Effects of lean distributed manufacturing on factory’s resilience: the current practice in UK food manufacturing sector

Original
Effects of lean distributed manufacturing on factory’s resilience: the current practice in UK food manufacturing sector / UL HAQ, Ijaz; Andrew Colwill, James; Backhouse, Chris; Franceschini, Fiorenzo. - In: INTERNATIONAL JOURNAL OF LEAN SIX SIGMA. - ISSN 2040-4166. - STAMPA. - 13:5(2022), pp. 1104-1136. [10.1108/IJLSS-07-2021-0124]

Availability:
This version is available at: 11583/2970869 since: 2022-09-02T07:55:15Z

Publisher:
Emerald

Published
DOI:10.1108/IJLSS-07-2021-0124

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2040-4166.htm

Received 17 July 2021
Revised 14 September 2021
Accepted 28 December 2021

Effects of lean distributed manufacturing on factory's resilience: the current practice in UK food manufacturing sector

Ijaz Ul Haq
Department of Management and Production Engineering (DIGEP), Politecnico di Torino, Turin, Italy

James Andrew Colwill and Chris Backhouse
School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, UK, and

Fiorenzo Franceschini
Department of Management and Production Engineering (DIGEP), Politecnico di Torino, Turin, Italy

Abstract

Purpose – Lean distributed manufacturing (LDM) is being considered as an enabler of achieving sustainability and resilience in manufacturing and supply chain operations. The purpose of this paper is to enhance the understanding of how LDM characteristics affect the resilience of manufacturing companies by drawing upon the experience of food manufacturing companies operating in the UK.

Design/methodology/approach – The paper develops a conceptual model to analyse the impact of LDM on the operational resilience of food manufacturing companies. A triangulation research methodology (secondary data analysis, field observations and structured interviews) is used in this study. In a first step, LDM enablers and resilience elements are identified from literature. In a second step, empirical evidence is collected from six food sub-sectors aimed at identifying LDM enablers being practised in companies.

Findings – The analysis reveals that LDM enablers can improve the resilience capabilities of manufacturing companies at different stages of resilience action cycle, whereas the application status of different LDM enablers varies in food manufacturing companies. The findings include the development of a conceptual model (based on literature) and a relationship matrix between LDM enablers and resilience elements.

Practical implications – The developed relationship matrix is helpful for food manufacturing companies to assess their resilience capability in terms of LDM characteristics and then formulate action plans to incorporate relevant LDM enablers to enhance operational resilience.

Originality/value – Based on the literature review, no studies exist that investigate the effects of LDM on factory's resilience, despite many research studies suggesting distributed manufacturing as an enabler of sustainability and resilience.

Keywords Lean distributed manufacturing, Factory resilience, Localized production, Food manufacturing

Paper type Research paper

International Journal of Lean Six Sigma
Vol. 13 No. 5, 2022
pp. 1104-1136
Emerald Publishing Limited
2040-4166
DOI 10.1108/IJLSS-07-2021-0124

1. Introduction

The uncertain and volatile political, economic, environmental and social conditions and competitive market requirements highlight the need for operational resilience in organizations capable of withstanding abrupt disruptions and adapting to external changes. The ongoing health emergency and post-pandemic world poses new challenges (raw material shortages, price hikes, disrupted supply chains, etc.) for food manufacturing companies to continue their manufacturing operations. These companies require to adapt appropriate practices to become more resilient and at the same time remain competitive. The operational resilience for food manufacturing companies is critical, as it ensures the food security – all people, at all times have physical and economic access to sufficient, safe and nutritious food (FAO, 2008) – for the community and enhances its efforts to become a sustainable society. This study will investigate the improvement in resilience capabilities of these companies to ensure food security through the continuity of their operations amid disruptions.

A resilient food system has the capacity to manage the potential disruption and adapt to changed operational conditions due to its characteristics of robustness, redundancy, flexibility and adaptability (Tendall *et al.*, 2015). A food system comprises different components including production, processing, distribution, retail and consumption (Elleuch *et al.*, 2016), and resilience in food processing is ensured by resilient manufacturing and supply chain operations of food manufacturing companies. To achieve the goals of resilience and sustainability, manufacturing companies need to adapt a dual strategic approach of flexible and innovative production processes and uninterrupted supply chain operations (Pham *et al.*, 2008; Pham and Thomas, 2012; Thomas *et al.*, 2016). In this regard, distributed manufacturing (DM) is gaining importance and being considered as a promising alternative which can decrease ecological impacts of manufacturing and improve social and organizational resilience to disruptions (Freeman *et al.*, 2017; Veldhuis *et al.*, 2019).

Lean distributed manufacturing (LDM) concept is introduced in this research in which lean practices focus on the wastage reduction and value addition in manufacturing processes while DM deals with the on-site and on demand production near the point of consumption. LDM, characterized with value-added, small-scale, reconfigurable and flexible manufacturing processes (DeVor *et al.*, 2012), has the potential to overcome the volatility and risks associated with global food supply chain and ensure the long-term resilience of food supply chains. As a shift from centralized to decentralized production, DM creates a more resilient and connected system to provide agile, user driven approach that will allow for personalization and customization of products to local markets (Moreno *et al.*, 2017). The characteristics of mass customization, democratization of design, market proximity and low logistics costs have made DM an alternative for sustainable production and improved resilience of food manufacturing companies (Rauch *et al.*, 2016). Whereas the implementation of lean practices, i.e. eliminating wastes, streamlining processes, improving value addition and developing eco-friendly products (Ruben *et al.*, 2018), leads to improve the company's operational performance. The concept of lean ensures the attainment of sustainability goals through eliminating waste and improving productivity (Dave and Sohani, 2019). DM paradigm integrated with lean practices has, thus, the capacity to accomplish the targets of resilience and sustainability in food production.

It is, therefore, proposed that LDM enables a localized, value-added and flexible production and supply network (driven by advanced manufacturing and digital technologies) which affects the operational resilience of food manufacturing companies. In this context, this paper enhances our understanding by investigating the effects of LDM on the operational resilience of food manufacturing companies. The following questions are addressed in this research study:

RQ1. How does a lean distributed manufacturing model impact the operational resilience of food manufacturing companies?

RQ2. What is the existing relationship between different lean distributed manufacturing enablers and resilience elements?

The first question is answered by developing a conceptual model based on literature to evaluate the effects of LDM on operational resilience. The second question is then investigated by collecting and analysing empirical evidence from the UK food manufacturing sector. This study will assist food manufacturing companies to assess their operational resilience capability, required to continue operations amid disruptions and improve it by implementing LDM enablers.

The remainder of this paper is organized into six sections. Section 2 consists of literature review, Section 3 discusses the development of theoretical framework and Section 4 describes the research methodology. Section 5 deals with findings, Section 6 details the discussion and conclusion, whereas Section 7 explains research limitation and further research.

2. Literature review

2.1 Lean distributed manufacturing

DM is defined as technology, systems and strategies that change the economics and organization of manufacturing, particularly with regard to scale and location (Pearson *et al.*, 2013). The tendency of small-scale production at multiple locations makes DM a feasible option for on demand production near the consumption point. This potential of DM as an alternative strategy to centralized manufacturing is currently being explored to estimate the benefits of personalized products, low quantity on demand production and local or regional economic growth (Rauch *et al.*, 2016; Veldhuis *et al.*, 2019).

Lean thinking is the identification of value-added and non-value-added activities of any process and elimination of waste to enhance process value (Antony *et al.*, 2017). Lean manufacturing enables a firm for reduction in cost, lead time, waste and improvement in productivity and flexibility (Goshime *et al.*, 2019). These characteristics (i.e. reduced lead time, inventories, equipment setup and downtime, rework, transportation time, defects and processing time) provide a pathway for the attainment of sustainability benefits for a manufacturing firm.

Lean thinking in the distribution of products involves the management of variable demand, optimization of distribution operations, smooth in and outflow of products and minimization of operations cost. In this study, LDM is defined as "the ability of small scale production, through value-added processes at multiple locations, to manufacture on demand products." DM deals with manufacturing at small scale, on demand and close to the point of consumption, whereas LDM eliminates the waste along the DM processes and results in value-added manufacturing.

Due to fierce competition which compels companies to cut costs for market survival, companies need to enhance quality, minimize waste, ensure customer satisfaction and increase productivity through reduction in resource wastage (Chauhan and Chauhan, 2019). The adaptation of lean practices by companies improves the optimization of resources (Goshime *et al.*, 2019), while digitalization, localized production and consumption characteristics (Prendeville *et al.*, 2016) of DM has the potential to establish local and circular economic patterns. These circular models of production and consumption – facilitated by LDM – enhance the resilience of manufacturing operations in their response to disturbances mainly due to economic, environmental and political uncertainties. In a study of relationship between resilience and sustainability of city-regions having manufacturing sectors, Freeman *et al.* (2017) presented interdependencies between environment, infrastructure, manufacturing sectors, disturbances impact, social resilience and concluded that DM has the potential to be more agile and resilient than traditional manufacturing. DM integrated with lean practices, therefore, can improve the resilience in manufacturing and supply chain operations, particularly for the food sector. The food industry needs to meet the upcoming challenges by offering personalized food products with dietary requirements (Rahimifard *et al.*, 2017), and LDM characteristics of agile and shorter supply chains, lower cost of food transportation and storage make it feasible. The effect of LDM on operational resilience of food manufacturing companies will be explored in this study.

2.2 Resilience for food manufacturing companies

Resilience is understood to entail strength (ability to withstand shock), flexibility (ability to bounce back), post-disaster flexibility and adaptability (McDaniels *et al.*, 2008). In the context of food systems, Tendall *et al.* (2015) defined resilience as the capacity overtime of a food system and its units at multiple levels to provide sufficient, appropriate and accessible food to all in the face of various and even unforeseen disturbances.

To improve food security, a resilient food system has the capability to identify system vulnerabilities (Babu and Blom, 2014), improve organizational capacities and deploy management practices (Higgins *et al.*, 2010) to deal with potential disruptions. By managing the potential risks and disruptions, a resilient food system, thus, ensures smooth operations and contributes towards the achievement of sustainability targets.

