescue basic assembly
Product architecture	There is high degree of user participation – device produced in clinic or by patient, with digital design to support local production. A DM approach has involved up-front asset investments and the need to redesign components as the traditional injection moulded designs do not easily lend themselves to 3DP. Also, local printed circuit board (PCB) production was not feasible and a new PCB design would need be ordered, shipped and stored in the conventional way. Final assembly of gauges and electrical connections have the potential to be too difficult for most consumers/prosumers, requiring expertise at final point of assembly	Recently emerging breakthroughs in engineering MSCs and clinical trials make it a promising high-value therapy for a number of chronic diseases, yet further research is needed to prove efficacy and address adverse effects. Advances in gene sequencing technologies may have a bearing on product developments and related manufacturing process improvements. The economic model is impacted heavily by the type and number of complex therapeutic stages (e.g. gene modification), the need to ensure supply chain provenance and issues around choices of preservation and transport methods	The company has developed a smart phone app that enables high levels of customisation by allowing their customers to capture over 200 data points on each foot. A key benefit to the sandal product is its modular design, where components can be easily replaced or recycled. This extends the life of the product but also reduces inventory and issues with over-production and material waste. The material used for the foot bed is fully closed-loop recyclable where any offcuts or waste can be recycled back into raw material. The company are now looking to embed smart technology into their insoles and footwear, allowing their customers to record real-time performance data. There are intentions to assess life cycle impacts of products	Introducing 3DP alongside the conventional lighting products enables customers to customise and personalise their lighting fixtures and fittings using an online software programme managed by a sales manager. With a focus on compressing lead times, the company has focussed on redesigning their products to reduce the number of non-printable components (currently 12 components in total). Having the majority of components as 3D printable items allows the cutting of assembly cost, much enhanced final product variety, a simplified component base, and full recyclability. There is also an opportunity to develop a service model on lighting provision for the B2C market.	The specific design parameters such as small, portable, easy-to-use, robust and inexpensive were identified. When using the sketching, photography and prioritisation tools for their design, many key factors including the limitations of cost and the geographical complexities due to disasters were considered. The initial prototype of the rescue technology involved using a reinforced vehicle tire inner tube. The second and third prototypes refined this idea, but were still not ideal so the design team prototyped alternative models using thick rubber flooring mats. All of the technology would be found in a regular truck-stop workshop. All components, such as air hoses, compressed air cylinders, inner tubes and valves can be sourced locally

(*continued*)

Table 2.

	Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field-ready rescue basic assembly
Local institutions	New regulations and standards are required by healthcare providers for manufacturing this medical device and the design of the redistributed medical device would be integral in certifying the manufacturing process	Automated platforms require regulatory compliance akin to existing Quality Management Systems (QMS) that must be consistently comparable across sites. Automated manufacturing will help meet this goal, but progress is needed in automating the administration, tracking and QMS stages. Institutional support needed in terms of standards, regulation and compliance of the redistributed operation to avoid litigation by the user	To establish their business the company relied on fundraising through online community fundraising platforms, then further funding via venture capital in order to acquire a competitor. Their 3DP process and equipment is custom-made which helps them circumvent counterfeiting issues in new markets	The new localised production model presents a number of benefits in terms of minimal duties due to local component manufacture and the ability to customise products at the point of assembly for local electrical regulations and standards. The 3DP equipment is bespoke to the company and protects against counterfeit threats which may arise despite patent and brand protection	FieldReady establish relationships with key institutions that help facilitate their entry to the effected disaster zone, examples are relationships with INGO's with a presence in the country, others include: Oxfam, World Vision and Communitere. FieldReady rely on donors, fundraising as well as local, regional and global funding mechanisms to enable their operations in new markets
Phys. and tech. infrastructures	Stand-alone 3DP equipment would need to be installed and maintained, with raw materials and non-printable parts stored nearby. Whilst inexpensive FDM equipment can be acquired, the more expensive higher specification kit may offer greater value to 3D print a wider variety of medical devices. The question of future design iterations and integration/ updating of software capability raises questions around the degree of local phys. support	Manufacturing facilities required are likely to take at least 90 M2 of cleanroom space, yet further technological developments may be required to scale-up production capability (e.g. the Select T automated platform could deliver 2500 doses a year vs. estimated demand around 500,000 doses a year)	The company is keen on setting up research collaborations with biomechanics in the markets they plan to expand into, currently they have academic and industrial research partners in the UK and Sweden. Further partnerships are required in new markets for access to capital and infrastructure	The physical infrastructure dependency is reduced from a primary transport perspective (factory to local distributor-retailer); however, secondary last-mile logistics becomes important to meet the JIT/ next-day(s) promise for customers. Factory site requirements for infrastructure become less demanding due to modular 3DP facilities. Continuity of power provision is crucial to ensure product quality and low wastage	In many deployments there have been limited supporting digital communication technologies and infrastructure. Thus, the local physical and technological infrastructure is totally dependent on the nature of the disaster where the product is being deployed

