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Distributed manufacturing

Proposal for a conceptual scale based on empirical evidence in the rubber and plastic sectors

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Abstract

Purpose – The purpose of this paper is to develop a preliminary conceptual scale for the measurement of distributed manufacturing (DM) capacity of manufacturing companies operating in rubber and plastic sectors.
Design/methodology/approach – A two-step research methodology is employed. In first step, the dimensions of DM and different levels of each dimension have been defined. In second step, an empirical analysis (cluster analysis) of database firms is performed by collecting the data of 38 firms operating in Italian mould manufacturing sector. Application case studies are then analyzed to show the use of the proposed DM conceptual scale.
Findings – A hyperspace, composed of five dimensions of DM, i.e. manufacturing localization; manufacturing technologies; customization and personalization; digitalization; and democratization of design, is developed and a hierarchy is defined by listing the levels of each dimension in an ascending order. Based on this hyperspace, a conceptual scale is proposed to measure the positioning of a generic company in the DM continuum.
Research limitations/implications – The empirical data are collected from Italian mould manufacturing companies operating in rubber and plastic sectors. It cannot be assumed that the industrial sectors in different parts of the world are operating under similar operational, regulatory and economic conditions. The results, therefore, might not be generalized to manufacturing companies operating in different countries (particularly developing countries) under different circumstances.
Originality/value – This is first preliminary scale of its kind to evaluate the positioning of companies with respect to their DM capacity. This scale is helpful for companies to compare their capacity with standard profiles and for decision making to convert the existing manufacturing operations into distributed operations.

Keywords Distributed manufacturing, Conceptual scale

Paper type Research paper

1. Introduction

The provision of value-added products and services is essential for manufacturing companies to remain competitive and increase their market share. Also, the growing emphasis on ecological and social impacts of organizations, on the surroundings they operate, compels manufacturing companies to adapt efficient and green product development, production and supply chain management strategies (Berrone *et al.*, 2013; Jasti *et al.*, 2015; Dangelico *et al.*, 2017; Sulistiarini *et al.*, 2018; Famiyeh *et al.*, 2018). The organizations undergo significant transformations due to financial crisis, new trade laws and social/economic reorganizations and need to assimilate new roadmaps, frameworks and systems able to maintain a sustainable business life cycle (Metaxas *et al.*, 2016). The manufacturing companies will achieve customer value in future not only through a product or a service realization but also through socially and environmentally responsible and economically efficient manufacturing processes encouraging positive effects for society (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016). To achieve the goal of sustainable manufacturing operations, organizations need to overcome several challenges. These challenges comprise new types of products, operations and organization models to comply with new constraints and objectives of sustainable manufacturing (Garetti and Taisch, 2012). The sustainability in manufacturing can be achieved by a holistic view spanning the product, the manufacturing process, the supply chain and the manufacturing systems across multiple product life

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cycle (Kabongo, 2018). The literature discusses different approaches used to implement sustainability in manufacturing. Some of these approaches include servitization (Neely, 2008), product life cycle management (Vila *et al.*, 2015), additive manufacturing (Ford and Despeisse, 2016), product–service system (PSS) (Huer *et al.*, 2018) and distributed manufacturing (DM) (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016). DM is considered as one of many production strategies for manufacturing companies to achieve their sustainability targets and objectives. DM is an appropriate strategy for sustainable production due to its micro production units which allow local production on demand, reduced transportation cost and strengthening of local economy (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016). DM as a promising production model for sustainable operations and the organizational capabilities required for its implementation is discussed in this study.

DM can be defined as localized and small-scale manufacturing of customized products through enhanced producer–customer interaction and induction of new production and digital technologies (Kohtala, 2015; Prendeville *et al.*, 2016; Veldhuis *et al.*, 2019). The utilization of local resources for customized products and adaptation of new production technologies (e.g. additive manufacturing) in a digitized environment make DM attractive for potential sustainability gains (Kohtala and Hyysalo, 2015; Jreissat *et al.*, 2017; Rahimifard *et al.*, 2017). The main advantages associated with decentralized production structures include higher flexibility to reflect local customer, lower logistics cost and shorter delivery times (Fox, 2015; Matt *et al.*, 2015; Roscoe and Blome, 2019; Tsimiklis and Makatsoris, 2019). Centralized manufacturing lacks these sustainability benefits associated with DM of products close to the end consumer (Mourtzis *et al.*, 2012; Zanetti *et al.*, 2015; Freeman *et al.*, 2017). Centralized manufacturing is deficient in two aspects of cost in the developing world and environmental impact, whereas a sustainable manufacturing system with optimized value calls for a broader and more holistic view and points to the potential for distributed manufacturing systems (DMS) (Gwamuri *et al.*, 2014).

DM has been discussed in literature as a potential approach to achieve sustainability objectives, i.e. sustainable production in emerging markets (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016), environmental sustainability of distributed production (DP) (Kohtala, 2015), DM potential to contribute to a sustainable and resilient city (Freeman *et al.*, 2017) and sustainable PSS implementation through DM (Petrulaityte *et al.*, 2017). However, little research has been completed to demonstrate how manufacturing companies can measure their capacity to adapt DM as a production methodology to avail the sustainability benefits associated with it. The opportunities and challenges of DM need to be explored by answering the questions about learning capabilities of organizations and management of localized production models (Moreno and Charnley, 2016). The transition of existing businesses and organizations into a DM structure is one of the issues which need to be addressed (Pearson *et al.*, 2013). This study deals with this prospect of transition as how a manufacturing company can transform its production from centralized to distributed and how it can be mapped in the proposed classification. The knowledge of existing capacity and capability gaps like quality assurance and operational is essential for decision makers based on which related strategies are designed and implemented in this transition process (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016). Two research questions are investigated in this study:

RQ1. How can the existing DM capacity of a manufacturing company be represented?

RQ2. How can the relevant positioning of a manufacturing company in comparison to current DM practices be measured?

For this purpose, a preliminary conceptual scale is developed to represent the DM capacity and positioning of a manufacturing company in the DM continuum. This capacity measurement and positioning of company are helpful for decision makers to identify and address the relevant areas in the process of DM adaptation. The scale is developed through identification of DM dimensions from literature and the empirical data collected from Italian mould manufacturing sector. The scale is based on DM reference profiles and the DM capacity of a firm is measured by the comparison of its positioning with the reference profiles. The structure of the paper is described as follows: Section 2 presents a literature review. Section 3 deals with the development of the conceptual scale, Section 4 describes the construction of the scale and Section 5 discusses the application case studies. Conclusion is given in Section 6 followed by implications and limitations of the research given in Section 7.

2. Literature review

This section is divided into three sub-sections: DM, DM dimensions and research gaps.

2.1 Distributed manufacturing

DM concept has been discussed in literature under different notations including DM (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016), DMS (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016), DP (Kohtala, 2015), distributed economies (DE) (Johansson *et al.*, 2005), and re-distributed manufacturing (RdM) (Pearson *et al.*, 2013). The DM term has been used in different contexts and evolved over the period. Seregni *et al.* (2015) described the evolution of DM concept from decentralized and modular production control of product components (Weston *et al.*, 1986; Rana and Taneja, 1988; Barekat, 1991) to geographically dispersed flexible and reconfigurable production units of a single enterprise (Piller, 2002; Strassburger *et al.*, 2003; Zaeh and Wagner, 2005; Buckley and Ghauri, 2004; Reichwald *et al.*, 2005) to a network of collaborative organizations complementing each other in skills and resources (Wiendahl *et al.*, 2007; Camarinha-Matos *et al.*, 2009; Mourtzis *et al.*, 2012). Windt (2014) argued the term DM was interpreted in two different ways. The first interpretation is related to the concept of value addition at geographically dispersed manufacturing locations of one enterprise. The second interpretation is in the context of DMS, defined as a class of manufacturing systems, focussed on the internal manufacturing control and characterized by common properties (e.g. autonomy, flexibility, adaptability, agility and decentralization).

DM concept is being researched to explore its potential as a manufacturing methodology that employs decentralized production facilities in consumer proximity and enhanced customer involvement in product development process (Moreno *et al.*, 2017; Soroka *et al.*, 2017; Zaki *et al.*, 2017). This paradigm is a shift from centralized manufacturing concept having conventional mass production with associated supply chains to deliver products to consumer over various destinations. The manufacturing paradigm has been transformed from craft production (manufacturing product on customer orders) to mass production (offering low-cost products in large volumes) to mass customization (MC) (incorporating customers demand to produce high-variety products) to DM (offering personalized and bespoke products) (Mourtzis and Doukas, 2012; Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016). This transformation is being facilitated by advancements in novel production technologies (Durao *et al.*, 2016), digitalization by cyber-physical systems (CPS) and Internet of Things (IoT) (Yew *et al.*, 2016) and an emphasis on local economies for sustainable development (Freeman *et al.*, 2017). DM is thus characterized by location, flexibility, production technology, customization, digital technologies and customer involvement in product development, and can be defined as, "reconfigurable and flexible production close to the consumption point, using novel production and digital technologies and offering personalised products by incorporating customers input in product design and specifications". A list of definitions of DM, presented in literature, is given in Table I.

Table I. List of distributed manufacturing definition and conceptual dimensions listed in literature

Authors	Year	Context	Definitions	Dimensions
Johansson *et al.*	2005	Economics	"With Distributed economies (DE), a selective share of production is distributed to regions where a diverse range of activities are organized in the form of small-scale, flexible units that are synergistically connected with each other and prioritize quality in their production"	Heterarchies and open innovation, flexible and small-scale production, no producer–consumer relationship, integrated design and innovation, collaboration and collective spirit, balance between intra-regional and inter-regional exchange of resources, symbiosis of small- and large-scale production systems
Mourtzis and Doukas	2012	Manufacturing	"Decentralized manufacturing units operate on the organizational principle of modularization which involves the reforming of the organizational structure into small, manageable units on the basis of integrated and customer-oriented processes"	Decentralized production, mass customization, changeability, interaction, decentralized decision-making, customer-oriented processes, automated manufacturing
DeVor *et al.*	2012	Manufacturing	"Work is beginning to emerge focused on creating the science, technology, and commercialization bases necessary for the realization of miniaturized unit processes and manufacturing equipment integrated into micro factories. This new manufacturing paradigm has the potential to be a key enabler in the realization of what we refer to here as distributed manufacturing based on desktop manufacturing (DM)2"	On or near site manufacturing, mass customization, multifunctional processing and assembly machines, flexible and autonomous operations
Pearson *et al.*	2013	Manufacturing	"Technology, systems and strategies that change the economics and organization of manufacturing, particularly with regard to location and scale"	Localized manufacturing, cloud manufacturing, customized/multi-variant products, flexible and agile operations, inter organizational reconfiguration, resource efficiency
Kohtala	2015	Sustainability	"Distributed production includes a wide range of current and emerging practices where private citizens have increased capacity to effect what is produced, from product personalization to personal fabrication"	Bespoke fabrication, mass customization, mass fabrication, personal fabrication
Rauch, Seidenstricker, Dallasega and Hammerl; Rauch, Dallasega and Matt	2016, 2016	Sustainable production	"So-called distributed manufacturing systems (DMS) represent an ideal approach to meet actual challenges regarding individualization of products, customer proximity, or a more sustainable production"	Regionalism/Authenticity, lower logistics cost, mass customization, democratization of design, market/customer proximity, megatrend sustainability
Moreno and Charnley	2016	Circular innovation	"The shift from centralized to decentralized manufacture with the aim to create a more resilient and connected	Localization, customization, distributed knowledge, distributed structure, distributed ownership