Food systems are complex and composed of many sub-systems. To achieve the goal of a resilient food system, the challenges faced by actors of each sub-system need to be overcome. Food systems comprise different processes, value chains, actors and interactions which lead to diverse and conflicting outcomes for multiple stakeholders and sectors (Tendall *et al.*, 2015). A food system consists of sub-systems which require specific capabilities in their domain to manage the vulnerabilities they encounter. A food system can be categorized into three sub-systems:

(1) policy system;

(2) markets, trade and institution; and

(3) production system (Babu and Blom, 2014) where the production sub-system refers to food supply chain consists of primary production, processing, distribution, retail and consumption of food products (Elleuch *et al.*, 2016).

A food supply chain is composed of multiple stages, and each stage is subjected to numerous and unique risks which may cause disruption of the whole supply chain. A traditional food supply chain has the challenges of large network, social drivers, genetic and environmental variability, low-value end products and declining margins which manifest as risk sources for each of its stages: primary production, processing, distribution, catering, retail and consumption (Stone and Rahimifard, 2018). The identification of stage-specific risks and vulnerabilities is, therefore, required to manage the potential disruptions and attain supply chain resilience.

The focus of this study will be on food processing component of food supply chain. As each component or stage of food supply chain (grower, processor, distributor, retailer) has different potential to be transformed through DM (Veldhuis *et al.*, 2019), this study will investigate the effects of LDM on food manufacturing companies (processor) to maintain resilient operations capable of managing the vulnerabilities. DM characteristics of shorter supply chains (Srai *et al.*, 2016), bespoke fabrication of customized products (Kohtala, 2015), production near the point of consumption (Rauch *et al.*, 2016), integrated with lean practices make it feasible to achieve the operational resilience of food manufacturing companies. To investigate the relationship between LDM and operational resilience, a conceptual model is proposed in the next section based on LDM enablers and resilience capabilities. This conceptual model is then used to analyse the companies from the UK food manufacturing sector.

3. Development of a conceptual model

In this section, a conceptual model is developed to evaluate the effects of LDM on factory's resilience. To develop the conceptual model, we identify the LDM enablers, resilience elements and their common characteristics from literature. These identified DM enablers and resilience elements are discussed below.

3.1 Identification of lean distributed manufacturing dimensions and enablers

In literature, different studies discussed opportunities and challenges of DM paradigm for the localized and decentralized production of customized products. The research studies discussed in literature review (Ul Haq and Franceschini, 2019), are exploratory in nature identifying different characteristics (dimensions) of LDM. These identified dimensions include manufacturing localization, manufacturing technology, customization and personalization, digitalization and democratization of design.

Manufacturing localization indicates the utilization of local resources (material, labour, etc.) in manufacturing facilities located near the end consumer, which is facilitated by the induction of new manufacturing technologies in the production process. The increasing ability of a consumer to influence the product development is a key characteristic in the construct of distributed production and is called customization and personalization. Digitalization is the incorporation of digital technologies in manufacturing operations to improve the information flow between processes, operators and suppliers, while democratization of design is defined as the incorporation of customers' input at design stage of the product development process through the development of specified tools like Web portals.

The literature review further highlights the different enabling methodologies or enablers being explored to implement these dimensions of LDM. For example, manufacturing localization is being adapted through establishing local suppliers' network, serving local consumers and developing near/on-site production facilities. Similarly, digitalization is being accomplished through implementing process control and automation, supply chain networking, production data analytic, product traceability and consumer data analytics techniques. These identified dimensions and their corresponding enablers are used in this study and listed in Table 1.

3.2 Identification of resilience elements

For the identification of different phases of resilience cycle and list of resilience elements, literature has been explored. The research database like Scopus, Emerald Insight, Science Direct, etc., have been searched with keywords food system resilience, food supply chain resilience, resilience elements, literature review of resilience to look for relevant definitions. This review has identified a list of resilience elements (Section 3.3) applicable to different phases of resilience action cycle to be used in this study.

This research study will focus on the operational resilience of manufacturing companies which is defined as "the ability of manufacturing and supply chain operations to prepare,

Table 1. LDM dimensions and enablers (adapted from Ul Haq and Franceschini, 2019)

LDM dimensions	Dimension enablers	Description	References
Manufacturing Localization	Local suppliers' network	The availability of production input (raw materials, labour, etc.) from local sources	Pearson *et al.* (2013), Prendeville *et al.* (2016)
	Local consumers	The end-users (or their large percentage) belong to the same region where production takes place	Srai *et al.* (2016), Moreno and Charnley (2016)
	Near/on-site manufacturing	The location of production facilities near the point of consumption	DeVor *et al.* (2012), Rauch *et al.* (2016)
Manufacturing Technology	New production technologies	The induction of novel production technologies in production process	Srai *et al.* (2016), Veldhuis *et al.* (2019)
	Novel innovation process	The adaptation of novel innovation process for products manufacturing	Zaki *et al.* (2019)
	Flexible production volume	The capability to produce flexible production volumes to meet variable demand	Mourtzis *et al.* (2012)
	Multifunctional processing	The process capability to produce a range of products under similar production arrangements	DeVor *et al.* (2012), Srai *et al.* (2016)
Customization and Personalization	Mass and late customization	The incorporation of customers' input in product specifications	Srai *et al.* (2016), Rauch *et al.* (2016)
	Bespoke fabrication	The production of tailored and individualized products on customers' orders	Kohtala (2015)
	Multivariant products	The capability to produce multiple products having different specifications	Prendeville *et al.* (2016), Gimenez-Escalante and Rahimifard (2018); Veldhuis *et al.* (2019)
	Customer services provision	The provision of additional services to increase the product value	Srai *et al.* (2016), Moreno and Charnley (2016)
Digitalization	Process control and automation	The usage of control and automation technologies to reduce waste and increase process efficiency	Mourtzis *et al.* (2012)
	Networking of supply chain	The networking of supply chain (production facilities, suppliers, distribution and sales channels) to obtain resource efficiency	Moreno and Charnley (2016), Gimenez-Escalante and Rahimifard (2018)
	Production data analytics	The analysis of generated production data on factory floor and its integration with production planning system	Soroka *et al.* (2017), Turner *et al.* (2017)
	Traceability of products	The traceability of finished products and suppliers' product ingredients	Moreno *et al.* (2017)
	Consumer data analytics	The analysis of customer and sales data to analyse consumers trends and market forecast	Zaki *et al.* (2019), Soroka *et al.* (2017)
Democratization of Design	Customized designs of products and packaging	The provision of customized product and packaging designs	Rauch *et al.* (2016), Zaki *et al.* (2019)

respond and recover from an unexpected disruption and its effects and adapt to altered conditions" (Fiksel, 2003; Ponomarov and Holcomb, 2009; Birkie, 2016). The operational resilience covers the aspects of organization resilience and supply chain resilience. The organizational and supply chain capabilities required to build operational resilience stretch across different phases, i.e. before, during and after the disruption (Stone and Rahimifard, 2018). Ponomarov and Holcomb (2009) defined readiness (preparation for unpredictable disruptions), response (reaction to mitigate the effects of disruptions) and recovery (return to the original or new desirable state) as three phases of resilience action cycle. Ponis and Koronis (2012) listed:

(1) proactive planning and designing;
(2) anticipating unexpected events;
(3) responding to disruption effectively; and
(4) adapting to post-event new equilibrium state, as four components of resilience cycle.

In the food system context, Tendall *et al.* (2015) broke down system resilience into:

- robustness, the capacity to withstand disturbance;
- redundancy, the extent to which elements of system are replaceable;
- flexibility and rapidity; and
- resourcefulness ad adaptability.

Stone and Rahimifard (2018) presented a list of organization-specific and supply chain specific resilience elements (core and supporting) discussed in literature and categorized these into four phases of resilience action cycle (preparation, response, recovery, adaptation).

In this study, we consider the categorization of resilience cycle discussed by Stone and Rahimifard (2018). This classification is used because it is derived from a systematic literature review and consolidates different phases of resilience action cycle with respective elements applicable to each component of the food supply chain, i.e. production, processing, distribution, retail and consumption, for the mitigation of associated risks.

3.3 Relationship matrix between lean distributed manufacturing enablers and resilience elements

In the next step, a relationship matrix is constructed between resilience elements and LDM enablers. To build a relationship matrix, a mapping approach (Franceschini *et al.*, 2010) is used, in which targets are listed on the left and performance measures are shown at the top of the relationship matrix. The LDM enablers are taken as targets to build operational resilience, and resilience elements are considered as performance measures to achieve these targets. The mapping is done by identifying their common characteristics and mutual influence from literature. This mapping methodology is used because it offers a way of unravelling the complex network of relationships and makes it possible to transform targets into control actions by including repeated cross-checks on the various analysed aspects (Franceschini *et al.*, 2009). This approach is used to boost up LDM enablers to build resilience in DM firms from an operational perspective.

The literature studies discussing resilience elements and their linkage with LDM enablers are discussed below, whereas the resultant relationship matrix is shown in Table 2.

3.3.1 Flexibility. Flexibility is the ability of an organization to adapt to the changing requirements of its surroundings with minimum time and effort (Erol *et al.*, 2010) and built

Table 2. The relationship matrix between LDM enablers and resilience elements

Lean Disributed manufacturing enablers	Resilience Elements: Flexibility	Redundancy	Early warning detection systems	Security	Robustness	Diversity	Inventory management	Collaboration	Visibility	Information flow	Established communication lines
Local supplier network		✓				✓	✓	✓	✓		
Near/on-site production	✓	✓					✓				
Local consumers									✓		
Novel innovation process											
Multifunctional processing	✓	✓			✓						
New production technology											
Flexible production volume	✓	✓			✓		✓				
Mass and late customization						✓					
Bespoke production								✓			
Multivariant products	✓	✓				✓					
Customer services provision										✓	✓
Supply chain networking	✓		✓	✓				✓	✓	✓	✓
Process control and automation							✓			✓	
Traceability of products				✓					✓		
Production data analytics			✓				✓				
Consumer data analytics			✓						✓		
Customized designs (product and packaging)											

(*continued*)

Table 2.