(*continued*)

	Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field-ready rescue basic assembly
Human resources	New specialist role(s) and skills would be required to: (1) Prepare a digital 3D file according to prescription (2) Prepare 3D printer parameters (3) Assemble 3D printed structures and off-the-shelf electronics subassembly. For health-service providers (e.g. NHS), the capability to produce a range of devices "on–demand" will require new centres of excellence and potentially greater public-private collaboration	Manufacturing within proximity of the clinic has the advantage of exploiting and developing the knowledge and experience of local medical professionals. Challenges relate to the organisation of labour and the role of the operator. A network of localised manufacturing sites will require more staff; however, the use of semi-skilled workers would reduce labour costs. Operators are needed at a prescribed, intermediate level of skill	Engineers are all in house. New production staff can be trained in two weeks. The company is running an affiliate programme to expand its sales, providing affiliates with up to 20% commission on sales	The introduction of 3DP and automation has led to new roles for supply and product managers within the company. From a skills perspective, product design and equipment operation has been devolved to a central corporate function with the local manufacturing facility having an execution role with very limited technology know-how requirements	A "How to Use" manual kit provides local engineers a step-by-step guide to develop rescue airbags using local materials and tools. Open-source instructions on the design aspects of the product are developed in UK, USA and Turkey in collaboration with engineers on the ground in order to replicate these products. A series of trainings are given in problem-solving and making techniques, as well as the provision of essential equipment

Table 2.

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.

4. Cross-case analysis and results

Cross-case analysis summarised in Table 3 involved analysis of the cases across the seven dimensions for coding purposes. For each case, the first-order thematic observations, as presented in Table 3, 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 3). Each of the second-order themes is evidence by at least three observations across the five case studies, the relevant observation highlighted in bold and cross-referenced by a case number in the final column (Table 3).

Supply network structure: Starting with the SN configuration perspective, and observing the data display (Table 3), 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 SN 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 3), proliferation in manufacturing sites (cases 1, 2, 3, 4, 5), rationalised upstream SN (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 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 digitalisation 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