(continued)

Authors	Year	Context	Definitions	Dimensions
			system taking advantage of digital intelligence and newly emerging technologies, to provide agile, user-driven approach that will allow for personalization and customization of products to local markets"	
Srai *et al.*; Srai, Harrington and Tiwari	2016, 2016	Manufacturing	"Distributed manufacturing paradigm indicates the changing nature of manufacturing from centralized, large-scale, long lead-time forecast-driven production to a decentralized, autonomous, near end user-driven activity"	Localization, digitalization, personalization, new production technologies, multi-user participation
Prendeville *et al.*	2016	Circular economy	"The emerging concept of re-distributed manufacturing captures the anticipated reshoring and localization of production from large scale manufacturing plants to smaller-scale, localized, customizable production units, largely drive by new additive digital production technologies"	Open digital networks, collaborative and open innovation, diffusion of new technologies, personalization and customization, prosumption, local networks and social interactions, sharing knowledge and skills, reshoring of manufacturing
Srai, Harrington and Tiwari	2016	Industry supply networks	"The ability to personalize product manufacturing at multiple scales and locations, exemplified by enhanced user participation across product design, fabrication and supply, and typically enabled by digitalization and new production technologies"	Geographical dispersion, mass and late customization, integrated design, customer interaction in product development, e-commerce-driven remote sales, reconfiguration of products and resources
Zaki *et al.*	2017	Big data application	"A connected, localized and inclusive model of production and consumption that is driven by the exponential growth and embedded value of big data"	Inclusive production, co-creation, co-production, big data applications, novel innovation process
Gimenez-Escalante and Rahimifard	2018	Food production	"Distributed and localized manufacturing (DLM) can be defined as a decentralized and closer to consumer production network which provides increased flexibility and faster response to market needs"	Shorter food miles, customization and personalization, optimal use of materials, visibility and transparency, production flexibility
Veldhuis *et al.*	2019	Food production	"Re-distributed manufacturing term revolves around changing location and scale of manufacturing activities, such that manufacturing units are of greater number, are therefore relatively smaller, and are located closer to the consumer of the final product"	Decentralized manufacturing, personalization, shared services, food waste recycling, new production technology, co-innovation

Table I.

This concept of DM as a methodology of localized production for personalized products is adapted for this research to develop a conceptual scale. At first, the dimensions of DM have been searched to use them as a basis for the proposed scale.

2.2 Dimensions of distributed manufacturing

For the identification of DM dimensions/characteristics, the literature has been explored. The research databases like Scopus, Emerald Insight, Google Scholar and ScienceDirect have been searched with keywords distributed manufacturing, re-distributed manufacturing, distributed production and distributed manufacturing systems to look for the relevant material about dimensions of DM. Table I gives a summary of papers published in DM research area. It highlights different contexts addressed in these research studies. DM concept has been discussed in the contexts of economy (Johansson *et al.*, 2005), manufacturing (Mourtzis and Doukas, 2012; DeVor *et al.*, 2012; Pearson *et al.*, 2013; Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016), sustainability (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016; Kohtala, 2015), circular innovation and economy (Moreno and Charnley, 2016; Prendeville *et al.*, 2016), supply chain (Srai, Harrington and Tiwari, 2016), big data application (Zaki *et al.*, 2017) and food production (Gimenez-Escalante and Rahimifard, 2018; Veldhuis *et al.*, 2019). These studies are exploratory in nature using case study, modelling and qualitative (thematic analysis) approaches to identify the opportunities and challenges of this manufacturing paradigm. The listed studies in Table I, detailing a set of conceptual dimensions of DM paradigm, have been discussed below.

Johansson *et al.* (2005) presented the concept of DE for sustainable industrial growth which described the transformation of centralized large-scale production units to decentralized small-scale, flexible and connected units. The proposed DE concept promotes growth through inter-regional networking rather by size of production units. The authors further elaborated the need of establishing a balance between large- and small-scale production – instead of completely abolishing large-scale production – to promote regional economies within newly defined regional boundaries. Mourtzis and Doukas (2012) presented a comparison between large-scale mass production and small-scale manufacturing of customized products. The authors argue that MC offers personalized products in a competitive business environment with increased complexity of manufacturing operations, whereas mass production reduces complexity by producing low-variety and high-volume products. And the decentralized production entities provide a trade-off by increasing product variety and reducing operations complexity through modularization and decentralization of decision making. In their further analysis, different decentralized production concepts are examined to check their level of applicability for a defined set of KPIs (complexity, modularization, integration, interaction, etc.). Contrary to decentralization of manufacturing operations at industrial level, DeVor *et al.* (2012) described and elaborated manufacturing decentralization at much smaller level and defined it as “distributed manufacturing based on desktop manufacturing”. The different scenarios (manufacturing at the point-of-use, manufacturing at the mall and personal manufacturing) of desktop manufacturing are discussed and termed as enablers for DM which would co-exist with centralized manufacturing but likely to take more share of the worldwide manufacturing market. Due to decentralized, local and small-scale production characteristics, DM is considered as a potential strategy for sustainable manufacturing operations. Rauch, Seidenstricker, Dallasega and Hammerl (2016) and Rauch, Dallasega and Matt (2016) discussed DMS as a possible approach for sustainable manufacturing due to its adaptable and decentralized characteristics and listed a set of six trends towards the development of DMS. These trends include sustainability, rising logistics cost, MC, democratization of design, market/consumer proximity and regionalism and authenticity. Kohtala (2015) conducted an integrated literature review about environmental sustainability of DP and concluded this manufacturing methodology could provide greater environmental sustainability but not a clearly cleaner production paradigm and related potential threats needed to be addressed to improve these emerging distributed practices.

The novelty of DM concept – as a methodology to produce localized and customized products – has been addressed by using exploratory research design in literature to identify the potential opportunities and challenges of this manufacturing paradigm. Pearson *et al.* (2013) listed outcomes of Engineering and Physical Sciences Research Council (EPSRC) workshop on RdM. The workshop identified four core fields, i.e. geographies of manufacturing; enabling production technologies; new models of economics, business, investment and quality; and regulation and legislation as potential research themes in the context of RdM. Srai *et al.* (2016) and Srai, Harrington and Tiwari (2016) performed a cross-case analysis, consisting of six case companies, to identify the challenges and opportunities associated with DM in terms of customization, digital infrastructural developments (IoT, big data) and new production technologies. This analysis concluded DM as a new paradigm having decentralized, autonomous, flexible and customer-driven production activity in its proximity opposed to centralized, large-scale, forecast-driven manufacturing of products in large volumes. In another study, Srai, Harrington and Tiwari (2016) explored the characteristics of re-distributed manufacturing systems within the context of emerging industry supply networks through cross-case analysis of six industrial systems (defence aerospace, maritime cluster, built environment, industrial biotechnology, photovoltaic and last-mile logistics) by using an industrial system mapping methodology. These characteristics include high product variety, lower inventory, enhanced production and distribution flexibility and closeness to demand location.

Moreno and Charnley (2016) examined the opportunities and challenges of digital intelligence in the transition towards a re-distributed and circular business model for consumer goods production by conducting an integrated literature review of RdM and circular innovation drivers. It was concluded that integration of digital intelligence has leveraged the decentralized, re-distributed and circular models of production and consumption through distribution of knowledge, structure, ownership and different customisation levels. The case studies were then analyzed against the criteria defined for RdM and circular innovation. In another similar study, Prendeville *et al.* (2016) explained the interplay between circular economy (a close loop system of repairing, remanufacturing, refurbishment and recycling) and RdM (smaller-scale, localized, customizable production units) and identified opportunities to combine makespaces with circular economy through RdM. The modelling techniques were also used to assess the potential of DM in consumers' goods industry. To demonstrate the use of RdM and PSS approach in enabling a circular economic model, Moreno *et al.* (2017) presented a shoe manufacturing case study using IDEFO modelling and concluded that this modelling technique could help in realizing the sustainability benefits (manufacturing and transportation of products with less material, energy and wastage) of RdM. By applying a similar approach to shoe manufacturing industry, Turner *et al.* (2017) used a data-driven methodology to business model development through the application of system dynamics modelling in which data-driven decisions have been used to simulate different RdM scenarios. In another study of business model development to support the diffusion of DP, Seidenstricker *et al.* (2017) used business model engineering approach and designed a business model for DMS based on four core elements (value proposition; value chain and processes; revenues and technologies; and competencies and key resources) and a three-level (designing, planning and operational) model to ensure the efficiency of production units within a distributed network.

The research has also been carried out to highlight the prospects of big data analytics as an enabler for the implementation of DM model. Zaki *et al.* (2017) investigated the role of big data in facilitation of RdM in consumer goods industry and proposed a conceptual framework – based on literature review and qualitative analysis of case studies – illustrating interrelationships among big data, co-creation and RdM. Soroka *et al.* (2017) conducted an exploratory survey about the customer and product data generation, storage and analytics for RdM model implementation by manufacturing SMEs (within the UK). The results showed that the current data analytics tools being used by majority of SMEs are not adequate and SMEs seemed ill-equipped to get the potential advantages offered by big data analytics and RdM. Besides big data analytics and digital intelligence, the diffusion of DM methodology into organizational and operational structure of companies requires the development of new business models. The prospects of DM for sustainable food production have also been explored. Gimenez-Escalante and Rahimifard (2018) developed implementation models for distributed localized manufacturing (DLM) of various food products. These models include DLM by manufacturer, DLM by retailer, DLM by food service provider and DLM by consumer. Veldhuis *et al.* (2019) discussed the role of RdM for establishing sustainable and localized food production system in connection with energy and water supply, also known as food–water–energy nexus, by choosing cases of two food products (bread and tomato paste) from engineering, business and policy perspectives. The study concluded that RdM could be a potential model for environmental sustainability, improved quality and local socio-economic development and this methodology would require innovation in technology, business modelling and policies.

DM, as discussed in literature, is a manufacturing paradigm which refers to decentralization of manufacturing operations, reconfigurable manufacturing strategies, novel production technologies, end-user-driven production, innovative digital infrastructure and enhanced consumer participation in product development. The manufacturing in decentralized and geographically dispersed production units represents the localized characteristic of manufacturing and taken as first dimension of DM for the development of the conceptual scale. These localized manufacturing facilities are equipped with new production technologies (e.g. additive manufacturing) which enable flexible production and incorporation of customers input in product specifications to produce customized and personalized products. The induction of new production technologies and bespoke production of personalized products are taken as second and third dimensions of DM, respectively. The literature highlights how the advancements in digital technologies like big data analytics, etc., facilitate the efficiency of production lines on factory floor. These digital technologies generate production data from machines which are then analyzed and integrated into production and maintenance planning systems. Besides production data, the generation, storage and analysis of customer data assist in understanding the consumer/market trends. The installation of digital technologies and infrastructure is considered as fourth dimension of DM. The involvement of customer in product development process at design stage to perform co-creation or co-innovation activities enables high customization. The standard product designs produce standard products while democratization of design, enabled by digital technologies, produces customized designs and products. The democratization of design is taken as fifth dimension. These five dimensions are considered for the development of conceptual scale and further explained below.