Lean Disributed manufacturing enablers	Resilience Elements Agility	Rapidity	Velocity	Adaptability	Innovation	Efficiency	Risk aware culture	Reference
Local supplier network								Prendeville *et al.* (2016), Tukamuhabwa *et al.* (2015); Soni *et al.* (2014), Pettit *et al.* (2013)
Near/on-site production	✓			✓				Tukamuhabwa *et al.* (2015), Pal *et al.* (2014), DeVor *et al.* (2012), Erol *et al.* (2010), Fiksel (2003)
Local consumers		✓	✓					Moreno and Charnley (2016), Spiegler *et al.* (2012); McDaniels *et al.* (2008)
Novel innovation process				✓	✓	✓		Zaki *et al.* (2019), Stone and Rahimifard (2018); Gölgeci and Ponomarov (2015)
Multifunctional processing	✓	✓		✓				Srai *et al.* (2016), Tendall *et al.* (2015); Pal *et al.* (2014), Dorf and Bishop (1998)
New production technology					✓	✓		Veldhuis *et al.* (2019), Kamalahmadi and Parast (2016); Pettit *et al.* (2013)
Flexible production volume	✓	✓	✓					Mourtzis *et al.* (2012), Spiegler et al.. (2012); Erol *et al.* (2010), Christopher and Peck (2004)
Mass and late customization			✓	✓	✓			Rauch *et al.* (2016), Tukamuhabwa *et al.* (2015); Gölgeci and Ponomarov (2015); Pettit *et al.* (2013)
Bespoke production		✓		✓	✓	✓		Kamalahmadi and Parast (2016), Kohtala (2015); Tendall *et al.* (2015), Fiksel (2003)
Multivariant products	✓				✓			Gimenez-Escalante and Rahimifard (2018), Tukamuhabwa *et al.* (2015); Erol et al.. (2010)
Customer services provision			✓					Jagtap and Rahimifard(2019); Srai *et al.* (2016), Ponomarov and Holcomb (2009)
Supply chain networking	✓					✓	✓	Stone and Rahimifard (2018), Moreno and Charnley (2016); Soni *et al.* (2014), Moore and Manring (2009)
Process control and automation						✓		Tukamuhabwa *et al.* (2015), Pettit *et al.* (2013); Mourtzis *et al.* (2012)
Traceability of products			✓					Moreno *et al.* (2017), Kamalahmadi and Parast (2016); Pettit *et al.* (2013)
Production data analytics	✓	✓					✓	Soroka *et al.* (2017), Turner *et al.* (2017); Tendall *et al.* (2015), Christopher and Peck (2004)
Consumer data analytics			✓				✓	Zaki *et al.* (2019), Jagtap and Rahimifard (2019); Soni *et al.* (2014), Spiegler *et al.* (2012)
Customized designs (product and packaging)				✓	✓			Rauch *et al.* (2016); Gölgeci and Ponomarov (2015); Fiksel (2003)

by building inter-operable standardized materials and processes, operations postponement, effective lean management and integration of processes (Pal *et al.*, 2014). Tukamuhabwa *et al.* (2015) listed flexible supply base, flexible transportation, flexible labour arrangement and orders fulfilment flexibility as adaptable practices to enhance supply chain resilience. The DM enablers of on-site production and supply chain networking assist to attain flexibility in supply chain operation, whereas flexibility in manufacturing operations is enhanced by characteristics of multi-functional processing, flexible production volume capacity and production of multivariant products.

3.3.2 Redundancy. Redundancy deals with the strategic and selective usage of spare capacity and inventory that can be used during a crisis and involves the duplication of capacity to continue operations during a failure (Tukamuhabwa *et al.*, 2015). The capacity of redundancy can be achieved by building redundancy of resources like unused capacity and multiple sourcing (Pal *et al.*, 2014). The availability of local suppliers' network and on-site production facilities assists in increased redundancy through acquiring of surplus raw materials, whereas the capacity of multifunctional processing arrangement and production of multivariant products in flexible numbers enhances the redundancy capability to meet the variable consumer demand.

3.3.3 Early warning detection systems. Early warning detection systems improve the resilience capability to estimate and anticipate potential disruptions through collection, exchange and sharing real-time data among various stakeholders and incorporating it into supply chain planning systems (Jagtap and Rahimifard, 2019). Anticipation is the ability to discern potential future events or situations through forecasting, monitoring, early warning signals, deviation and near-miss analysis, forecasting and risk management (Pettit *et al.*, 2013). The DM enablers of supply chain networking, production and consumer data analysis assist in forecasting and informed decision-making.

3.3.4 Security. This resilience capability refers to the security of both electronic information and physical assets (Stone and Rahimifard, 2018). Pettit *et al.* (2013) described a list of factors to enhance the security of assets which include cyber security, persona security, layered defences, access restrictions and employee involvement. The enabler of supply chain networking relates to the security of physical and electronic assets along the complete supply chain, whereas traceability of products and product ingredients by using digital technologies (barcodes, RFID, trackers, etc.) increase the security of materials and finished products.

3.3.5 Robustness. A supply chain or a system is called robust if it functions properly even in the presence of uncertain parameters (Spiegler *et al.*, 2012). Robustness is considered as the capacity of a system to have acceptable changes in performance due to model or parameter changes and moderate modelling errors (Dorf and Bishop, 1998). The multifunctional processing ability of production unit to produce multiple products and the capacity to produce flexible volumes of products ensure the robustness of manufacturing operations.

3.3.6 Diversity. Diversity refers to multiple product configurations, extensions in product system and existence of multiple forms and behaviours (Fiksel, 2003). The portfolio diversification increases resilience capability by indulging in the production of different products to reduce dependence on particular products and suppliers (Tukamuhabwa *et al.*, 2015). The three enablers, local suppliers' network, mass or late customization and multivariant products, incorporate the diversity capability to improve the operational resilience of the manufacturing companies.

3.3.7 Inventory management. Inventory management refers to the strategic alignment of inventory using a system-wide approach to minimize inventory risks (Tukamuhabwa *et al.*, 2015).

These inventory risks arise due to disruption in supply chain operations which interrupt the materials and information flow among suppliers, manufacturers, retailers and customers within a supply chain (Christopher and Peck, 2004). The DM enablers of local suppliers' network and on-site production ensure the smooth flow of input materials from different suppliers. Meanwhile, the capability of process control on factory floor, production data analysis for production planning and production of flexible products volume enhance the resilience capacity to continue uninterrupted flow of finished products.

3.3.8 Collaboration. Collaboration defines the ability to work effectively with other entities for mutual benefit through collaborative forecasting, customer management, communications, postponement of orders and risk sharing with partners (Pettit *et al.*, 2013). The increased inter-organizational relationships enable rapid implementation of decisions, develop supply dependencies and incorporate customers' input in the value chain (Pal *et al.*, 2014). The enablers of local suppliers' network and supply chain networking improve collaboration among different supply chain actors, whereas bespoke production capability develops collaboration through incorporation of customers' input in the product designing and production.

3.3.9 Visibility. Visibility is the ability to see one end of the pipeline from the other end and the knowledge of status of the operations assets and the environment (Kamalahmadi and Parast, 2016). This visibility improves resilience by addressing information about entities and events regarding end-to-end orders, inventory, transportation, distribution and any event in the environment (Soni *et al.*, 2014). The DM enablers of local suppliers' network, local consumers and supply chain networking facilitate the knowledge and information exchange across the supply chain which improves visibility. On the other hand, consumer data analytics capability helps in collecting business intelligence, whereas product traceability enhances product, people and equipment visibility.

3.3.10 Information flow. The collaborative working and enhanced cooperation among supply chain members can be achieved through exchange of information (Christopher and Peck, 2004), and this sharing of information among process stakeholders assists in mitigating risks across the supply chain (Ponomarov and Holcomb, 2009). The DM enablers of supply chain networking, process control and customer services provision allow information sharing among inter- and intra-organization process stakeholders, which assist in identifying and solving the unforeseen disruptions in a supply chain.

3.3.11 Established communication lines. The resilience capability of established communication lines refers to planned communication infrastructure and protocols that aid response speed and effectiveness in a disruption situation (Stone and Rahimifard, 2018). The utilization of information technology (Erol *et al.*, 2010) and Internet of Things (Jagtap and Rahimifard, 2019) enhance the production and supply chain connectivity and facilitates the resilience capability of a firm. The supply chain networking provides communication lines for manufacturing operations while customer services provision in the form of dedicated customer online portals or customers helplines serve the purpose of efficient communication.

3.3.12 Agility. Agility is the ability to respond quickly to unpredictable demand and supply changes which can be achieved through a rapid change to business processes and systems (Erol *et al.*, 2010). The DM characteristics of on-site manufacturing and supply chain networking improve the responsiveness of supply chain and its ability to act quickly to disruptions. Another aspect of agility is its emphasis on the rapid system configuration in the face of unforeseeable changes (Kamalahmadi and Parast, 2016). The multi-functional processing and flexible production volume capacity enhance the company's ability of rapid system configuration, whereas production data analysis helps to manage unforeseeable changes in manufacturing operations on the factory floor.

3.3.13 Rapidity. Rapidity is related to post-disaster adaptation efforts, both within the infrastructure system and by system users and related systems, which affect the time required to restore the system to normal function (McDaniels *et al.*, 2008). In the context of food system resilience, Tendall *et al.* (2015) described rapidity as the ability with which food system can recover any lost food security. The early recovery of loss function in quick time is enabled by bespoke production and local consumers, which guide the resumption of product manufacturing and delivery quickly. Similarly, the production capabilities on factory floor (multi-functional processing, flexible production and production data analytics) facilitate the quick and early recovery of operations lost in the face of disruption.

3.3.14 Velocity. Velocity is considered as the speed with which product reaches the end consumer, and this speed is increased through streamlined processes, eliminating non-value-added time (Christopher and Peck, 2004) and reduction in lead-times (Spiegler *et al.*, 2012). The enablers local consumers (for delivery time reduction), flexible production of customized products (production lead time reduction), customer services provision, customer data analytics and traceability of products eliminate the non-value-added times and improve the velocity.

3.3.15 Adaptability. Adaptability is the capacity to change in response to new pressures (Fiksel, 2003) and the ability to modify operations in response to challenges or opportunities through fast rerouting of requirements, lead time reduction, strategic simulation and seizing advantage from disruptions (Pettit *et al.*, 2013). The enablers on-site production, utilization of novel innovative and multi-functional production processes allows the manufacturing operations to be adapted to changed environment. Whereas the capabilities of producing customized products and bespoke production facilitate the ability of fast rerouting of production resources on the factory floor according to changed requirements.