Table 3. Data-display for the cross-case analysis of five cases on DM

Cases		Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field ready rescue basic assembly	Emerging constructs (2nd order themes), with case study sources
		First-order thematic observations					
Coding dimensions							
Supply Network configuration	*Supply network structure*	*Point-of-care production* of device and some internal components; *Reduced inbound supply chain* except electronics from Asia to be integrated locally. Device manuf. at health service provider	Therapy *microfactories distributed* across hospital sites or regional centres of excellence; Supply chain designed *around patient treatment*; Reduced patient travel and logistical tails	Raw material suppliers based in China and Vietnam; AM feedstock from *selected US suppliers* and from internal recycling. *Lead US mfg site* with small and agile *decentralised* manufacturing units planned to be *close to the point of delivery*	Factory *network expansion* for *short lead times; Rationalised inbound* tier structure; Operating the SN more complex with *hub-spoke* information flows; Non-printable components from Asia	Entire supply chain is located locally where disaster takes place; *Local manufacturing* models carried out in Nepal and Syria; *primary site* scaling up to replicable model with local contextual attributes	Proximity to end-use / consumption (1, 2, 3, 4, 5) Proliferation in manufacturing sites (1, 2, 3, 4, 5) Rationalised upstream (1, 3, 4) Central actor in a hub-spoke network (3, 4, 5)
	Process flows and technology	*Fast 2-h production time* with 3DP Fused *Deposition Modelling*; Reprocessing of devices post-use Integrated digital readings capture and upload for personal location use; *MTO* at health service provider sites vs. previous MTS	Part-automated processes and data collection to control quality and increase efficacy; *Reduced number of manufacturing steps* to ensure integrity of therapy	Two AM SLS printers used; Technical patent pending on *AM process; Lead time is five days*; Subscription model to provide customer with new unit every six months; JIT production – no product inventory	Automated 3DP *modular process* with cobots enable flexible lines, *customisation* and reduced CO2; Long material lead times, aim to compress; Opportunity to use predictive analytics for planning and scheduling leveraging digital end-user platform	Replenishment takes place locally and is dependent on locally available materials; Significant *reduction in lead time* compared to traditional imported product; Product designed using digital sketching, photography and prioritisation tools	Short lead time (1, 2, 3, 5) Production to order rather to forecast/ stock (1, 3, 4) Modular-build process for simpler assembly (1, 3, 4)
	Inter-firm and intra-firm relationships	Future pharmacy or hospital dispensing; Reduced supply actors *Increased patient involvement. Integration* of design and production functions	Products delivered through services, *specific to individual patients*, and enabled by automated and *centrally regulated platforms*	*Partnerships* for capacity sharing and capital/ infrastructure support; Arm's length for production process outsourcing; *Trust-based* with universities; Investment from AM feedstock suppliers	*Partnerships* with local 3PL operators required for enabling MTO; *End-user OEM direct engagement* creates lock-in opportunities; *Integration* of design and production functions	Field-ready plays a central role where relationships are based on *partnerships* requiring high levels of trust; *Open-source platforms* for product manufacture	Consumer co-creation (1, 2, 4) *Integration* of product design and manufacture (1, 4, 5) IP-driven lock-in partnerships upstream and open partnerships downstream (3, 4, 5)

(*continued*)

Table 3.