2.2.1 Manufacturing localization. Manufacturing localization indicates the presence of manufacturing facilities close to the point of consumption utilizing local resources (energy, labour, material, etc.) for manufacturing operations. This characteristic of DM is listed in all reference studies under different notions of flexible and small-scale production (Johansson *et al.*, 2005), decentralized production (Mourtzis and Doukas, 2012), on or near site manufacturing (DeVor *et al.*, 2012), localization (Moreno and Charnley, 2016; Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016), localized manufacturing (Pearson *et al.*, 2013), local networks (Prendeville *et al.*, 2016), geographical dispersion (Srai, Harrington and Tiwari, 2016) and regionalism (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016). Manufacturing localization is taken as first dimension of DM.

2.2.2 Manufacturing technology. DM is being facilitated by new production technologies (additive manufacturing, etc.) for flexible and on-demand production. The reference studies mentioned the new manufacturing technologies under different titles which include cloud manufacturing (Pearson *et al.*, 2013), new production technologies (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016; Veldhuis *et al.*, 2019), flexible and autonomous operations (DeVor *et al.*, 2012), reconfiguration of processes and resources (Srai, Harrington and Tiwari, 2016), diffusion of new technologies (Prendeville *et al.*, 2016), multifunctional processing and assembly machines (DeVor *et al.*, 2012) and novel innovation process (Zaki *et al.*, 2017). These terms are represented by the notation manufacturing technology and taken as the second dimension of DM.

2.2.3 Customization and personalization. DM is characterized by offering personalized products by incorporating customers' specification into product development process. The potential of offering highly customized products prepared on customer orders (bespoke production) using flexible reconfiguration processes and new production technologies makes DM adaptable to new MC trends. This characteristic is mentioned in the reference studies as MC (DeVor *et al.*, 2012; Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016; Moreno and Charnley, 2016), customer-oriented processes (Mourtzis and Doukas, 2012), bespoke fabrication (Kohtala, 2015), customized/multi-variant products (Pearson *et al.*, 2013), mass and late customisation (Srai, Harrington and Tiwari, 2016) and personalization technologies (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016; Prendeville *et al.*, 2016; Gimenez-Escalante and Rahimifard, 2018; Veldhuis *et al.*, 2019) and is taken as third dimension of DM for the development of conceptual scale.

2.2.4 Digitalization. Digitalization represents the usage of digital technologies in DM operations which facilitates the information flow between process operators, suppliers, customers, etc. The advancements in digital infrastructure (IoT, CPS, etc.) provide a platform for the better integration of production and customisation processes. This characteristic is represented as open digital networks (Prendeville *et al.*, 2016), e-commerce-driven remote sales (Srai, Harrington and Tiwari, 2016), distributed knowledge Moreno and Charnley, 2016), shared services (Veldhuis *et al.*, 2019), automated manufacturing (Mourtzis and Doukas, 2012), big data applications (Zaki *et al.*, 2017) and digitalization (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016) in literature and is taken as fourth dimension.

2.2.5 Democratization of design. The co-creation or co-innovation is the involvement of customer in product development process and becomes feasible due to increased digitalisation of manufacturing operations. The end-user participation in product development at design stage is the fifth characteristic and is defined under the titles of democratization of design (Rauch, Seidenstricker, Dallasega and Hammerl, 2016; Rauch, Dallasega and Matt, 2016), integrated design and innovation (Johansson *et al.*, 2005), co-innovation (Veldhuis *et al.*, 2019), co-creation (Zaki *et al.*, 2017), collaborative and open innovation (Prendeville *et al.*, 2016), multi-user participation (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016) and integrated design (Srai, Harrington and Tiwari, 2016) in literature. The term democratization of design is used as fifth dimension for this study.

2.3 Research gaps

From literature review, it may be inferred that DM concept has been evolved from a network of decentralized and geographically dispersed production units for DE to small-scale, flexible and localized production facilities for the provision of personalized products. The decentralized, localized and on-demand production of customized products ensure the sustainability goals and benefits for the manufacturing companies. This manufacturing paradigm is being driven by advancements in production and digital technologies which are promoting open innovation, enhanced user participation in product development process, sharing of knowledge and circular production and consumption models. The new business models for the diffusion of this manufacturing methodology in different industrial sectors like consumer goods, food production, etc., are being developed to identify the sector-specific opportunities and challenges. In addition to potential sustainability benefits, DM also brings various challenges (of operation, organization, resources, etc.) for the companies. Despite the benefits DMS have, some barriers in applying DMS also exist which include economies of scale and complexity in management of independent production units (Seidenstricker *et al.*, 2017). The outcome of EPSRC workshop identifies availability of skilled labour, sustainable resources, transition from existing businesses, organization and socio-legal structures and establishing of digital infrastructure as emerging issues related to DM which need to be considered in further research (Pearson *et al.*, 2013).

In order to shift from the centralized paradigm to distributed one, the transition process comes with the tasks of cost, quality assurance, process reconfiguration and new organizational structures. The transition from existing business can be initiated once the understanding of company's capability gaps is known. DM offers a means for organizations to create and capture value; however, there are capability gaps like quality assurance and operational skills which need to be addressed in the transformation process (Srai *et al.*, 2016; Srai, Harrington and Tiwari, 2016). A measurement scale is thus needed to measure the existing capability of companies. This study presents the development of the conceptual scale to measure the DM capacity in a manufacturing company. The knowledge of current capacity is helpful to devise the operational strategies and implementation plans required to transform the centralized operations into distributed operations. The five dimensions, identified from literature, are taken as basis for the development of a conceptual scale to measure the DM capacity of manufacturing companies and discussed in detail in the next section.

3. Development of the conceptual scale

The next step is the development of a conceptual scale to evaluate the development level of DM in companies.

As a first step, we propose the use of an ordinal scale to measure the levels of the five DM dimensions, identified from literature. Ordinal scales are used in assessing the attributes of products or services like performing visual controls on manufactured products or assessing the perceived quality of a service (Franceschini *et al.*, 2004, 2015, 2019). The five dimensions are described in detail in the next sub-sections.

3.1 Dimension 1 (D1): manufacturing localization

DM concept has the basic characteristic of geographical dispersion of manufacturing facilities close to the consumer or market. This localization of manufacturing is descried as a "connected, localised and inclusive model of production" (Zaki *et al.*, 2016). This manufacturing arrangement of geographically distributed localized factories – having same technological standards – eliminates the need of long and complex supply chains (Petrulaityte *et al.*, 2017). To implement DLM in practice, Matt *et al.* (2015) presented eight design forms of DP units. The first four forms represent individual evolution stages of decentralized model factories, i.e. standardized and replicable model factory; modular and scalable model factory; flexible and reconfigurable model factory; and changeable and smart model factory, whereas the remaining four forms illustrate other special forms of DP which include service model of industrial contract manufacturing; mobile and non-location-bound model factories; production franchise; and additive manufacturing in production laboratories. Based on these design forms, Rauch, Seidenstricker, Dallasega and Hammerl (2016) and Rauch, Dallasega and Matt (2016) defined five models – micro-production networks, contract manufacturing networks, mobile factory networks, production franchise networks and collaborative cloud manufacturing – as business model clusters of DMS.

These five business model clusters are used in this study to define the levels, from basic to advanced, of the localized manufacturing dimension. The basic level indicates conventional centralized manufacturing, low level corresponds to decentralized model factories and medium level indicates contract manufacturing. The high level consists of production franchise and mobile model factory. Mobile or non-location-bound model factory form is usually associated with construction projects or other defined duration projects and production franchise defines flexible manufacturing systems adaptable to changing customer requirements in different regions. These two forms represent different industries and are placed together as indication of high level of localized manufacturing dimension. The advanced level is associated with collaborative cloud manufacturing. A further description of these levels is given below.

3.1.1 Basic: centralized manufacturing. The central production factories produce products in large quantities in highly automated environment and these products are delivered to end customers through associated supply chains. Central manufacturing structures are less complex to organize than networked decentralized production sites and offer cost advantages in terms of economies of scale (Matt *et al.*, 2015). A centralized production facility has the characteristic of mass production, i.e. manufacturing low-variety products in large volumes, which reduces the production cost. Mass production allows low-cost manufacturing of large volumes of products with limited variety, enabled by dedicated manufacturing systems (Mourtzis and Doukas, 2012). This centralized manufacturing model is taken as a basic level of manufacturing localization dimension for the development of the conceptual scale.

3.1.2 Low: decentralized model factories. This production model offers decentralized and geographically dispersed manufacturing facilities in the consumer or market proximity. The configuration of these networks varies from complete replication and defined factory structures to highly reconfigurable and modular structure-based smart factory. The replication factory unit gives geographical advantage, whereas smart factory further adds the highly self-optimized and adaptable production system features to these networks. Mourtzis *et al.* (2012) developed a discrete event simulation model of automotive manufacturing networks in form of a prototype software tool. The functionality of the tool has been tested utilizing data from a European automotive manufacturer. As a result, the decentralized network shows 4.01 per cent reduced cost, 19.87 per cent reduced lead time and 10.7 per cent less environmental impact as compared to centralized production network.

3.1.3 Medium: contract manufacturing. This model defines the hiring of a specialised manufacturer in the desired location instead of establishing company's own DM unit. This arrangement saves investment of company, improves processes and provides collaboration opportunities to the locally distributed manufacturers to become part of globally extended value chain (Franceschini *et al.*, 2003). Kaipia *et al.* (2010) described the use of integration mechanism to manage the uncertainties in contract manufacturing relationship using case study approach. One of the case companies in this study – a globally operating electronics manufacturer – used contract manufacturing arrangement with different production suppliers to meet the customers demand. This model is taken as medium level of localized manufacturing dimension.

3.1.4 High: production franchise and mobile model factory. This design form shows DM facilities operated independently in various defined regions as franchises. These franchise production networks adopt changeable and flexible manufacturing systems to meet the specific customer requirements in the allocated region or area. Matt and Rauch (2012) introduced a two-stage "master franchising" concept for a European medium-size producer of food. This system allows a so-called master franchisee to purchase the rights to sub-franchise within a certain territory. The franchisor assigns a defined market territory to the master franchisee who then recruits franchisees to open units within this area. The mobile factory networks provide the mobility of complete temporary mini factory set up to the desired location. For short periods, this compact and temporary set up offers the production on desired site. Rauch, Matt and Dallasega (2015) demonstrated the operation of a mobile factory in which a small production cell was developed and installed at the construction site to avoid long transportation. Instead of completing the bending process in Scotland, machining and pre-assembly in Italy and finally installation in UK, the established production cell made it possible to manufacture the product on site and reduced the long transportation. The production franchise and mobile factory models are taken as high level of localized manufacturing dimension for the development of the conceptual scale.