3.3.16 Innovation. Innovation refers to the capability to invent new products, technologies, processes and strategies to reduce vulnerability (Gölgeci and Ponomarov, 2015) and enhance organizational resilience. The innovation in an organization is associated with culture of learning, participative decision-making and an organization-wide understanding of innovation (Kamalahmadi and Parast, 2016). The inclusion of novel innovation processes and new production technology in production increases the innovative capacity of a company, whereas bespoke production of customized products enhances company knowledge and learning required for developing an innovative culture.

3.3.17 Efficiency. Efficiency is the practice in which resources are used in a way to avoid unnecessary waste and disruption (Stone and Rahimifard, 2018) and a capacity to produce outputs with minimum resource requirements, labour productivity, asset utilization, product variability reduction and failure prevention (Pettit *et al.*, 2013) which results in enhanced resilience. The induction of novel innovation processes and new production technology improves efficiency by waste elimination while supply chain networking improves inventory supplies without delays. The process automation and control and bespoke production capability reduce product variability and stockpiles (of materials and finished products).

3.3.18 Risk aware culture. Soni *et al.* (2014) argue that risk management should be an essential element of every organization which needs to be extended beyond the boundaries of corporate risk and business continuity management and implemented across the supply chain to enhance resilience. Moore and Manring (2009) described organizational behaviour and characteristics as important drivers in the evolution towards a resilient organization. The supply chain networking promotes gathering of information and enhancement of cooperation among supply chain actors to minimize supply chain disruption risks, whereas data analytics applications to analyse consumer and production data allows preventive measures to mitigate potential risks and lead to an organizational risk management culture.

3.4 Structure of the conceptual model

Based on these findings, a conceptual model is proposed to analyse the effect of LDM on factory resilience. This model provides a basis to analyse the impact of DM characteristics on the operational resilience of manufacturing companies.

The lower part of the model consists of five components corresponding to dimensions of DM. Each of these dimensions is mentioned with its enablers. The upper part of the model has two components; resilience capability and risks mitigation. The first subpart contains resilience elements (core and supporting) required to improve the operational resilience. These elements are categorized into four resilience action cycles, i.e. preparation, response, recovery, adaptation (Ponomarov and Holcomb, 2009; Stone and Rahimifard, 2018). The presence of these resilience elements in manufacturing configuration and supply chain operations improves the operational capability of company to mitigate the potential risks. The second subpart contains a list of internal and external risks having potential to disrupt the food manufacturing operations. The external risks include political, social, economic, environmental and infrastructure risks (Vlajic *et al.*, 2013), while internal risks are categorized into organization-specific (Pettit *et al.*, 2013) and supply chain specific risks (Tukamuhabwa *et al.*, 2015). The conceptual model is shown in Figure 1.

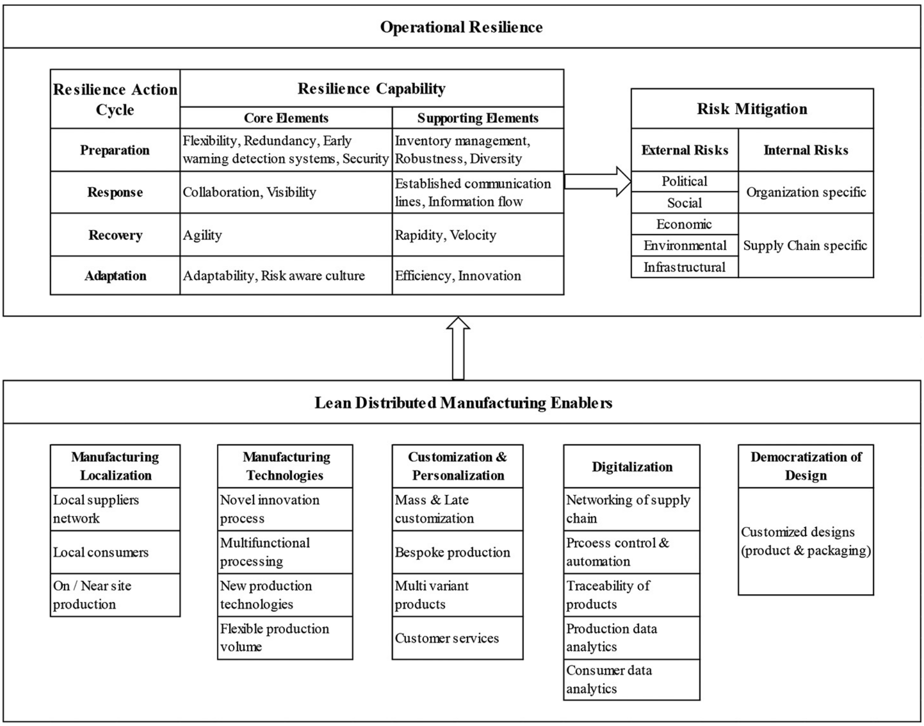

Figure 1.
The reference conceptual framework between LDM enablers and operational resilience

4. Research methodology

A triangulation research methodology is used to investigate the effects of LDM on operational resilience. This methodology includes the analysis of secondary data, observations and surveys or structured interviews (Thomas *et al.*, 2016).

In the previous section, the process mapping approach is used, as used in quality function deployment (QFD) methodology (Franceschini *et al.*, 2010, 2015, 2019), to develop the relationship matrix. The prioritization of resilience elements (in relationship matrix) is accomplished by using triangulation methodology. The prioritization of resilience elements has been completed by assigning each LDM enabler an importance rank and determining the intensity of relationships between resilience elements and LDM enablers. The importance ranks have been assigned by a panel of experts (Table 3), selected and interviewed based on their experience and knowledge in the subject matter. The interviews were conducted by using an online questionnaire tool.

To establish the intensity of relationships, empirical evidence is collected from the UK food manufacturing sector. This intensity is established by determining the status of resilience elements, i.e. practised, partially practised, non-practised, in the number of companies incorporated by LDM enablers. A criteria-based sampling method is used to select the food manufacturing companies operating in the UK food sector. This method is based on the conceptual ground instead of representative ground (Miles and Huberman, 1994; Zaki *et al.*, 2019). Similar to research studies by Moreno and Charnley (2016), Zaki *et al.* (2019), the companies are selected based on the following set of criteria:

- localized manufacturing by using local resources (raw materials, labour, infrastructure, etc.); and
- serving a customer base (or major portion of it) of a localized territory (near the manufacturing point).

The companies are selected from different sub-sectors (SS) of the UK food manufacturing industry according to the database of Food and Drink Federation (FDF), UK. These SS include Dairy, Chilled foods, Drinks, Bakery products (snacks and pies), Fruits and Seeds processing and Meat processing. The choice of six SS was made to establish a diverse outlook of collected data which facilitates analysis and examination (Voss *et al.*, 2002).

Initially, a total of 42 companies (seven from each SS) were shortlisted from secondary data and tested for the selected criteria. The resulting number of companies fulfilling the criteria, is 18, with each SS being represented by three companies (Table 4). For data collection initially, the database of FDF (UK) was used, which provides brief introduction and contact information of companies. The further data was collected through different sources, which include company websites, annual reports, news articles, blogs and

No	Designation	Institution
1	Associate Professor	Politecnico di Torino
2	Assistant Professor	Politecnico di Torino
3	Postdoctoral Researcher	Loughborough University
4	Senior Lecturer	Loughborough University
5	Production Manager	Nestle
6	Technical Manager	Pepsi Co
7	Asst. Production Manager	English Biscuit Manufacturer
8	Senior Planning Engineer	Nestle

Table 3. Designation and institution of respondents

Food sub-sector	Companies	Product range
Dairy Products	F1	Yogurt, Cheese
	F2	Milk (fresh, powdered), Yogurt
	F3	Cheese
Chilled Foods	F4	Eggs (Retail, Boiled, Poached)
	F5	Chicken, Prawns, Pasta Salad, Noodles
	F6	Sandwich filling, Mayonnaise, Vegetable Pates
Drinks	F7	Beer
	F8	Coffee
	F9	Juices, Juice drinks
Bakery Foods	F10	Snacks, Nuts
	F11	Meat Pies
	F12	Vegetable snacks (Spring rolls, Patties, Samosas)
Fruits and Seeds Processing	F13	Frozen, Chilled and Fresh Fruits
	F14	Pressed seed oils (Pumpkin, Sun flower etc.)
	F15	Vegetables, Fruits, Herbs, Mushrooms, Root crop
Meat Processing	F16	Raw meat (Beef, Lamb, Pork)
	F17	Fried chicken (Nuggets, Drumsticks), Pizza Cheese
	F18	Burgers, Sausages, Kebabs, Sliced Meat, Hot dogs

Table 4.
Description of food manufacturing companies

observations during field visits in the form of informal interviews with representatives of companies.

A questionnaire (Appendix 1) was developed to guide the collection of relevant information. An online survey tool was used to conduct interviews and collect the responses. Online tools like online questionnaires are often used to gather the opinion from several experts (Vohra *et al.*, 2016). The questions covered the topic of LDM enablers and their current application status in food manufacturing companies. Based on these responses, from operations managers, production engineers, planning engineers, etc., companies are categorized into groups by using clustering method. Clustering technique is frequently used for the purpose of segregating groups having similar properties. Clustering is the partitioning of a set of objects into a number of subsets such that a similar type of data is present in each subset. These subsets are called clusters.

Cluster analysis is an exploratory analysis technique which is performed to find similarity or dissimilarity between different groups. Clustering procedure is based on Euclidean distance which is a measure of similarity or dissimilarity between two objects and defined as the straight distance between two points which is calculated to find similarity between two objects or groups. Euclidean distance is calculated for LDM enablers to put them into same cluster if they exist at a similar distance from the centre. The details of cluster analysis are described in Appendix 3.