Cases		Medical diagnostic devices	Personalised cell and tissue based therapy (CATBT)	Fully customised insoles through 3DP	Advanced 3DP lighting fixtures and LUX supply	Field ready rescue basic assembly	Emerging constructs (2nd order themes), with case study sources
				First-order thematic observations			
	Product architecture	Redesigned architecture to suit 3DP methods, rather than replicating mass produced design; Potential for circular manufacture. *Standard product portfolio with limited variety*; Digital *readings available instantly* as a service	Medicines and medical interventions applied locally to *human cells* and tissue, where a redistributed approach seeks to automate and streamline therapeutic delivery to increase patient benefit and assure quality	Opportunity to embed smart technology allows recording of real-time data and provide new markets; Business model involves *end-of-life product recycling schemes*. Products fully *personalised* for individual customer	*Fewer components* (12); Majority 3DP components lowers assembly cost, much enhanced final product variety; New 3DP materials with many fully recyclable. Development of lighting provision *service model* due to B2C *customisation*	*Limited number of components* with low material complexity (wood, rubber, valves); Small, portable, easy-to-use materials; Air hoses and compressed air cylinders sourced locally	Component rationalisation (1, 4, 5) Mass customisation involving end-users in product design (2, 3, 4) Service/repair offering (1, 3, 4)
Infrastructural provisioning	*Local institutions*	*Regulatory compliance* is required for new design and actors involved in local processes *New quality system* must be implemented by local provider	*New regulatory regimes* are required for both evolving advanced therapies and production facilities	No institutional barriers and mass customisation may support niche customer requirements from a health care perspective. *Governance* of personal biomechanics data of consumer populations	Local manufacturing minimally affected by import duties; *Responsive to local electrical standards*; Bespoke 3DP process protects against counterfeits	Product required to meet *British Standard* (BS EN 13731:2007) and lift 5,000 kg up to 15 cm under 2.5 bars of pressure	Agile regulation supporting innovation (1, 2, 3) Adaptation to, or development of new quality standards on production and product (1, 4, 5)
	Physical and technological infrastructures	Investment in higher spec and higher cost 3DP equipment is favourable, that allows wider product range manufacture. Remote *diagnostic data handling requirements*	Sophisticated *on-site clinical facilities required*, that mitigate risks of operator and clinician handling	Factory scale is sig. reduced and enables production close to retail, and thus *less demanding on factory infra*. 3DP is maturing and not a significant barrier. *Infrastructure required* for biomechanics data handling	*Transport infra.* for last-mile logistics important; Smaller modular factories less demanding on site infra.; *High reliability power provisioning* important. *Digital platform* for B2B/B2C e-commerce	Designed to thrive without local supporting technological infrastructure due to emergency situations such as earthquakes and conflict	Investment in data/digital infrastructures (1, 3, 4) Requiring distributed physical infrastructure (2, 3, 4)
	Human resources	3DP *operator skills required locally* Patient guidance needed	Strong end-user participation and feedback in the production and application processes; Increased levels of staffing and variety of skills at central facility	High levels of engineering employee competence in *lead site* with ambition to be thought leader in biomechanics and custom manufacturing; *Employees trained in 2 weeks on production processes*	*Centralised product design* and production technology authority. Routine *production fully automated*, requiring minute. human involvement	*Design for assembly developed centrally.* Involves targeting search and rescue authorities *locally with training in problem-solving and assembly techniques* using local materials	Product and process design expertise centralised (2, 3, 4, 5) Production expertise less critical and distributed (1, 3, 4, 5)

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, for example, 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 customised 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).

5. 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 focussed 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 3, we now examine how DM compares with the more established multi-domestic and indigenous production models. Table 4 sets out, using the conceptual contrasting approach, how each of the three production models compares against our seven dimensions of analysis from the literature and empirical case study perspectives.

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 SN 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 SN configurations (that consider "vertical" SN 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.

Table 4. Comparison of the three localised production models

Production models Analytical dimensions	1. Multi-domestic production (based on literature)	2. Indigenous production (based on literature)	3. Distributed manufacturing (based on literature review)	Emerging discriminators (based on case studies)
SN configuration SUPPLY NETWORK STRUCTURE	*Complex network* with variety-flexible operations near markets Ferdows (1997), Prahalad and Doz (1987) *Limited coordination* Bartlett and Ghoshal (1987) *International sourcing* only for selected components Rezk *et al.* (2016)	*Simple network* with typically single site with *no coordination* needed, local sourcing and distribution due to low expert propensity Markusen (1996) *Limited scale of operation and exports* Foley and Griffith (1992)	*Mixed network complexity* with *small-scale decentralised and flexible* manufacturing networks Kapletia *et al.* (2019) *Ambidexterity* capability Roscoe and Blome (2019) *Geographic dispersion, close to the market* Hennelly *et al.* (2019), Srai *et al.* (2016)	(high) *Density of manufacturing sites* (on full commercialisation) (low) *Inbound-to-outbound supplier ratio* (high) *Degree of centrality* around lead site
Process flows and technology	*Some standardisation*, allowing for some local flexibility and SOPs (Morrison and Roth (1993) *Local adaptations* (and expertise) to manufacturing technologies and IT systems Bartlett and Ghoshal (1987)	Geared towards *mass customisation*, processes involve significant tacit knowledge *Limited opportunities for de-coupling* with low economy of scale Operations demonstrate often *bespoke processes* for high-value manufacturing. Rezk *et al.* (2016)	*Advanced technological developments,* involving digital transformations (AM, 3DP, enabling IT; DeVor *et al.* (2012), Kumar *et al.* (2016) *Design, manufacture (and service) integrated* in recycle, re-use and re-manufacture context Phillips (2018), Moreno *et al.* (2019)	(short) *Lead time* (high) *Modularity*, with fewer and standardised production stages, digitally controlled to ensure conformance across sites *Product and production process design fully integrated to order* rather than to forecast/ stock
Intra-firm and inter-firm relationships	Relatively *low power* towards global suppliers, but *significant power* on local supply base Hong and Snell (2013) *Plant-role variety* in terms of how *inter-organisational relationships* are governed Ferdows, (1997). *Limited procurement coordination* Trautmann *et al.* (2009) and *limited horizontal coupling* Rezk *et al.* (2016)	*Long-term* and stable relationships with indigenous partners, limited network of partner suppliers with *trust-based* governance, managed by the owner-entrepreneurs. Morrissey and Pittaway (2006)	*Prosumer* relationship model Kohtala (2015) Intra-firm *integration* of product design and manufacturing functions Srai *et al.* (2016) *Mass customisation drives integration* of order placement and production Eyers *et al.* (2018)	*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)