3.1.5 Advanced: collaborative cloud manufacturing. This template of cloud production introduces new concepts and techniques in production. It requires the inclusion of customer in product design process, using of advanced manufacturing technologies (AMTs) (e.g. additive manufacturing) and transferring of product data to distributed locations instead of physical product. The transferring of product data and the use of AMTs at the distributed facility by skilled staff make the production of highly customized and resource efficient products possible. Durao *et al.* (2016) used an applied research approach based on designing, implementing and testing a DM scenario for spare parts. The production of the bottom part of pneumatic cylinder was conducted in this experiment. The scenario implementation was based on low-cost AM technology (FDM machine) and communication technologies (sensors, Arduino, Raspberry Pi, open source software, creating a connected environment using the internet) as the objective of the project was to analyze organizational and process impacts in different use cases. The description of scale levels is summarized in Table II.

3.2 Dimension 2 (D2): manufacturing technology

The second dimension of DM is manufacturing technology. The manufacturing technologies evolved over time and number of advanced technologies have been inducted in production facilities which include computer integrated manufacturing, computer numerical control (CNC) machines, quality control tools and techniques, 3D drawing environment (3D CAD), information and communication technologies (ICT), cloud computing, robotics, IoT and additive manufacturing (Franceschini and Rossetto, 1999; Chen *et al.*, 2015; Schumacher *et al.*, 2016; Liao *et al.*, 2017; Raut *et al.*, 2019). The implementation of these AMTs on factory floor improves production efficiency and are considered as a source of strategic competitive benefits which include improved quality, greater flexibility and productivity (Narkhede, 2017). These advancements in manufacturing technologies are driving and facilitating the implementation of DM model and being considered as enablers for this manufacturing paradigm. The connection of machines in a networked environment can provide the basis to

Manufacturing localization

Name	Centralized manufacturing	Decentralized model factories	Contract manufacturing	Production franchise	Mobile model factory	Collaborative cloud manufacturing
Scale level	Basic	Low	Medium	High		Advanced
Level description	Mass production of high-volume and low-variety products at one location	Manufacturing standardize products in dispersed facilities	Manufacturing products from specialized manufacturer	Outsource flexible manufacturing systems	On site manufacturing facility	Product data transfer and advance manufacturing techniques

Table II. Scale levels of manufacturing localization dimension (Dimension D1) establish an integrated DP system and additive manufacturing may be considered as a central production technology for deploying this system (Durao *et al.*, 2016). The RdM concept involves deploying new technologies (e.g. big data) to facilitate flexible, sustainable and consumer-oriented manufacturing processes (Zaki *et al.*, 2019).

In literature, the term AMTs has been often used to differentiate new manufacturing technologies from the existing ones. Some definitions of these AMTs are listed below: "A group of integrated hardware based and software-based technologies, which if properly implemented, monitored and evaluated will lead to improving the efficiency and effectiveness of the firm in manufacturing a product or providing a service" (Baldwin and Diverty, 1995). "An Automated production system of people, machines and tools for the planning and control of the production process including the procurement of raw materials, parts, components and the shipment and service of finished products" (McDermott and Stock, 1999). "AMT are a group of computer-based technologies including: computer-aided design, robotics, group technology, flexible manufacturing systems, automated material handling systems, storage and retrieval systems, computer numerically controlled machine tools, and bar-coding or other automated identification techniques" (Percival and Cozzarin, 2010). The AMTs are categorized into further sub-groups. Gunawardana (2006) classified AMTs into six groups – processing, fabrication and assembly; automated material handling; design and engineering; inspection and communications; manufacturing information systems; and integration and control. Percival and Cozzarin (2010) divided AMTs into six categories – design and engineering; processing, fabrication and assembly; automated material handling; inspection technology; network communications; and integration and control. Kapitsyn *et al.* (2017) classified AMTs into seven categories – design and engineering; production, processing and assembly; communication and control; automated transportation of materials and parts; automated monitoring equipment; industrial information systems; and integrated management and control.

For the development of a manufacturing technologies ordinal scale, this dimension is divided into four levels, i.e. basic (MT1), low (MT2), medium (MT3) and high (MT4). In each level, the extent of manufacturing technologies is defined by estimating the performance of companies under the six sub-groups of AMTs proposed by Percival and Cozzarin (2010). This categorization of Percival and Cozzarin (2010) is taken to define manufacturing technologies dimension levels as it encompasses all the sub-categories of manufacturing technologies like design (CAD, 3D modelling), processing (CNC machines, additive manufacturing), network (local area network, IoT) and control technologies (SCADA, big data analytics). The required performance merit against these six sub-groups for each scale level is shown in Table III.

3.3 Dimension 3 (D3): customisation and personalization

DM contributes in the development of customized and personalized products and services. The decentralized production facilities equipped with advance production technologies (e.g. additive manufacturing) and enhanced user participation in product development possess the ability to deliver customized products and tailored solutions to diversified customer segments (Kohtala and Hyysalo, 2015; Bessière *et al.*, 2019; Hennelly *et al.*, 2019). Kohtala (2015) conceptualized the DP landscape in four dimensions, i.e. MC, bespoke fabrication, personal fabrication and mass fabrication. In this landscape, mass fabrication (designing and fabrication of unique products by users) and MC (designing and fabrication of modular, personalized products by producer) define DP at larger scale, while bespoke fabrication (designing and fabrication of tailored, individualized products by producer) and personal fabrication (designing and fabrication of unique products by users) at smaller scale. Fox and Li (2012) presented a relationship between authority (opportunity to give design and production inputs) and economy (choice of products with lower price and shorter delivery times)

Manufacturing technologies classification	Manufacturing technologies levels MT1 (basic)	MT2 (low)	MT3 (medium)	MT4 (high)
Design and engineering technologies	Standard designs and design catalogues	Computer-aided design and engineering (CAD/CAE)	Modelling or simulation technologies	Electronic exchange of digital CAD files and prototyping
Processing, fabrication and assembly technologies	Batch production/line production	Flexible manufacturing cells (FMC)/flexible manufacturing systems (FMS)	Computerized numerical control machines and processes	Additive manufacturing technologies
Automated material handling technologies	Manual material handling	Part identification for manufacturing automation	Automated storage and retrieval system (AS/RS)	Automated guided vehicle systems (AGVS)
Inspection technologies	Standard/Manual inspection procedures for finished products	Automated vision-based systems for inspection of inputs/final products	Automated sensor-based systems for inspection of inputs and statistical process control systems for quality control	Virtual reality/augmented reality techniques for inspection and quality control
Network technologies	No network technologies	Local area network (LAN) for engineering/production	Company-wide and inter-company computer networks (WAN, EDI)	Industrial Internet of Things (IIoT) to collect or transfer product data
Integration and control technologies	Computers used for control on factory floor	Computer integrated manufacturing	Supervisory control and data acquisition (SCADA) and digital remote-controlled process plant control	Big data analytics and machine learning

Table III. Levels of manufacturing technologies dimension (Dimension D2) based on Percival and Cozzarin's (2010) categorization

in MC context and defined five scenarios, i.e. make-to-forecast, assemble-to-order, tailor-to-order, engineer-to-order and prosumption. The economy of production decreases and customer authority increases as we move from make-to-forecast to engineer-to-order, whereas prosumption has the characteristics of high authority and high economy. Based on these five customization scenarios, customization and personalization dimension (D3) is categorized into five levels of mass production, MC, bespoke fabrication, personal fabrication and peer production. These levels are discussed below.

3.3.1 Basic: mass production. The term mass production relates to high-volume production rates with very low product variety. Mass production deals with the manufacturing of standardized products according to a specific design in a large facility for a customer group of passive consumers having little or no influence on products' design (Chen *et al.*, 2015). Tuck *et al.* (2008) described the process characteristics in a relationship matrix of product variety and product volume in which mass production is placed at the bottom pertaining to its specific attribute of high product volume and low product variety. Mass production is taken as basic level of customisation and personalization dimension for the development of the conceptual scale.

3.3.2 Low: mass customization. The term mass production relates to high-volume production rates and customization refers to individualized product to meet the specific customer needs. The notion "MC" defines production of customized products in relatively large volume. MC is the efficient integration of customers in flexible, inter-company value creation to create customized products and services at an efficiency equal to that of mass production (Reichwald *et al.*, 2005). MC is a production strategy focussed on the board provision of personalized products and services, mostly through modularized product/service design, flexible processes and integration between supply chain members (Fogliatto *et al.*, 2012). Make-to-forecast is the fabrication of products in bulk by forecasting customer demand and assemble-to-order offers customers the choice of standard or mass custom goods. These two customization categories are taken as low level for this dimension of DM.

3.3.3 Medium: bespoke fabrication. The tailor-to-order and engineer-to-order methodologies – which involve design and production inputs from the customers, but production is accomplished in producer's premises – are termed as bespoke fabrication. These two categories offer customers more authority over design and production specifications as compared to make-to-forecast and assemble-to-order. Kohtala (2015) defined bespoke fabrication in distribution production context as "bespoke fabrication deals with tailored, individualized products in which design and fabrication of products are in hands of the producer". These two customization scenarios are taken as medium level for the customization and personalization dimension.

3.3.4 High: personal fabrication. Personal fabrication is the making of personalized goods using the manufacturing methods and facilities at smaller scale by the consumers themselves. The consumer thus assumes the role of "prosumer", a term coined by Alvin Tofler (1980). Personal fabrication constitutes a network of physical and virtual nodes of design and manufacturing operations that allow agents to design, customize and fabricate products on their own (Malone and Lipson, 2007). The provision of product designs or fabrication services or both by different companies is enabling the production of personalized products at home or at mini factories. Personal fabrication at home (where consumers own a 3D printer) has the capacity to improve the value delivery (part of value proposition) of product as each consumer with a printer becomes a potential distribution channel (Rayna and Striukova, 2016). This customization type is taken as high level for third dimension (D3) of DM.

3.3.5 Advanced: peer production. Peer production is a "prosumption" activity which deals with the involvement of many persons or community to fabricate products at personal level. Commons-based peer production is a new collaborative and distributed form of organization emerging from this new interconnected digital and physical environment of technological-economic feasibility spaces (Kostakis *et al.*, 2015). These technological-economic feasibility spaces – in form of free software, open source knowledge sharing platforms – are diminishing the traditional factory-based production and promoting the trend of open or peer production. The emergence of Web 2.0 and social media led to the development of platforms which follow a variety of organizational models, oscillating between sharing economy, crowdsourcing or commons-based peer production (Rosnay and Musiani, 2016). These peer production platforms work through creation and contribution of users' generated contents. Peer production is taken as advanced level for the customization and personalization dimension. The description of scale levels for this dimension is summarized in Table IV.

Table IV. Levels of customization and personalization dimension (Dimension D3)

Customization and personalization							
Name	Mass Fabrication	Mass customization		Bespoke fabrication		Personal fabrication	Peer production
Scale level	Basic	Low		Medium		High	Advanced
Level description	High-volume, low-variety production	Make-to-forecast	Assemble-to-order	Tailor-to-order	Engineer-to-order	High authority and high economy	Commons-based production

3.4 Dimension 4 (D4): digitalization

The ICT evolution changed the world in the late 1980s and the early 1990s and left a huge impact on manufacturing and process industries. ICT – the collection of primarily digital technologies to gather, organize, store, process and link information within and external to an organization – is a significant source of economic value and important tool in the competitive international economic structure (Kassem *et al.*, 2019). The developments in automation and control techniques assisted these industries to eliminate waste, streamline operations and integrate resources to increase productivity. This progress caused the integration of physical assets at factory floor with communication and information technologies results in the development of CPS. CPS perfectly integrate computation with physical processes, and provide abstractions, modelling, design and analysis techniques for the integrated whole (Wan *et al.*, 2011). The advancements in digital technologies and infrastructure, i.e. big data analytics (Zaki *et al.*, 2019), CPS (Verma *et al.*, 2016) and cloud-based manufacturing (Helo *et al.*, 2014), are enabling and driving the DM paradigm.