5. Findings

5.1 Prioritization of resilience elements

The companies from six SS were examined to analyse the current application status of DM and usage of different LDM enablers. Each company is assessed to understand which LDM enabler has been implemented, and if it is not practiced, the field is left blank (Appendix 2). Each LDM enabler is assigned one level rank based on the number of companies of each SS practising this enabler. The following codification is allocated to the three levels of each LDM enabler:

L1: Practiced by one company, L2: Practiced by two companies, L3: Practiced by three companies

For example, one LDM enabler, "Local supplier's network," has been assigned the following ranks for each SS (see Table A6):

SS1: Dairy sector = L3
SS2: Chilled foods = L2
SS3: Drinks = L1
SS4: Bakery products = L2
SS5: Fruits and Seeds processing = L2
SS6: Meat processing = L3

The results of these assigned level ranks with corresponding codification are shown in Appendix C (Table A6).

5.1.1 Cluster analysis. In the ext step, we perform the clustering of LDM enablers to identify similarity among them. The DM enablers are sorted into three clusters, and the number of companies practising each enabler of these three clusters is counted. For example, in Cluster 1, the number of companies are:

E1: Local supplier's network = 13
E2: On/near site production = 18
E3: Local consumers = 18
E7: Flexible Production volume = 16
E11: Customers service provision = 15
E13: Process control and automation = 14
E14: Traceability of products = 17

The nature of relationship between LDM enablers and resilience elements is determined on the basis of the number of companies in each cluster. For Cluster 1, the minimum number of companies practising a LDM enabler is 13, while the maximum number of companies practising a LDM enabler is 18. Since the number of companies is maximum in this cluster, each enabler is assigned a value of strong relationship with corresponding resilience elements.

- = 9 (strong relationship, if $13 \leq x \leq 18$), where x is the number of companies

Similarly, for Cluster 2, the minimum number of companies practising a LDM enabler is 1, while the maximum number of companies practising a DM enabler is 4. In this cluster, each enabler is assigned a weak relationship value with corresponding resilience elements.

□ = 1 (weak relationship, if $1 \leq x \leq 4$)

And for Cluster 3, the minimum number of companies practising a LDM enabler is 5, while the maximum number of companies practising a LDM enabler is 12. In this cluster, each enabler is assigned a medium relationship value with corresponding resilience elements.

○ = 3 (medium relationship, if $5 \leq x \leq 12$)

The assigned values of these relationships are then used to build a relationship matrix. The enablers of DM are indicated by the corresponding identification mark (defined above). And if any enabler of DM dimension is not practised in a case study company, the field is left blank.

5.1.2 Ranking of lean distributed manufacturing enablers. In the next step, each LDM enabler is assigned with an importance rank. These relative importance scores are assigned by a panel of academic and industrial experts (4 each) in interviews conducted through an online survey tool. The collection of information through interviews is a commonly used method in QFD studies, as evident from literature studies about logistic services

(Bottani and Rizzi, 2006) and shipping industry (Lam and Bai, 2016). The interviewees were provided the option to rank all listed LDM enablers on a scale with a score ranging from 1 to 5 (where 1 being the lowest and 5 the highest) according to the following classification:

Rank 1: Not important
Rank 2: Less important
Rank 3: Important
Rank 4: Very important
Rank 5: Critical

The importance ranking scale is an ordinary scale in which numbers are assigned to objects for the indication of relative extent to which the objects possess some characteristic. Therefore, a median value is calculated to allocate a single rank for each LDM enabler. The relative weightage of DM enablers and their importance score is shown in Table 5.

The prioritization of each resilience element is then calculated by summing up the products of relative importance of each LDM enabler, multiplied by the quantified score of the relationship (weak = 1, medium = 3 or strong = 9) between j-th LDM enabler and each of the resilience elements associated with it (Franceschini, 2001). The resultant equation is given below:

$$z_{j=} \sum_{i=1}^{m} x_i y_{ij}$$

where

z_j = absolute prioritization rating of j-th resilience element, where j = 1, 2,. . .n;
x_i = degree of importance of i-th LDM enabler, where i = 1, 2,. . .m;
y_{ij} = codified relationship between i-th LDM enabler and j-th resilience element according to the adopted codification;
n = number of resilience elements; and
m = number of LDM enablers.

LDM enablers	Importance score (median value)	Relative weight (%)
Local supplier's network	3.5	6.36
Near/on-site production	3.0	5.45
Local consumers	4.0	7.27
Novel innovation process	2.5	4.54
Multifunctional processing	3.5	6.36
New production technologies	3.0	5.45
Flexible production volume	3.0	5.45
Mass and late customization	3.5	6.36
Bespoke production	3.0	5.45
Multivariant products	3.0	5.45
Customer services provision	3.0	5.45
Supply chain networking	4.0	7.27
Process control and automation	3.5	6.36
Traceability of products	3.0	5.45
Production data analytics	3.5	6.36
Customer data analytics	3.0	5.45
Customized designs (product and packaging)	3.0	5.45

Note: Scale of importance weightage is 1–5, with 5 being the most important

Table 5.
Importance score of LDM enablers

5.1.3 Weightage of resilience elements for prioritization. The food manufacturing companies from six SS are analysed, and relationship matrix between LDM enablers and resilience elements is built (Table 6).

It can be concluded from the developed relationship matrix that resilience elements of redundancy, inventory management and velocity attained the maximum score (above 100), which is an indication of a strong relationship of these elements with lean LDM enablers; local suppliers' network, near/on-site manufacturing, local consumers, flexible production volume, customer service provision and traceability of products. These LDM enablers are being practised by the maximum number of companies and enhance the factory's resilience of these companies.

The resilience elements of flexibility, visibility, agility and rapidity are ranked with high scores (average 87) and being incorporated by the LDM enablers of flexible production volume, local consumers (strong relationship), multifunctional processing, multivariant products (medium relationship) and mass and late customization, supply chain networking and production data analytics (weak relationship). The resilience elements of diversity, collaboration, information flow, adaptability and efficiency attained a medium score (average 52) due to medium relationship with LDM enablers of bespoke production and weak relationship with supply chain networking and novel innovation process whereas the remaining resilience elements, i.e. early warning detection systems, security, robustness, established communication lines, innovation and risk aware culture got a minimum score (average 27) due to weak relationship with corresponding LDM enablers.

The analysis indicates that LDM enablers in digitalization dimension (supply chain networking, production data analytics, consumer data analytics), customization domain (mass and late customization) and in manufacturing technologies domain (new production technologies, novel innovation process) are the least practised enablers (as indicated in Appendix 2). On the other hand, the LDM enablers of local suppliers' network, near/on-site production, local consumer, flexible production volume, customer services provision, process control and automation and traceability of products are practiced by the maximum number of companies. The usage of innovative production and digital technologies and production of customized products is not common among the companies.

6. Discussion and conclusion

This study discussed the impact of LDM on operational resilience of manufacturing companies. The DM concept is being considered as a potential manufacturing strategy with associated sustainability advantages (Rauch *et al.*, 2016). Similarly, lean manufacturing incorporates sustainability by eliminating waste and enhancing value through eco-friendly, economic and safe production processes (Robin *et al.*, 2019). In this way, the DM characteristics of on-site, on demand and customized production integrated together with lean practices lead to sustainable manufacturing operations.

These sustainable manufacturing operations help mitigate the risks and effectively manage the disruptions (Thomas *et al.*, 2016). The potential of DM for resilient operations can be materialized through technology innovation, new business models and finding opportunities in value chain components (Veldhuis *et al.*, 2019) integrated with lean practices, which focus on efficiency (less cost and less time) along the adaption of these processes. In this context, this study investigates the impact of LDM on factory's resilience by identifying their characteristics and mutual influence.

The QFD approach is used to develop a relationship matrix between resilience capacity elements and LDM enablers. A QFD approach is helpful to investigate the relationship

Table 6.
The relationship matrix for the prioritization of resilience elements

LDM			Resilience elements								
			Preparation strategy							Response strategy	
LDM dimensions	Dimension enablers	Importance score	Flexibility	Redundancy	Early warning detection systems	Security	Robustness	Diversity	Inventory management	Collaboration	Visibility
Manufacturing localization	Local supplier network	3.5		9				9	9	9	9
	Near/on-site production	3	9	9					9		
	Local consumers	4									9
Manufacturing technology	Novel innovation process	2.5									
	Multifunctional processing	3.5	3	3	3		3				
	New production technology	3									
	Flexible production volume	3	9	9			9		9		
Customization and personalization	Mass and late customization	3.5						1			
	Bespoke production	3								3	
	Multivariant products	3	3	3				3			
	Customer services provision	3									
Digitalization	Supply chain networking	4	1		1	1				1	1
	Process control and automation	3.5							9		
	Traceability of products	3				9					9
	Production data analytics	3.5			1				1		
	Consumer data analytics	3									
Democratization of design	Customized designs (product and packaging)	3									
Absolute importance score		77.5	105	18	31	37.5	44	120.5	44.5	98.5	62.5

(*continued*)

LDM	Resilience elements: Response strategy		Recovery strategy			Adaptation strategy			
LDM dimensions	Information flow	Established communication lines	Agility	Rapidity	Velocity	Adaptability	Innovation	Efficiency	Risk aware culture
Manufacturing localization									
			9			9			
				9	9				
Manufacturing technology						1	1	1	
			3	3		3			
							1	1	
			9	9	9				
Customization and personalization			1	1	1	1	1		
				3		3	3	3	
			3				3		
	9	9			9				
Digitalization	1	1	1					1	1
	9							9	
					9				
			1	1					1
Democratization of design						3	3		
Absolute importance score	31	84.5	89.5	120.5	61.5	36	50	7.5	

Table 6.

between different variables, and QFD model can be used to build resilience in companies with a link to customers' requirements (Lam and Bai, 2016).

The prioritization of these resilience elements, based on importance score and intensity of relationship (strong, medium, weak), indicates the current resilience capability of food manufacturing companies attributed by different LDM enablers. The analysis revealed that LDM enablers of near/on-site production units, multi-functional processing, flexible production volume, local supplier network, customer service provision and traceability of products enhance the resilience capabilities of redundancy, velocity, inventory management, flexibility, visibility, agility and rapidity and practised by the maximum number of companies (15 to 18). This outcome is strengthened by another study (implementation models for DM) by Gimenez-Escalante and Rahimifard (2018), which concludes that LDM characteristics of production flexibility, product traceability, local production and local supply chains enhance the sustainability and resilience of food manufacturing operations. The other LDM enablers of supply chain networking, production data analytics, consumer data analytics, mass/late customization, new production technologies and novel innovation processes enhance diversity, early warning detection systems, security, innovation, efficiency and risk aware culture capabilities of resilience and practised by few companies (1 to 4). These enablers are less practised which is understandable as new technologies of food production and digital infrastructure require broader product and system-level considerations. The adaptation of new food technologies and incorporation of real-time data into supply chain planning systems by digital technology improves the resilience capabilities (Jagtap and Rahimifard, 2019), but these technologies (specially food manufacturing) are at different stages of development which makes it difficult for food manufacturers to make reliable cost models and resource efficiency assessments (Gimenez-Escalante and Rahimifard, 2018).