(*continued*)

Table 4.

Production models Analytical dimensions	1. Multi-domestic production (based on literature)	2. Indigenous production (based on literature)	3. Distributed manufacturing (based on literature review)	Emerging discriminators (based on case studies)
Product architecture	*Complex*, with *broad product ranges* produced in variety-flexible sites. Products characterised as having *low value-density* Rezk *et al.* (2016)	Targeting of *narrow market segments*. With some options for *customised* MTO variants. Likely orientation towards *high quality niche segments*. Collins and Burt (1999)	*Reduction of components*/WIP. Significant *increase in product variety* but *customisation* options are constrained. Through life management based on use profiles. Mourtzis and Doukas (2012)	*Rationalisation of components (high) Levels of customisation* Service/repair offering
Infrastructural provisioning				
Local institutions	Projects are handled at *sub-national level* involving capacity building within provincial and municipal government targeting industry development zones representing long-term capital investment (UNCTAD, 2008)	*Flexible specialisation* building on regional branding. *Requires* protective trade *policies*, supportive *regulation* and culture for entrepreneurship Ribeiro-Soriano and Galindo-Martín (2012)	*Agile regulation* supporting innovation to support commercial protection and patent enforcement Despeisse and Minshall (2017)	Agile regulation supporting innovation Adaptation to, or development of, new quality standards on production and product
Phys. and tech. infrastructures	*Accommodates with established infrastructure, adapts autonomously* to local conditions Arvis *et al.* (2018), with *responsive strategies* Wei and Nguyen (2017) Insourced-outsourced decision-making *adapted to local capabilities* Lorentz *et al.* (2013)	*Unique local infrastructures* as factors of production required for supporting indigenous production Porter (1990)	*Less demanding factory infrastructure investment* (Graham *et al.*, 2017) *Higher requirements for IT infrastructure* Kumar *et al.* (2016), Graham *et al.* (2017)	Investment in data/digital infrastructures Requiring distributed physical infrastructure for both manufacturing and distribution Factory services part externally provisioned, e.g. co-location with SN or institutional partner
Human resources	Level of *specialised skills dependent on plant role*. Skill sets are *functionally* based and separated Bartlett and Ghoshal (1987)	Unique and specialised skills are required *locally* with the needed *tacit* knowledge and skills regarding processes and products Belussi and Caldari (2008)	*Differentiated* production skills needed locally Despeisse and Minshall (2017) Advanced *multi-skill expertise co-located centrally* for product-process design Hennelly *et al.* (2019)	Product and process design expertise centralised Production expertise less critical and distributed Digital platforms provide mechanisms for knowledge transfer

Second, the research applies the SN 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 suggest 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;

(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 4) 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 SN configuration design (Srai and Gregory, 2008), 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 focussed on factors of production such as land, labour and capital in determining SN 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 demonstrates 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
Interview and workshop protocol for all cases

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

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