The induction of digital technologies (IoT, big data, embedded systems and cloud computing) with production and supply chain operations is changing the manufacturing landscape and termed as a strategic initiative formally known as Industry 4.0. The integration of CPS with production, logistics and services in the current industrial practices would transform today's factories into Industry 4.0 factories with significant economic potential (Lee *et al.*, 2015). In Industry 4.0 research domain, different maturity models have been proposed to implement and track the progress of digitalisation of manufacturing processes. PricewaterhouseCoopers has developed a four-stage and seven-dimension Industry 4.0 maturity model (2016 Global Industry 4.0 Survey, 2016). Schumacher *et al.* (2016) developed Industry 4.0 maturity model which includes 62 maturity items grouped in 9 company dimensions. These dimensions are strategy, leadership, customers, products, operations, culture, people, governance and technology. Qin *et al.* (2016) presented a hierarchical manufacturing framework for Industry 4.0 by combining three intelligence stages (control, integration and intelligence) with three engineering production system stages (machine, process and factory). This framework describes nine intelligence applications for production systems ranges from low intelligence and simple automation to high intelligence and complicated automation.

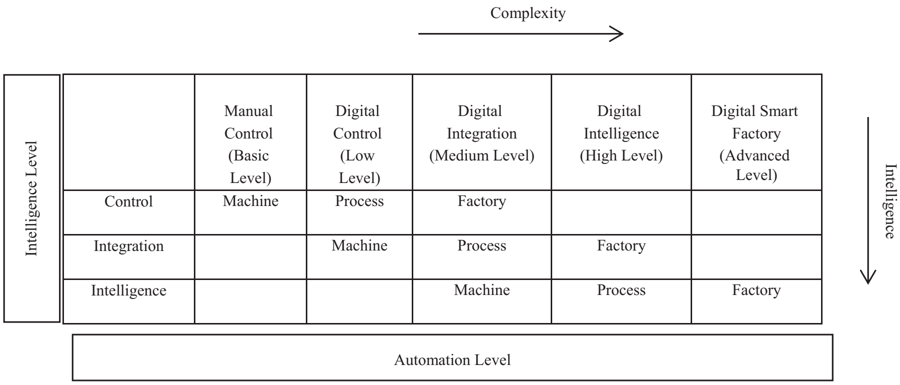
For the development of a conceptual measurement scale, the digitalisation dimension is organized into five levels (basic, low, medium, high and advanced) based on hierarchical framework presented by Qin *et al.* (2016). And the nine applications of digital intelligence are divided among these five levels. These five levels of digitalization dimension are listed below and shown in Figure 1.

3.4.1 Basic: manual control. Manual control is the level of digitalization deals with the machine control. It represents the control of machines by statistical methods like control charts to control the product and process quality.

3.4.2 Low: digital control. The digital control level of digitalization comprises of process control and machine integration. It represents digital control which corresponds to control of manufacturing/production processes like computerized numerical control and integration of machines on factory floor by enterprise resource planning or manufacturing execution systems.

3.4.3 Medium: digital integration. The digital integration of digitalization dimension includes control at factory shop floor, integration of processes and machine intelligence. The example of control at factory floor is the implementation of programme logic controls (PLCs), whereas integration of processes can be exemplified by IoT and machine intelligence by robotics.

3.4.4 High: digital intelligence. The digital intelligence level of digitalization represents integration at factory level and process intelligence. The integration at factory level includes CPS while the process intelligence includes big data analytics and machine learning.



Source: Adapted from Qin *et al.* (2016)

Figure 1.
Digitalization progression (Dimension D4)

3.4.5 Advanced: digital smart factory. The digital smart factory level of digitalization defines intelligence at factory level. This indicates the implementation of major Industry 4.0 aspects, i.e. big data analytics, artificial intelligence, machine learning and advance production technologies like additive manufacturing.

3.5 Dimension 5 (D5): democratization of design

The democratization of design in DM operations is the integration of different design resources, i.e. customers design, design catalogues and third-party design services, in the product development process. The integrated design in distributed resource environment has the features of centring on specific design requirements, organizing related design resources for design activities and outputting design results (Dai *et al.*, 2011). The terms "open innovation" and "co-creation" are often used to define the customer or end-user involvement in product design process (Lettl, 2007; Payne *et al.*, 2009; Wulfsberg *et al.*, 2011). To meet customer needs in the increasingly discontinuous environment, efforts for customer integration in the form of open innovation must be made by utilizing user design and product configurations toolkits in product development (Redlich *et al.*, 2008).

The digitalization of production systems and distributed networks improves the consumer and producer cooperation in product development. The paradigm shift in value creation (individualized production, co-creation experience, etc.) is initiated and driven by new ICT, new manufacturing technologies and decentralized, local and modular production systems (Basmer *et al.*, 2015). This consumer–producer cooperation results in open innovation and co-creation. Open source innovation offers a closer interaction between consumer, designer and producer in which co-creation is busted through shared knowledge (Moreno and Charnley, 2016). The vision of open innovation is that end-users design and create their product using digital design and product development tools (Rauch, Dallinger, Dallasega and Matt, 2015). Collective innovation as well as the terms crowdsourcing and co-creation describes the cooperation of a lot of people to create goods, while their activity is not related to a regular employment (Redlich *et al.*, 2008). The online 3D printing services provide an open source innovation platform where consumers generate, obtain, share and co-produce the designs of their customized products. Rayna *et al.* (2015) described the services of these online platforms into following categories: design supply and hosting; design customization; co-design service; and design crowdsourcing. Design supply and design hosting platforms have design catalogues for customers developed by the platforms host and contributed by third-party designers. Design customization platforms offer services to customers to customize their designs by enlisting their requirements and accordingly giving inputs. Co-design platforms offer the services of converting 2-D image into 3-D product model to users. Consumers can visualize final product model and incorporate further changes by themselves. Design crowdsourcing online platforms work in a manner where users share the details of their project and finalize it with the inputs from the crowd.

For the scale development, democratization of design dimension is categorized into following four levels:

(1) basic: no customer input in design;

(2) low: design supply and design hosting;

(3) medium: design customization; and

(4) high: co-design services and design crowdsourcing.

4. Construction of the conceptual scale

After the description of DM basic dimensions, we may proceed to the construction of the overall DM scale. The DM conceptual scale is developed in two steps:

- Step 1: in this step, we define the DM hyperspace composed by the five DM basic dimensions (Figure 3).
- Step 2: in this step, we perform the construction of some reference profiles. Each profile represents a specific scale element (milestone) of the DM continuum (Figure 4).

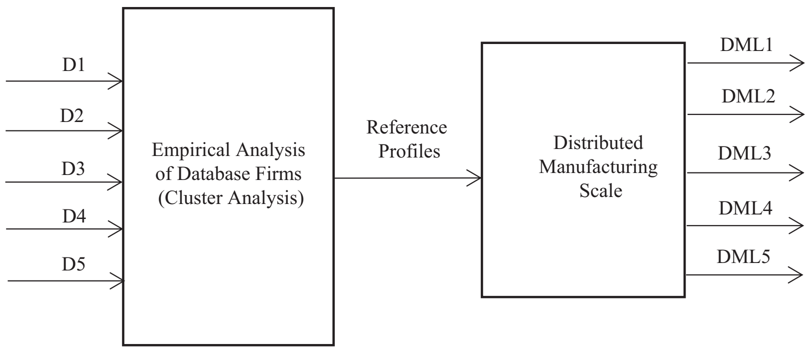
The scheme of the process to build the DM conceptual scale is shown in Figure 2 and the conceptual framework for the construction of a DM scale is show in Figure 3.

4.1 Empirical study for the construction of distributed manufacturing reference profiles

For the construction of the reference profiles, we proceed as follows.

According to the DM basic dimensions, a sample of firms operating in Italian mould making industrial sector (AMAPLAST, 2017) is analyzed in detail.

The database of AMAPLAST was chosen to collect the sample. AMAPLAST is an Italian-based non-profit organization built in 1960 to promote the circulation of Italian plastic and rubber processing technologies. It represents 170 companies operating in



Notes: D1 = localized manufacturing; D2 = manufacturing technologies; D3 = customization and personalization; D4 = digitalization; D5 = democratization of design; DML1 = level 1 (basic); DML2 = level 2 (low); DML3 = level 3 (medium); DML4 = level 4 (high); DML5 = level 5 (advanced)

Figure 2. Scheme of the process to build the distributed manufacturing conceptual scale

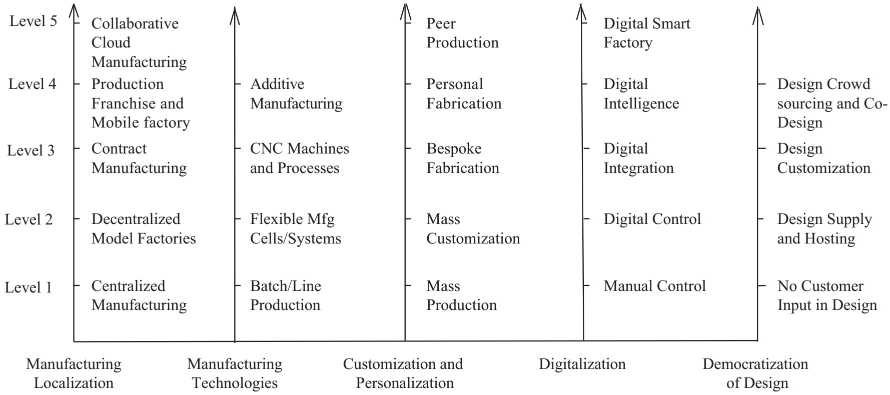


Figure 3.
Conceptual framework for the construction of a distributed manufacturing scale

plastics and rubber machinery, ancillary equipment and mould manufacturing. The database divides the search operation into two options: search by "company name" and search by "machine type". The search by "machine type" further divides the database into groups and sub-groups based on machines application and function.

The following are the main groups categorized in the search option of "machine type":

- Plastics machinery
- Rubber machinery
- Measuring and Control equipment
- Machinery parts and equipment
- Process control technique and Vision systems
- Moulds and Dies
- Plastics and Rubber machinery's reconditioners
- Others

The group of "Moulds and Dies" is selected for this study. A total of 38 companies appeared in search results under this category. The database provides brief introduction of companies and their contact information. The further data about listed companies were collected through secondary resources, i.e. website, annual reports and news articles. A questionnaire (Appendix 1) was made to collect the relative information about each case company. The DM scale is classified on a scale with five levels, i.e. basic, low, medium, high and advance. Each company from the sample is analyzed and assigned one level rank against each DM dimension. The following codification is allocated to the five levels of each DM dimension:

- L1: basic
- L2: low
- L3: medium
- L4: high
- L5: advance

For example, one company from sample, CANTONI, has been assigned the following ranks against the five DM dimensions:

- D1: manufacturing localization = L1

- D2: manufacturing technologies = L3
- D3: customization and personalization = L3
- D4: digitalization = L2
- D5: democratization of design = L2

The results of these assigned level ranks with corresponding codification are shown in Table AII.