In this paper, two research questions are asked (see Section 1), and following conclusions can be drawn. For *RQ1*, a conceptual model is proposed to describe the impact of LDM on operational resilience of food manufacturing companies. As regard the relationship between LDM enablers and resilience elements (*RQ2*), a relationship matrix is constructed through a clustering procedure based on empirical evidence from the UK food manufacturing sector.

The conceptual model proposes that LDM enablers (defined under five LDM dimensions) can improve the resilience capabilities of manufacturing companies at different stages of resilience action cycle, i.e. preparation, response, recovery, adaptation, enabling more resilient organizational and supply chain operations to mitigate the potential disruptions. This model forms the basis of further research, based on a large sample size, to be tested and to develop a scale for the measurement of resilience capacity of food manufacturing companies.

The increased uncertainty and disturbance to global supply chains pose significant threats to food production and supplies and food manufacturers need to respond to these disturbances by finding new ways of producing food and building resilient supply chains (Colwill *et al.*, 2016). Freeman *et al.* (2017) explored the potential impact of DM during a range of short and long-term frequent disturbances and concluded this manufacturing strategy might prove more resilient than traditional manufacturing. Whereas the lean practices integration ensure the continuous improvement of value-adding processes (Chaple *et al.*, 2021) in adapting this manufacturing strategy. Based on these findings, this study further contributes to knowledge by investigating the relationship among different LDM enablers and resilience elements which will be helpful for food manufacturers in the process of achieving resilient operations.

7. Research limitations and further research

This study proposes a relationship matrix which is helpful for food manufacturing companies to assess their resilience capability in terms of LDM characteristics. The production managers or decision makers then can formulate action plans to incorporate relevant LDM strategies to enhance the corresponding resilience capabilities, e.g. the networking of supply chain operations through digital technologies to enhance security, visibility and efficiency, etc.

This research deals with case study companies which belong to the UK food sector and operate under specific regulatory, operational and economic conditions. These results for other regional markets outside the UK, might not be completely generalized due to different operating conditions. Moreover, the companies belong to six SS of food manufacturing industry; therefore, generalization for other SS should be done with caution by considering sector-specific requirements.

This study considered manufacturing configuration and supply chain related resilience aspects only and did not consider other resilience determinants in financial domain like financial strength, market share, etc. Therefore, further research needs to be conducted to analyse the impacts of LDM on operational resilience capabilities including these resilience elements. The next research study will be focused on manufacturing companies operating in a particular food SS to build a resilience scale, based on this conceptual model, for the measurement of resilience level of companies. And mapping of resilience capabilities required to overcome the potential external (political, social, environmental, economic, etc.) and internal (supply chain, organization) risks related to that SS.

References

Antony, J., Snee, R. and Hoerl, R. (2017), "Lean Six Sigma: yesterday, today and tomorrow", *International Journal of Quality and Reliability Management*, Vol. 34 No. 7, pp. 1073-1093.

Babu, S.C. and Blom, S. (2014), "Capacity development for resilient food systems: issues, approaches and knowledge gaps", *2020 Conference papers 6*, *International Food Policy Research Institute (IFPRI)*.

Birkie, S. (2016), "Operational resilience and lean: in search of synergies and trade-offs", *Journal of Manufacturing Technology Management*, Vol. 27 No. 2, pp. 185-207.

Bottani, E. and Rizzi, A. (2006), "Strategic management of logistics service: a fuzzy QFD approach", *International Journal of Production Economics*, Vol. 103 No. 2, pp. 585-599.

Chaple, A.P., Narkhede, B.E., Akarte, M.M. and Raut, R. (2021), "Modeling the lean barriers for successful lean implementation: TISM approach", *International Journal of Lean Six Sigma*, Vol. 12 No. 1, pp. 98-119, doi: 10.1108/IJLSS-10-2016-0063.

Chauhan, G. and Chauhan, V. (2019), "A phase-wise approach to implement lean manufacturing", *International Journal of Lean Six Sigma*, Vol. 10 No. 1, pp. 106-122, doi: 10.1108/IJLSS-09-2017-0110.

Christopher, M. and Peck, H. (2004), "Building the resilient supply chain", *The International Journal of Logistics Management*, Vol. 15 No. 2, pp. 1-13.

Colwill, J., Despoudi, S. and Bhamra, R.S. (2016), "A review of resilience within the UK food manufacturing sector", in Goh, Y.M. and Case, K. (Eds), *Advances in Manufacturing Technology XXX: Proceedings of the 14th International Conference on Manufacturing Research, Loughborough University*, September 6-8, pp. 451-456.

DeVor, R.E., Kapoor, S.G., Cao, J. and Ehmann, K.F. (2012), "Transforming the landscape of manufacturing: distributed manufacturing based on desktop manufacturing (DM)^2", *Journal of Manufacturing Science and Engineering*, Vol. 134 No. 4, p. 41004.

Dave, Y. and Sohani, N. (2019), "Improving productivity through Lean practices in central India-based manufacturing industries", *International Journal of Lean Six Sigma*, Vol. 10 No. 2, pp. 601-621.

Dorf, R.C. and Bishop, R.H. (1998), *Modern Control Systems*, Addison Wesley Longmann, New York, NY.

Elleuch, H., Dafaoui, E., Elmhamedi, A. and Chabchoub, H. (2016), "Resilience and vulnerability in supply chain: literature review", *IFAC-PapersOnLine*, Vol. 49 No. 12, pp. 1448-1453.

Erol, O., Sauser, B. and Mansouri, M. (2010), "A framework for investigation into extended enterprise resilience", *Enterprise Information Systems*, Vol. 4 No. 2, pp. 111-136.

FAO (2008), *Climate Change and Food Security: A Framework Document*, Food and Agriculture Organization of the United Nations, Rome.

Fiksel, J. (2003), "Designing resilient, sustainable systems", *Environmental Science and Technology*, Vol. 37 No. 23, pp. 5330-5339.

Franceschini, F. (2001), *Advanced Quality Function Deployment*, CRC Press, Boca Raton, FL.

Franceschini, F., Galetto, M. and Turina, E. (2010), "Water and sewage service quality: a proposal of a new multi-questionnaire monitoring tool", *Water Resources Management*, Vol. 24 No. 12, pp. 3033-3050.

Franceschini, F., Galetto, M. and Maisano, D. (2019), *Designing Performance Measurement Systems: Theory and Practice of Key Performance Indicators*, Springer International Publishing, Cham, Switzerland.

Franceschini, F., Galetto, M., Maisano, D. and Mastrogiacomo, L. (2015), "Prioritization of engineering characteristics in QFD in the case of customer requirements orderings", *International Journal of Production Research*, Vol. 53 No. 13, pp. 3975-3988.

Franceschini, F., Galetto, G. and Turina, E. (2009), "Service quality monitoring by performance indicators: a proposal for a structured methodology", *International Journal of Quality and Reliability Management*, Vol. 5 No. 9, pp. 251-273.

Freeman, R., McMahon, C. and Godfrey, P. (2017), "An exploration of the potential for re-distributed manufacturing to contribute to a sustainable, resilient city", *International Journal of Sustainable Engineering*, Vol. 10 No. 4-5, pp. 1-12.

Gimenez-Escalante, P. and Rahimifard, S. (2018), "Challenges in implementation of a distributed and localised approach to food manufacturing", *Food Studies: An Interdisciplinary Journal*, Vol. 8 No. 3, pp. 1-14.

Gölgeci, I. and Ponomarov, S.Y. (2015), "How does firm innovativeness enable supply chain resilience? The moderating role of supply uncertainty and interdependence", *Technology Analysis and Strategic Management*, Vol. 27 No. 3, pp. 267-282.

Goshime, Y., Kitaw, D. and Jilcha, K. (2019), "Lean manufacturing as a vehicle for improving productivity and customer satisfaction: a literature review on metals and engineering industries", *International Journal of Lean Six Sigma*, Vol. 10 No. 2, pp. 691-714, doi: 10.1108/IJLSS-06-2017-0063.

Higgins, A.J., Miller, C.J., Archer, A.A., Ton, T., Fletcher, C.S. and McAllister, R.R. (2010), "Challenges of operations research practice in agricultural value chains", *Journal of the Operational Research Society*, Vol. 61 No. 6, pp. 964-973.

Jagtap, S. and Rahimifard, S. (2019), "Unlocking the potential of the internet of things to improve resource efficiency in food supply chains", in Theodoridis A., Ragkos A. and Salampasis M. (Eds), *Innovative Approaches and Applications for Sustainable Rural Development*, Springer, Cham, HAICTA 2017, Springer Earth System Sciences.

Kamalahmadi, M. and Parast, M.M. (2016), "A review of the literature on the principles of enterprise and supply chain resilience: major findings and directions for future research", *International Journal of Production Economics*, Vol. 171 No. 1, pp. 116-133.

Kohtala, C. (2015), "Addressing sustainability in research on distributed production: an integrated literature review", *Journal of Cleaner Production*, Vol. 106 No. 1, pp. 654-668.

Lam, J.S.L. and Bai, X. (2016), "A quality function deployment approach to improve Maritime supply chain resilience", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 92, pp. 16-27.

McDaniels, T., Chang, S., Cole, D., Mikawoz, J. and Longstaff, H. (2008), "Fostering resilience to extreme events within infrastructure systems: characterizing decision contexts for mitigation and adaptation", *Global Environmental Change*, Vol. 18 No. 2, pp. 310-318.

Miles, M.B. and Huberman, A.M. (1994), *Qualitative Data Analysis: An Expanded Sourcebook*, 2nd ed., Sage, Thousand Oaks, CA.