4.1.1 *Cluster analysis*. The next step involves the clustering of case companies to identify any similarity or dissimilarity pattern. Clustering technique is useful in segregating groups having similar traits. Franceschini *et al.* (2010) proposed a clustering procedure to cluster similar interviews for the evaluation of water and sewage service quality. The details of cluster analysis are described in Appendix 3.

The companies are sorted in five clusters and level of each DM dimension for these five clusters is assigned by noting the most frequent value. For example, in Cluster 1 the values are as follows:

- D1: manufacturing localization = L2
- D2: manufacturing technologies = L3
- D3: customization and personalization = L3
- D4: digitalization = L3
- D5: democratization of design = L3

The reference profile built from the levels of DM dimensions obtained in Cluster 1 is shown in Figure 4.

These five clusters are then plotted on the conceptual scale and resulted in the generation of five profiles as shown in Figure 5.

These five profiles are considered as reference profiles to measure the status of DM in any generic firm. Each profile represents a specific level (milestone) (DML1 or DML2 or DML3 or DML4 or DML5) of DM continuum. The DM capacity of firms is measured by plotting their respective profiles on the scale. The profile of a firm is plotted according to the respective level (L1–L5) of each dimension present in that firm. These levels are measured

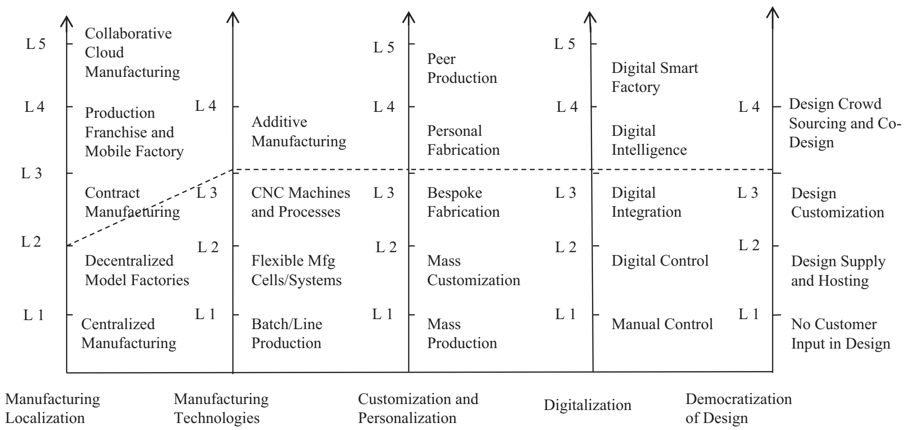


Figure 4.
Reference profile plotted for Cluster 1

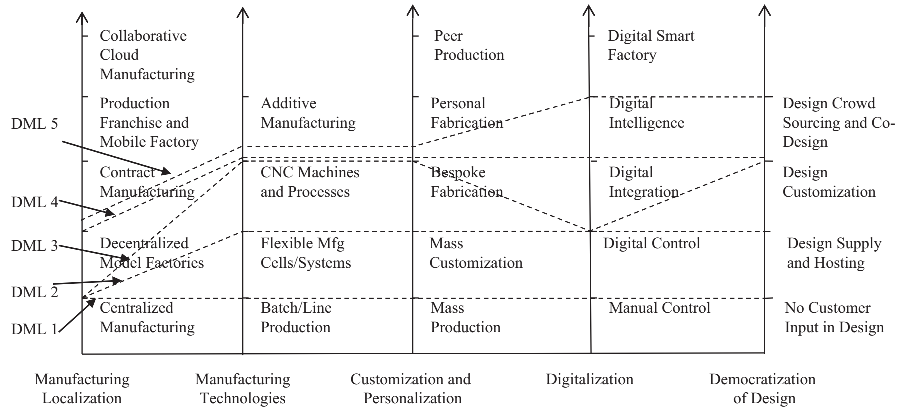


Figure 5.
Reference profiles (i.e. distributed manufacturing scale levels) for distributed manufacturing continuum

based on the corresponding status of each dimension of DM. The plotted profile is then compared with reference profiles to measure the existing DM capacity of the firm.

For example, if the plotted profile of a firm is equal to or close to DML3, it indicates for manufacturing localization the firm stands at Level 1 (centralized manufacturing operations), for manufacturing technologies it is at Level 3 (CNC machines and operations in factory premises), for customization and personalization it stands at Level 3 employing bespoke fabrication of products, for digitalization the firm is at Level 2 utilizing digital control technologies and for democratization of design the firm stands at Level 3 by incorporating design customization for product development. This information explains the current status of DM in the firm to decision makers and identifies the areas need to be addressed for further improvement in the transition process from centralized to decentralized manufacturing operations.

For the DM scale, the five levels are ordered as follows:

$$DML1 < DML2 < DML3 < DML4 < DML5.$$

These are five scale levels to determine the relative positioning of any generic firm operating in plastic and rubber manufacturing sector. Of course, the number of scale level for DM can grow over time with technological increasing. These scale levels are built, based on the empirical evidence obtained from one sector (rubber and plastic manufacturing). The number of these scale levels can also change depending upon the choice of particular industrial sector.

5. Application case studies

With the aim to show the use of the DM conceptual scale, we analyze some application case studies. These case studies are analyzed to determine the positioning of firms with respect to reference profiles on the conceptual scale. This positioning is helpful for firms to assess their current capacity and plan accordingly to adopt DM.

The case examples were structured to capture the information about location of production facility or facilities, the manufacturing technologies employed, extent of product customization, the adopted digital technologies and available design practices. The information about case companies are collected and then compared against the DM dimensions levels and a score is assigned to each of them.

The different levels of each dimension are assigned a numeric value according to the following codification:

- L1: basic level
- L2: low level
- L3: medium level
- L4: high level
- L5: advanced level

The DM status of the case company is then plotted on the conceptual scale and compared against the reference profiles.

The following case studies, representing companies in UK plastic manufacturing sector, were selected for this analysis.

5.1 Case Study 1: One Plastic Group

This case study analyzes a firm which deals in injection and blow moulded plastic products. One Plastic Group deals in injection and blow moulded plastic products for education, automotive, agricultural, construction, waste management, pharmaceutical and material handling markets/sectors through its production facilities in Ireland, the UK and China. The company operates a business model which deals with planning, designing and manufacturing of custom-made plastic products. The company offers integrated service solutions in form of product development and re-engineering and recycled material substitution according to customers' specifications of product, material and application. The company also manufactures its own range of products and offers contract manufacturing services to several companies.

The design process includes customer input of product specifications and rapid prototyping to offer customized solutions. A simulation software Moldflow is also used to simulate the flow of material which assists the design team to make any modifications to the tooling design and identify optimized parameters for product and manufacturing enhancement. The flexible manufacturing processes, automated assembly lines and application of robotics on factory floor in production facilities of this company – some characteristics of an Industry 4.0 factory – ensure better production planning, quality control and in-time delivery of products. Under the Industry 4.0 paradigm, manufacturing consists of exchanged information, controlled machines and production units acting intelligently and autonomously in interoperable (Qin *et al.*, 2016).

The digitalization and automation of factory units, customized product development and production in different geographical locations provide a DM solution to ensure the flexibility and capability for a diversified market of plastic products. The DM dimension levels table and profile of case study firm One Plastic Group are shown in Table V and Figure 6.

In comparison with reference profiles (Figure 5), the DM status of company "One Plastic Group" profile can be associated to DML4.

5.2 Case Study 2: Weltonhurst Limited

This case study analyzes the DM capacity of a firm deals in plastic blow moulded products. Weltonhurst Limited operates a manufacturing facility in the UK and produces blow moulded plastic products for automotive, leisure and healthcare sectors.

Weltonhurst made partnerships with third-party design services companies to better integrate customers requirement in the design process for customized solutions delivery. These specialised companies offer different services to incorporate customers' specifications in product design. These services include computer-aided engineering, simulation software,

Table V. Distributed manufacturing dimensions levels for case company "One Plastic Group"

Dimensions	Distributed manufacturing dimensions levels					Observation	Level score
Manufacturing localization	Mass production in one location	Manufacturing standardized products in dispersed locations	Manufacturing from specialized contractor	Outsource flexible manufacturing and mobilized factories	Product data transfer for remote manufacturing	Production in multiple geographical locations	L2
Manufacturing technologies	Batch/Line production, standard design catalogs, standard inspection techniques	Flexible manufacturing systems, computer-aided design, automated vision-based system for inspection	Computerized numerical control machines, design simulation and modelling, automated sensor-based systems for inspection	Additive manufacturing technologies, rapid prototyping, virtual/augmented reality for inspection		Mould flow process (simulation), prototyping, design FMEA, advanced quality planning techniques	L3
Customization and personalization	High volume and low variety	Make-to-forecast or assemble-to-order	Tailor-to-order or engineer-to-order	High authority and high economy for customer	Commons-based production	Delivering injection moulded products as per customized specifications	L3
Digitalization	Use of control charts	Computerized control and manufacturing execution systems	Programme logic controls, Internet of Things and robotics	Cyber-physical systems and machine learning	Big data analysis and artificial intelligence	Automated injection moulding presses and assembly lines	L3
Democratization of design	Standard design	Design catalogs for selection	Customized design on customer demand	Customer interface for design input		Incorporation of customer input in product design	L3

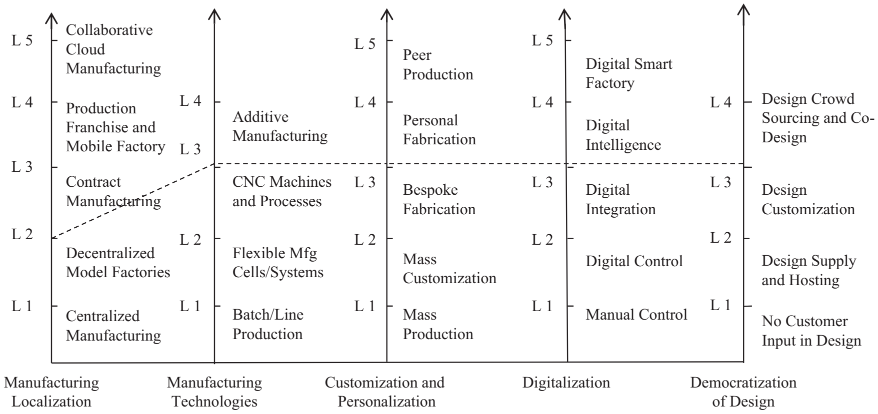


Figure 6.
Positioning of firm "One Group" in the distributed manufacturing framework

process modelling and rapid prototyping with 3D printed models. The integration of customer input in product development process results in better customization. Redlich *et al.* (2008) defined open innovation as an approach for the integration of customers and users along the value creation process and elaborates this approach – in form of customer integration and in form of development activity outsourcing – brings benefits to enterprise through its cost reduction potential.

The contract designing enables Weltonhurst to outsource this product development design process to address specific needs of different industrial sectors. Weltonhurst also sub-contracts the transportation and distribution of finished products to customers for in-time delivery. This distributed arrangement in form outsourcing of design process and last-mile delivery operations to contract firms enables Weltonhurst to focus on its core competency of blow moulding process and offer integrated solutions to its diversified customer base. The DM dimension levels table and profile of case study firm Weltonhurst are shown in Table VI and Figure 7.

In comparison with reference profiles (Figure 5), the DM status of company "Weltonhurst" profile can be associated to DML3.

6. Conclusion

The growing emphasis on sustainability, resource efficiency and minimal waste, makes DM a promising alternative to overcome the barriers of unresponsive supply chains and wastage of scarce resources (Ratnayake, 2019; Hennelly *et al.*, 2019; Tziantopoulos *et al.*, 2019). The today's business environment has become highly volatile and manufacturing companies need to be adaptive to new technologies and changing consumer trends in order to offer customized products and increase their market share. Meanwhile, sustainability considerations are also important to reduce the environmental impact of production, minimizing operational costs and socially more responsive. The highly competitive market, regulatory pressures and consumer awareness compel organizations to improve their social and environmental performance besides financial performance by achieving sustainability in manufacturing practices, supply chain operations and offering sustainable products to market (Brockhaus *et al.*, 2016; Sarkis *et al.*, 2016; Ray and Mondal, 2017). The cornerstones of new sustainable world, including the manufacturing sector, will be new technology, new business models and new lifestyle models (Garetti and Taisch, 2012). In this context, DM paradigm is being researched as a potential methodology to meet the challenges of competitive advantage and sustainability. DM enables sustainability by producing products at or near the consumption point in small, efficient, adaptable and customer-oriented

Table VI. Distributed Manufacturing dimensions levels for case company “Weltonhurst”

Dimensions	Distributed manufacturing dimensions levels					Observation	Level score
Manufacturing localization	Mass production in one location	Manufacturing standardized products in dispersed locations	Manufacturing from specialized contractor	Outsource Flexible manufacturing and mobilized factories	Product data transfer for remote manufacturing	Single production facility for blow moulding products	L1
Manufacturing technologies	Batch/Line production, standard design catalogs, standard/ manual inspection techniques	Flexible manufacturing systems, computer-aided design, automated vision-based system for inspection	CNC machines and processes, design simulation and modelling, automated sensor-based systems for inspection	Additive manufacturing technologies, rapid prototyping, virtual/ augmented reality for inspection		22 diverse size blow moulding machines, Manual finishing and packaging of products, quality control procedures	L2
Customization and personalization	High volume and low variety	Make-to-forecast or assemble-to-order	Tailor-to-order or engineer-to-order	High authority and high economy for customer	Commons-based production	Delivering customized products and bespoke assembly and packaging solutions	L3
Digitalization	Use of control charts	Computerized control and manufacturing execution systems	Programme logic controls, Internet of Things and robotics	Cyber-physical systems and machine learning	Big data analysis and artificial intelligence	Computerized control blow moulding machines, in-house automation	L2
Democratization of design	Standard design	Design catalogs for selection	Customized design on customer demand	Customer interface for design input		Outsourced design services for customer input integration	L3

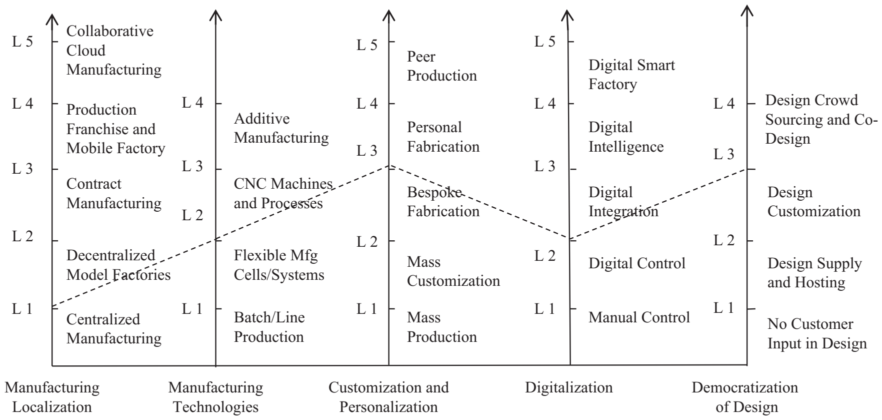


Figure 7.
Positioning of Firm B in the distributed manufacturing framework

production units (Rauch, Dallinger, Dallasega and Matt, 2015). For a manufacturing company, a shift from centralized to distributed paradigm not only brings opportunities in terms of sustainable operations and processes but also poses challenges (of cost, quality and efficiency) in this transition process. The transition process can be initiated once the existing status of DM in the company is well understood and precisely documented.

The development of a conceptual scale is initiated with the identification and selection of DM dimensions from the literature. This analysis is focussed on the scope of DM with respect to location, digital and advanced production technologies and customer involvement. Five dimensions, i.e. manufacturing localization, manufacturing technologies, customization and personalization, digitalization and democratization of design, are identified. Based on these dimensions, a conceptual scale to measure the status of DM in a manufacturing company is proposed. This conceptual scale is developed in two steps. In first step, a hyperspace, based on five dimensions of DM, is developed. A scale is then constructed listing levels of each dimension in an ascending order. Five levels: basic, low, medium, high and advanced are individuated. In a second step, to develop reference profiles on the conceptual scale, a sample of 38 companies operating in Italian mould manufacturing sector is taken and analyzed. The cluster analysis, using hierarchical clustering methodology, is performed to group the companies based on similarity. The findings of empirical data demonstrate the clustering of case companies into five segments based on similarity observed among the five dimensions of DM. The five clusters are represented by reference profiles, i.e. DML1, DML2, DML3, DML4, DML5. And for the DM scale the five reference profiles are ordered as follows:

$$DML1 < DML2 < DML3 < DML4 < DML5.$$

The DML1 profile represents the minimum level of DM, whereas the DML5 indicates the highest level. The DM capacity of companies is the measurement of each dimension level being employed in companies and represented by their respective profiles. The generated profile of a specific company is then compared with the reference profiles to estimate its capacity of DM.

In this paper, two research questions are asked (see Section 1) and the following conclusions can be drawn. As regards the possibility of representing the DP capacity of a company (*RQ1*), a conceptual scale is developed, based on the five dimensions (manufacturing localization, production technologies, personalization and customization, digitalization and democratization of design) that characterize a generic DM. For the second research question (*RQ2*), the relevant positioning of a manufacturing company is determined by the comparison with some specific reference profiles. Each profile represents an element (milestone) of the scale of the DM continuum, constructed through a clustering procedure, based on empirical evidence from rubber and plastic sectors.

Two case studies are conducted to test and verify the developed measurement scale. The dimensions of DM are analyzed with respect to these two case study companies and their corresponding status is plotted on the scale and compared with reference profiles. In comparison with reference profiles DML1, DML2, DML3, DML4 and DML5, the DM status of case Company 1 profile can be associated to DML4 and that of case Company 2 profile can be associated to DML3. This scale is a generalized scale for the measurement of DM status in manufacturing companies.

7. Implications and limitations

7.1 Implications of the research study

The proposed conceptual scale in this study assists mould manufacturing companies operating in rubber and plastic manufacturing sectors to analyze their existing capacity of DM. The existing capacity is determined by measuring DM capabilities in terms of localization, manufacturing technologies, customization and personalization, digitalization and democratization of design. The scale plots the general profile of a manufacturing company in a hyperspace constituted of five dimensions by indicating corresponding level (i.e. L1 or L2 or L3 or L4 or L5) of each dimension. This information helps companies' managers to know the current level of each dimension practiced in their companies and plan the improvement strategies according to the specific requirements of companies' organizational structures and business environment. In the process of adapting DM paradigm and availing the sustainability advantages associated with it, measurement of existing distributed capacity is the first step and this scale is an attempt to perform this measurement.

The developed scale contains five reference profiles (DMLI, DML2, DML3, DML4 and DML5). These reference profiles represent different clusters of manufacturing companies in rubber and plastic sectors. The general profile of a manufacturing company is compared with these reference profiles. The reference profiles are an indication of different levels of DM and comparison with these profiles helps companies to know their relevant level with respect to existing clusters. This comparison leads to the identification of areas to be focussed upon and helpful for decision makers (company owners, consultants, stakeholders, etc.) to formulate the required action plans – of design, digitalization, localization technology and personalization – to convert the existing manufacturing operations into DM ones.

The reference profiles are an indication of practices employed in rubber and plastic sectors. The manufacturing companies can also use this scale as a benchmarking tool to evaluate against the best practice, i.e. the highest DM level represented by the profile DML5.

7.2 Limitations of the research study

The research studies are usually associated with some limitations. The main limitations of this research study are described below. First, the empirical data are collected from Italian mould manufacturing companies operating in rubber and plastic sectors. It cannot be assumed that the industrial sectors in different parts of the world are operating under similar operational, regulatory and economic conditions. The results, therefore, might not be generalized to manufacturing companies operating in different countries (particularly developing countries) under different circumstances. Second, the capacity of DM is assessed from manufacturing point of view only and other aspects like human resource availability, financial constraints, etc., are not considered in this study. The study is focussed on mould manufacturing companies operating in rubber and plastic sectors. Further research work will be conducted by analyzing empirical data from different industrial sectors (e.g. food, automotive, etc.) to consolidate reference profiles in the DM scale.

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Appendix 1

In total, 38 companies are selected for building the distributed manufacturing (DM) conceptual scale. To collect information a questionnaire was built and by going through secondary data the answers of these questions were acquired. These answers are taken as observations to determine the level of DM in case companies.

Dimension	Dimension levels	Questions
Manufacturing localization	Mass production in one location	Are there more than one manufacturing facilities present?
	Manufacturing standardized products in dispersed locations	Manufacturing facilities are operated by same management. Or different managements under product sales or service contract?
	Manufacturing from specialized contractor	Is there any contract/agreement present between management of two or more production facilities? What is the type of this contract?
	Manufacturing by franchise and mobilized factories	Is the production facility location bound? Or Is there any franchise arrangement between different organizations?
	Product data transfer	Is there any product data (CAD digital file) transfer between the production facilities?
Manufacturing technologies	Design and engineering	Which design catalogues or software or modelling techniques are being used?
	Processing and assembly	Which processing technologies (flexible manufacturing, computerized control, additive manufacturing) are being used?
	Material handling	Which manual or automated material handling systems are being used in factory premises?
	Quality control	What inspection technologies (statistical, digital, etc.) are being employed to maintain product and process quality?
	Communication network	Which network technologies have been used for communication within and outside the factory?
	Integration and control	Which integration and control technologies have been installed for process control?
Customization and personalization	High volume and low variety	Are there few standard products being manufactured in large quantities?
	Make-to-forecast and assemble-to-order	How the estimation of customers demand and planning of production accordingly are being done?
	Tailor-to-order and engineer-to-order	Which channel/method is used to incorporate customers input in design process without increasing the cost and delivery time?
	Personal fabrication	Is the company offering product designs and specifications to the customers for manufacturing goods using the manufacturing methods and facilities at their own premises?
	Commons-based production	Is the company offering peer-based service or platforms where customers can get product designs and product manufacturing done from different providers?
Digitalization	Use of control charts	Are there statistical techniques being used for process control?
	Manufacturing execution systems and CNC machines	What types of manufacturing execution system/enterprise resource planning software are being used on factory floor?
	PLCs, IoT and robotics	Are robotics being used in production? Is the production process automated by using programme logic controls?
	Cyber-physical systems and machine learning	Is there any mechanism employed to collect, transmit and analyze production data from factory floor?
	Big data analysis and artificial intelligence	Is there any usage of data collection and algorithms for production planning and control?
Democratization of design	Standard design	How many products' standard designs are being used for production?
	Design catalogues for selection	Does the company offer its own design catalogues or use third-party design catalogues?
	Customized design on customer demand	How customer input in 2D/3D designing is being incorporated? Do customers provide their own product designs or products specification?
	Customer interface for design input	Is there any web-based customer interface developed to allow customer design their own products?