Moore, S.B. and Manring, S.L. (2009), "Strategy development in small and medium sized enterprises for sustainability and increased value creation", *Journal of Cleaner Production*, Vol. 17 No. 2, pp. 276-282.

Moreno, M. and Charnley, F. (2016), "Can Re-Distributed manufacturing and digital intelligence enable a regenerative economy? An integrative literature review", in Setchi R., Howlett R., Liu Y. and Theobald P. (Eds), *Sustainable Design and Manufacturing 2016*, Springer, Cham, Vol. 52, Smart Innovation, Systems and Technologies.

Moreno, M., Turner, C., Tiwari, A., Hutabarat, W., Charnley, F., Widjaja, D. and Mondini, L. (2017), "Re-distributed manufacturing to achieve a circular economy: a case study utilizing IDEFO modeling", *Procedia CIRP*, Vol. 63, pp. 686-691.

Mourtzis, D., Doukas, M. and Psarommatis, F. (2012), "A multi-criteria evaluation of centralized and decentralized production network in a highly customer-driven environment", *CIRP Annals - Annals*, Vol. 61 No. 1, pp. 427-430.

Pal, R., Torstensson, H. and Mattila, H. (2014), "Antecedents of organizational resilience in economic crises – an empirical study of Swedish textile and clothing SMEs", *International Journal of Production Economics*, Vol. 147 No. 1, pp. 410-428.

Pearson, H., Noble, G. and Hawkins, J. (2013), "Workshop on Re-Distributed manufacturing", *Understanding Change in the NHS*, Vol. 66, pp. 297-317, Technical report November. Pettigrew, a., Mckee, L. and Ferlie, E. (1988).

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2013), "Ensuring supply chain resilience: development and implementation of an assessment tool", *Journal of Business Logistics*, Vol. 34 No. 1, pp. 46-76.

Pham, D.T. and Thomas, A.J. (2012), "Fit manufacturing: a framework for sustainability", *Journal of Manufacturing Technology Management*, Vol. 23 No. 1, pp. 103-123.

Pham, D.T., Pham, P.T.N. and Thomas, A.J. (2008), "Integrated production machines and systems – beyond lean manufacturing", *Journal of Manufacturing Technology Management*, Vol. 19 No. 6, pp. 695-711.

Ponis, S.T. and Koronis, E. (2012), "Supply chain resilience: definition of concept and its formative elements", *Journal of Applied Business Research (JABR)*, Vol. 28 No. 5, p. 921.

Ponomarov, S.Y. and Holcomb, M.C. (2009), "Understanding the concept of supply chain resilience", *The International Journal of Logistics Management*, Vol. 20 No. 1, pp. 124-143.

Prendeville, S., Hartung, G., Purvis, E., Brass, C. and Hall, A. (2016), "Makespaces: from redistributed manufacturing to a circular economy", in Setchi R., Howlett R., Liu Y. and Theobald P. (Eds), *Sustainable Design and Manufacturing 2016*, Springer, Cham, Vol. 52, Smart Innovation, Systems and Technologies.

Rahimifard, S., Woolley, E., Webb, D.P., Garcia-Garcia, G., Stone, J., Jellil, A., Gimenez-Escalante, P., Jagtap, S. and Trollman, H. (2017), "Forging new frontiers in sustainable food manufacturing", in Campana G., Howlett R., Setchi R. and Cimatti B. . . .(Eds), *Sustainable Design and Manufacturing 2017, (SDM 2017)*, Springer, Cham, pp. 13-24.

Rauch, E., Dallasega, P. and Matt, D.T. (2016), "Sustainable production in emerging markets through distributed manufacturing systems (DMS)", *Journal of Cleaner Production*, Vol. 135 No. 1, pp. 127-138.

Robin, B.R., Vinodh, S. and Asokan, P. (2019), "State of art perspectives of lean and sustainable manufacturing", *International Journal of Lean Six Sigma*, Vol. 10 No. 1, pp. 234-256, doi: 10.1108/IJLSS-11-2016-0070.

Ruben, R.B., Vinodh, S. and Asokan, P. (2018), "Lean Six Sigma with environmental focus: review and framework.", *Int J Adv Manuf Technol*, Vol. 94, pp. 4023-4037.

Soni, U., Jain, V. and Kumar, S. (2014), "Measuring supply chain resilience using a deterministic modeling approach", *Computers and Industrial Engineering*, Vol. 74 No. 1, pp. 11-25.

Soroka, A., Liu, Y., Han, L. and Haleem, M.S. (2017), "Big data driven customer insights for SMEs in redistributed manufacturing", *Procedia CIRP*, Vol. 63, pp. 692-697.

Spiegler, V.L.M., Naim, M.M. and Wikner, J. (2012), "A control engineering approach to the assessment of supply chain resilience", *International Journal of Production Research*, Vol. 50 No. 21, pp. 6162-6187.

Srai, J.S., Kumara M., Graham G., Phillips W., Tooze J., Ford S., Beecher P., Raj B., Gregory M., Tiwari M.K., Ravi B., Neely A., Shankar R., Charnley F., Tiwari A., (2016), "Distributed manufacturing: scope, challenges and opportunities", *International Journal of Production Research*, Vol. 54 No. 23, pp. 6917-6935.

Stone, J. and Rahimifard, S. (2018), "Resilience in Agri-food supply chains: a critical analysis of the literature and synthesis of a novel framework", *Supply Chain Management: An International Journal*, Vol. 23 No. 3, pp. 207-238.

Tendall, D.M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q.B., Kruetli, P., Grant, M. and Six, J. (2015), "Food system resilience: defining the concept", *Global Food Security*, Vol. 6 No. 1, pp. 17-23.

Thomas, A., Byard, P., Francis, M., Fisher, R. and White, G. (2016), "Profiling the resiliency and sustainability of UK manufacturing companies", *Journal of Manufacturing Technology Management*, Vol. 27 No. 1, pp. 82-99.

Tukamuhabwa, B.R., Stevenson, M., Busby, J. and Zorzini, M. (2015), "Supply chain resilience: definition, review and theoretical foundations for further study", *International Journal of Production Research*, Vol. 53 No. 18, pp. 5592-5623.

Turner, C., Tiwari, A., Rivas Pizarroso, J.L., Moreno, M., Vladimirova, D., Zaki, M., GeiBdörfer, M. (2017), "Digital redistributed manufacturing (RdM) studio: a Data-Driven approach to business model development", in Campana G., Howlett R., Setchi R. and Cimatti B. (Eds), *Sustainable Design and Manufacturing 2017, SDM 2017*, Springer, Cham, Vol. 68, Smart Innovation, Systems and Technologies.

Ul Haq, I. and Franceschini, F. (2019), "Distributed manufacturing: proposal for a conceptual scale based on empirical evidence in the rubber and plastic sectors", *Benchmarking: An International Journal*, Vol. 27 No. 1, pp. 430-470.

Veldhuis, A.J., Glover, J., Bradley, D., Behzadian, K., López-Avilés, A., Cottee, J., Downing, C., Ingram, J., Leach, M., Farmani, R., Butler, D., Pike, A., De Propris, L., Purvis, L., Robinson, P. and Yang, A. (2019), "Re-distributed manufacturing and the food-water-energy nexus: opportunities and challenges", *Production Planning and Control*, Vol. 30 No. 7, pp. 593-609.

Vlajic, J.V., van Lokven, S.W., Haijema, R. and Van der Vorst, J.G. (2013), "Using vulnerability performance indicators to attain food supply chain robustness", *Production Planning and Control*, Vol. 24Nos No. 8-9, pp. 785-799.

Vohra, V., Rikkonen, P. and Rasi, S. (2016), "Futures of distributed small-scale renewable energy in Finland – a Delphi study of the opportunities and obstacles up to 2025", *Technological Forecasting and Social Change*, Vol. 104, pp. 30-37.

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002), "Case research in operations management", *International Journal of Operations and Production Management*, Vol. 22 No. 2, pp. 195-219.

Zaki, M., Theodoulidis, B., Shapira, P., Neely, A. and Tepel, M.F. (2019), "Redistributed manufacturing and the impact of big data: a consumer goods perspective", *Production Planning and Control*, Vol. 30 No. 7, pp. 568-581.

Further reading

Deradjat, D. and Minshall, T. (2017), "Implementation of rapid manufacturing for mass customization", *Journal of Manufacturing Technology Management*, Vol. 28 No. 1, pp. 95-121.

Franceschini, F. and Rossetto, S. (2002), "QFD: an interactive algorithm for the prioritization of product's technical design characteristics", *Integrated Manufacturing Systems*, Vol. 13 No. 1, pp. 69-75.

Holling, C.S. (1973), "Resilience and stability of ecological systems", *Annual Review of Ecology and Systematics*, Vol. 4 No. 1, pp. 1-23.

Hundal, G.S., Thiyagarajan, S., Alduraibi, M., Laux, C.M., Furterer, S.L., Elizabeth, A., Cudney, E.A. and Antony, J. (2021), "Lean six sigma as an organizational resilience mechanism in health care during the era of COVID-19", *International Journal of Lean Six Sigma*, Vol. 12 No. 4, pp. 762-783 doi: 10.1108/IJLSS-11-2020-0204.

Praharsi, Y., Jami'in, M.A., Suhardjito, G. and Wee, H.M. (2021), "The application of lean six sigma and supply chain resilience in Maritime industry during the era of COVID-19", *International Journal of Lean Six Sigma*, Vol. 12 No. 4, doi: 10.1108/IJLSS-11-2020-0196.

Corresponding author
Fiorenzo Franceschini can be contacted at: fiorenzo.franceschini@polito.it

Appendix 1

LDM dimension	LDM enablers	Questions
Manufacturing Localization	Local suppliers' network	How many local suppliers (within the UK) are there for raw material supply?
	Local consumers	What percentage of customers are locally based (within the UK) and what percentage is based abroad (approximately)?
	Near/on-site manufacturing	Are there more than one manufacturing facilities present?
Manufacturing Technologies	New production technologies	Are there any novel food technologies (physical or physicochemical) being used on factory floor?
	Novel innovation process	Is there any novel innovation production process being used on factory floor?
	Flexible production volume	Does the company have the capability to produce flexible production volumes to meet variable demand?
	Multifunctional processing	Are there different products being manufactured by multifunctional processing lines? Or batch production of few standardized products is being accomplished?
Customization and Personalization	Mass and late customization	Up to which level, firm incorporates customers input in products' specifications (no customer input or customers select from products ingredients list or customers specify product ingredients)?
	Bespoke fabrication	Up to which level, firm offers customization of products (standardized products or products by demand forecast or products on orders)?
	Multivariant products	How many product groups or types of products are being manufactured?
	Customer services provision	What additional customers services are being offered to retain customers?
Digitalization	Process control and automation	Which techniques are being used for process control and automation? (manual control, semi-automated production lines, fully automated production lines
	Supply chain networking	Does the firm use digital technology (Internet of Things, etc.) for networking of supply chain components (suppliers, production facilities, distribution channels)?
	Production data analytics	Is there any data collection and analysis methodology employed to collect, transmit and analyses production data from factory floor?
	Traceability of products	Is there any mechanism being used by the firm to trace finished products and suppliers' product ingredients?
	Consumer data analytics	Does the firm use any big data application to analyse consumer trends and market forecast?
Democratization of Design	Customized design on customer demand	How does the firm incorporate customers input in product design? (no design input or design catalog for selection or customers input during designing)

Table A1.
List of questions to identify the application status of LDM enablers

Appendix 2

Table A2. LDM enablers being practiced in food manufacturing companies

Food sub-sector	Case Study companies	LDM enablers: Manufacturing localization: Local uppliers network	Manufacturing localization: On/near site production	Manufacturing localization: Local consumers	Novel innovation process	Manufacturing technology: Multifunctional processing	Manufacturing technology: Novel production technologies	Flexible production volume	Customization and personalization: Mass and late customization	Customization and personalization: Bespoke production	Customization and personalization: Multivariant products
Dairy Products	F1	•	•	•				•			
	F2	•	•	•	•	•		•	•		•
	F3	•	•	•				•	•		
Chilled Foods	F4	•	•	•	•		•	•	•		
	F5		•	•		•		•	•	•	•
	F6	•	•	•		•		•	•	•	•
Drinks	F7	•	•	•				•	•		
	F8		•	•	•			•	•		
	F9		•	•	•			•	•		•
Bakery Foods	F10	•	•	•				•	•		
	F11	•	•	•					•		
	F12	•	•	•				•	•		
Fruits and Seeds Processing	F13	•	•	•		•		•	•	•	•
	F14	•	•	•		•		•	•	•	•
	F15		•	•		•		•		•	•
Meat Processing	F16	•	•	•				•	•	•	•
	F17	•	•	•		•		•	•	•	
	F18	•	•	•		•		•	•	•	•

(*continued*)

Table A2.

Food sub-sector	LDM enablers: Customization and personalization: Provision of customers services	Digitalization: Networking of supply chain	Digitalization: Process control and automation	Digitalization: Traceability of products	Digitalization: Production data integration and analytics	Digitalization: Consumer data analytics	Democratization of design: Customized designs (product and packaging)
Dairy Products				•			
	•	•	•	•	•		
	•	•	•	•			
Chilled Foods	•		•	•			
	•	•	•	•			•
	•	•	•	•			
Drinks	•		•				
	•	•	•				
	•		•	•			
Bakery Foods			•	•			
	•	•	•				
	•		•				
Fruits and Seeds Processing	•	•	•	•			•
	•	•	•	•	•		•
				•			
Meat Processing	•	•		•			
	•	•	•	•			
	•	•	•	•			•

Appendix 3

As a first step, Euclidean distance is calculated for cluster analysis. The Euclidean distance between every two LDM enablers, of 17 total enablers, is calculated by using following formula:

$$D = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2 + (x_4 - y_4)^2 + (x_5 - y_5)^2 + (x_6 - y_6)^2}$$

where

x_1 = Number of companies practicing enabler 1 (E1) in sub-sectors 1 (SS1)
x_2 = Number of companies practicing enabler 1 (E1) in sub-sectors 2 (SS2)
x_3 = Number of companies practicing enabler 1 (E1) in sub-sectors 3 (SS3)
x_4 = Number of companies practicing enabler 1 (E1) in sub-sectors 4 (SS4)
x_5 = Number of companies practicing enabler 1 (E1) in sub-sectors 5 (SS5)
x_6 = Number of companies practicing enabler 1 (E1) in sub-sectors 6 (SS6)
y_1 = Number of companies practicing enabler 2 (E2) in sub-sectors 1 (SS1)
y_2 = Number of companies practicing enabler 2 (E2) in sub-sectors 2 (SS2)
y_3 = Number of companies practicing enabler 2 (E2) in sub-sectors 3 (SS3)
y_4 = Number of companies practicing enabler 2 (E2) in sub-sectors 4 (SS4)
y_5 = Number of companies practicing enabler 2 (E2) in sub-sectors 5 (SS5)
y_6 = Number of companies practicing enabler 2 (E2) in sub-sectors 6 (SS6)

Example:

Enabler E1: $x_1 = 3, x_2 = 2, x_3 = 1, x_4 = 2, x_5 = 2, x_6 = 3$
Enabler E2: $y_1 = 3, y_2 = 3, y_3 = 3, y_4 = 3, y_5 = 3, y_6 = 3$
D = 2.64

A hierarchical clustering method with complete linkage (where dissimilarities between objects pairs in a cluster are less than a specific level) is used in this study. A statistical software package SPSS is used for this purpose. The results are shown in Tables A3, A4, A5 and Dendogram is shown in Figure A1.

The DM enablers are divided into three clusters as shown in Table A6. The choice of three clusters is considered to divide DM enablers into three categories of strong, medium and weak relationships.

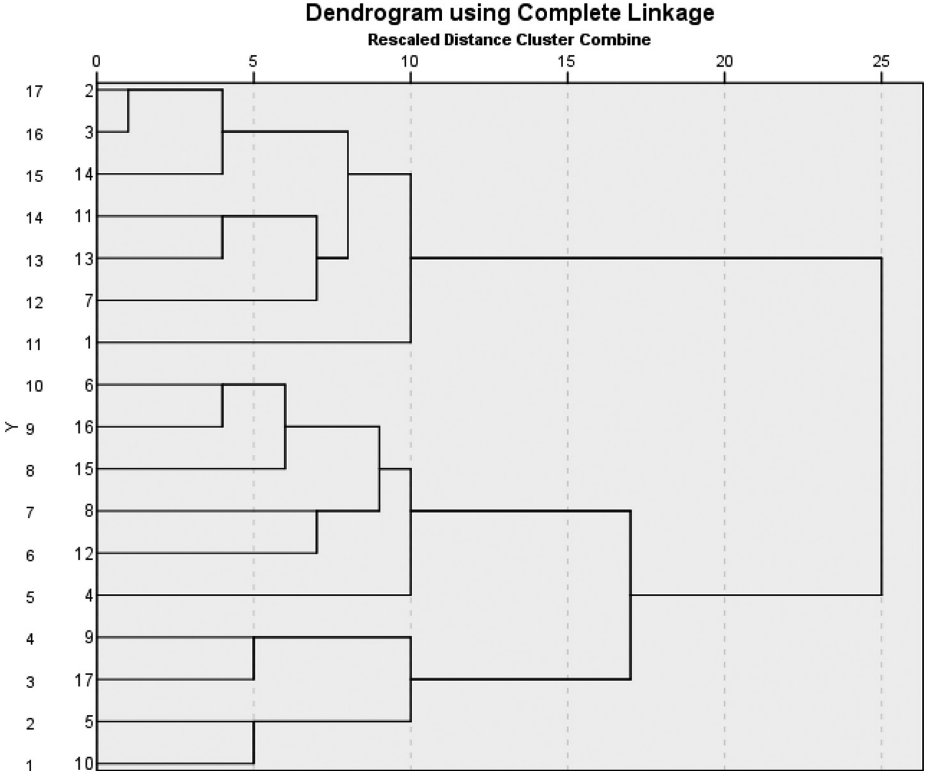

Figure A1.
The Dendogram clustering of the 17 Distributed Manufacturing (DM) Enablers

Stage	Cluster combined		Coefficients	Stage cluster first appears		Next stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	2	3	0	0	0	3
2	6	16	1	0	0	7
3	2	14	1	1	0	10
4	11	13	1	0	0	9
5	9	17	1.414	0	0	14
6	5	10	1.414	0	0	14
7	6	15	1.732	2	0	11
8	8	12	2	0	0	11
9	7	11	2	0	4	10
10	2	7	2.236	3	9	13
11	6	8	2.449	7	8	12
12	4	6	2.646	0	11	15
13	1	2	2.646	0	10	16
14	5	9	2.828	6	5	15
15	4	5	4.796	12	14	16
16	1	4	7.348	13	15	0

Table A3.
Agglomeration schedule

Case	Three clusters
1	1
2	1
3	1
4	2
5	3
6	2
7	1
8	2
9	3
10	3
11	1
12	2
13	1
14	1
15	2
16	2
17	3

Table A4.
Cluster membership

Table A5.
Case processing summary[a,b]

Cases					
Valid		Missing		Total	
N	(%)	N	(%)	N	(%)
17	100	0	0	17	100

[a]Euclidean distance used. [b]Complete linkage

Table A6.
Classification of DM enablers in clusters

DM enablers	Dairy products *(SS1)*	Chilled foods *(SS2)*	Drinks *(SS3)*	Bakery foods *(SS4)*	Fruits and seeds processing *(SS5)*	Meat processing *(SS6)*	Total no. of companies
Cluster 1							
E1	3	2	1	2	2	3	13
E2	3	3	3	3	3	3	18
E3	3	3	3	3	3	3	18
E7	3	3	3	1	3	3	16
E11	2	3	3	2	2	3	15
E13	2	3	3	2	2	2	14
E14	3	3	2	3	3	3	17
Cluster 2							
E4	0	1	2	0	0	0	3
E6	0	1	0	0	0	0	1
E8	0	1	1	0	2	0	4
E12	1	2	0	0	1	0	4
E15	1	0	0	0	1	0	2
E16	0	0	0	0	0	0	0
Cluster 3							
E5	1	2	0	1	3	2	9
E9	0	3	0	0	3	1	7
E10	1	2	1	2	3	2	11
E17	0	2	0	0	2	1	5