Table AI.
List of questions to identify the levels of distributed manufacturing dimensions

Appendix 2

	Manufacturing Localization					Manufacturing Technologies				Customization and Personalization					Digitalization					Democratization of Design			
	Centralized Manufacturing	Decentralized Model Factories	Contract Manufacturing	Production Franchise and Mobile Factory	Collaborative Cloud Manufacturing	Batch/Line Manufacturing	Flexible Manufacturing Cells/Systems	CNC Machines and Processes	Additive Manufacturing	Mass Production	Mass Customization	Bespoke Fabrication	Personal Fabrication	Peer Production	Manual Control	Digital Control	Digital Integration	Digital Intelligence	Digital Smart Factory	No Customer Input in Design	Design Supply and Hosting	Design Customization	Co-Design
BORGHI		L2						L3				L3					L3					L3	
B-TEC	L1						L2				L2					L2					L2		
CANTONI	L1							L3				L3				L2					L2		
CAPUZZI SYSTEM	L1					L1				L1					L1					L1			
CIMA IMPIANTI	L1						L2				L2				L1					L1			
CMG	L1						L2				L2					L2					L2		
BARUFFALDI	L1							L3				L3					L3					L3	
COMAT	L1							L3				L3					L3						L4
DELIA	L1					L1				L1					L1					L1			
FRIULFILIERE	L1						L2					L3				L2						L3	
GEFIT		L2						L3			L2					L2					L2		
HONESTAMP	L1						L2					L3				L2						L3	
INGLASS		L2						L3				L3						L4				L3	
LTL	L1						L2					L3					L3					L3	
GIMAC	L1					L1				L1					L1					L1			
MARANGONI		L2						L3				L3					L3					L3	
MARA	L1						L2				L2					L2					L2		
MECCANICA GENERALE	L1							L3				L3					L3						L4
MECCANO STAMPI	L1							L3				L3						L4				L3	
NTS		L2						L3				L3				L2						L3	
OMIPA	L1						L2				L2						L3				L2		
OMMP	L1							L3				L3				L2						L3	
OMS BESSER		L2						L3				L3				L2						L3	
PERSICO		L2						L3				L3						L4				L3	
PLAXTECH	L1						L2				L2					L2					L2		
POLIVINIL		L2					L2				L2					L2					L2		
PROFILE DIES	L1					L1				L1					L1					L1			
QS Group		L2						L3				L3						L4				L3	
ROMPLAST	L1						L2				L2					L2					L2		
SACMI		L2						L3				L3						L4				L3	
SIMPLAS	L1						L2				L2					L2					L2		
SIPA		L2						L3				L3					L3						L4
SPM	L1							L3				L3					L3					L3	
T2	L1						L2				L2						L3				L2		
TECNOMATIC	L1						L2				L2					L2					L2		
TERMOSTAMPI		L2						L3				L3				L2						L3	
THERMOPLAY		L2						L3				L3					L3						L4
UNION SPA	L1						L2				L2					L2					L2		

Notes: L1 = basic, L2 = low, L3 = medium, L4 = high, L5 = advanced

Table AII. Level of distributed manufacturing dimensions assigned to case companies

Appendix 3

Cluster analysis

Pandit and Gupta (2011) defined cluster as "a collection of data objects similar to objects within same cluster and dissimilar to those in other clusters" and clustering as "partitioning a set of objects into different subsets such that data in each subset are similar to each other". For cluster analysis, similarity or dissimilarity between two objects is calculated by using distance measurement.

Euclidean distance is the measurement of straight distance between two points and is considered to find similarity between two companies. The Euclidean distance is first calculated between each pair of companies.

Euclidean distance is calculated for the case companies as it is measure of the distance from the centre and in performing the clustering if two companies exist in opposite directions but at similar distance from the centre, they will be placed in the same cluster.

The Euclidean distance between every 2 companies of 38 total companies is calculated by using the following formula:

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

where: x_1 is the localized manufacturing level of Company A; x_2 the manufacturing technology level of Company A; x_3 the customization and personalization level of Company A; x_4 the digitalization level of Company A; x_5 the democratization of design level of Company A; y_1 the localized manufacturing level of Company B; y_2 the manufacturing technology level of Company B; y_3 the customization and personalization level of Company B; y_4 the digitalization level of Company B; and y_5 the democratization of design level of Company B.

For example:

- Company C1: $x_1=2$, $x_2=3$, $x_3=3$, $x_4=3$, $x_5=3$
- Company C2: $y_1=1$, $y_2=2$, $y_3=2$, $y_4=2$, $y_5=2$
- $D=2.24$

These sample companies are then clustered by using hierarchical clustering technique. The complete linkage option is used for hierarchical clustering method in which dissimilarities between pairs of objects in a cluster are less than a specific level.

The software tool Minitab is used for this clustering of case study companies.

The results are shown in Table AIII. The dendrogram of cluster analysis is shown in Figure A1.

Amalgamation steps

The case companies are divided into five clusters as shown in Table AIV. For a sample of 38 companies, a choice of five clusters is taken to avoid few numbers of clusters (three or less) having maximum set of companies and large number of clusters (seven or above) having minimum set of companies.

Step	No. of clusters	Similarity level	Distance level	Clusters joined		New cluster	No. of observations in new cluster
1	37	100.000	0.00000	35	38	35	2
2	36	100.000	0.00000	32	37	32	2
3	35	100.000	0.00000	20	36	20	2
4	34	100.000	0.00000	31	35	31	3
5	33	100.000	0.00000	25	34	25	2
6	32	100.000	0.00000	7	33	7	2
7	31	100.000	0.00000	30	32	30	3
8	30	100.000	0.00000	29	31	29	4
9	29	100.000	0.00000	28	30	28	4
10	28	100.000	0.00000	17	29	17	5
11	27	100.000	0.00000	24	28	24	5
12	26	100.000	0.00000	15	27	15	2
13	25	100.000	0.00000	11	26	11	2
14	24	100.000	0.00000	16	23	16	2
15	23	100.000	0.00000	10	22	10	2
16	22	100.000	0.00000	18	19	18	2
17	21	100.000	0.00000	1	16	1	3
18	20	100.000	0.00000	9	15	9	3
19	19	100.000	0.00000	4	9	4	4
20	18	80.755	1.00000	21	25	21	3
21	17	80.755	1.00000	18	24	18	7
22	16	80.755	1.00000	12	20	12	3
23	15	80.755	1.00000	6	17	6	6
24	14	80.755	1.00000	10	14	10	3
25	13	80.755	1.00000	1	13	1	4
26	12	80.755	1.00000	2	5	2	2
27	11	72.783	1.41421	11	21	11	5
28	10	72.783	1.41421	8	18	8	8
29	9	72.783	1.41421	7	12	7	5
30	8	72.783	1.41421	3	7	3	6
31	7	66.667	1.73205	6	11	6	11
32	6	66.667	1.73205	3	10	3	9
33	5	66.667	1.73205	2	4	2	6
34	4	61.510	2.00000	1	8	1	12
35	3	56.967	2.23607	3	6	3	20
36	2	36.172	3.31662	1	3	1	32
37	1	0.000	5.19615	1	2	1	38

Note: No. of clusters: 5

Table AIII. Clustering of case study companies

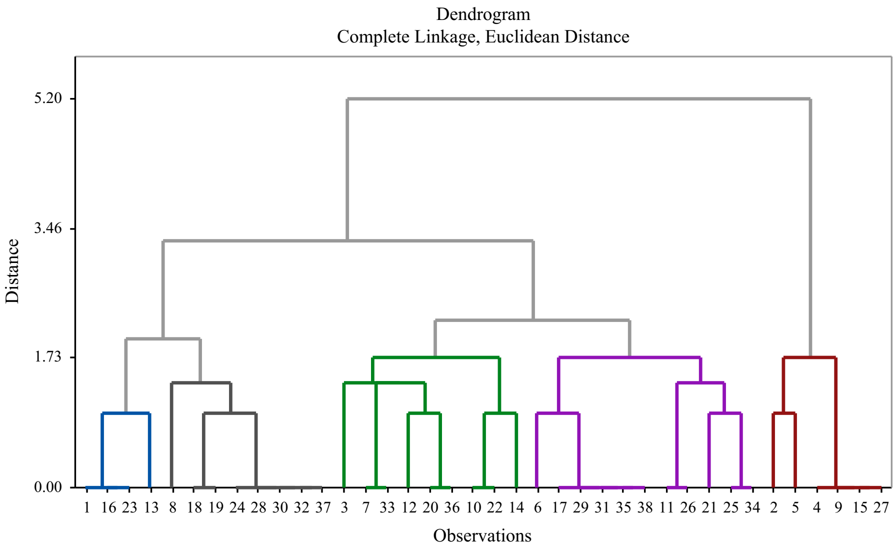

Figure A1.
The dendrogram clustering of the 38 sample companies

	Localized manufacturing	Manufacturing technologies	Customization and personalization	Digitalization	Democratization of design
Cluster 1					
C1	2	3	3	3	3
C16	2	3	3	3	3
C23	2	3	3	3	3
C13	2	3	3	4	3
Final rank	2	3	3	3	3
Cluster 2					
C2	1	2	2	1	2
C5	1	2	2	1	1
C4	1	1	1	1	1
C9	1	1	1	1	1
C15	1	1	1	1	1
C27	1	1	1	1	1
Final rank	1	1	1	1	1
Cluster 3					
C3	1	3	3	2	2
C7	1	3	3	3	3
C33	1	3	3	3	3
C12	1	3	3	2	3
C20	2	3	3	2	3
C36	2	3	3	2	3
C10	1	2	3	2	3
C22	1	2	3	2	3
C14	1	2	3	3	3
Final rank	1	3	3	2	3
Cluster 4					
C6	1	3	2	2	2
C17	1	2	2	2	2
C29	1	2	2	2	2
C31	1	2	2	2	2
C35	1	2	2	2	2
C38	1	2	2	2	2
C11	2	3	2	3	2
C21	1	3	2	3	2
C26	2	3	2	3	2
C25	1	2	2	3	2
C34	1	2	2	3	2
Final rank	1	2	2	2	2
Cluster 5					
C8	1	2	3	4	4
C18	1	3	3	4	4
C19	1	3	3	4	3
C24	2	3	3	4	4
C28	2	3	3	4	4
C30	2	3	3	4	4
C32	2	3	3	3	4
C37	2	3	3	4	4
Final rank	2	3	3	4	4

Table AIV.
Classification of case companies in clusters

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