Distributed Manufacturing: proposal for a conceptual scale based on empirical evidences in the rubber and plastic sectors

DISTRIBUTED MANUFACTURING: PROPOSAL FOR A CONCEPTUAL SCALE BASED ON EMPIRIAL EVIDENCES 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 distributed manufacturing 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 analysed to show the use of the proposed distributed manufacturing conceptual scale.

Findings:

A hyperspace, composed of five dimensions of distributed manufacturing i.e. (i) manufacturing localization, (ii) manufacturing technologies, (iii) customization and personalization, (iv) digitalization and (v) 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 distributed manufacturing continuum.

Originality / Value:

This is first preliminary scale of its kind to evaluate the positioning of companies with respect to their distributed manufacturing 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, Manufacturing continuum, Localized production, Firm's distributed capacity, Decentralized manufacturing

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 lifecycle (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 et al. 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 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 (Huer et al. 2018) and distributed manufacturing (Srai et al. 2016). Distributed manufacturing is considered as one of many production strategies for manufacturing companies to achieve their sustainability targets and objectives. Distributed manufacturing 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 et al. 2016). Distributed manufacturing as a promising production model for sustainable operations and the organizational capabilities required for its implementation is discussed in this study.

Distributed manufacturing 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 customised products and adaptation of new production technologies (e.g. additive manufacturing) in a digitized environment make distributed manufacturing 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 & Blome, 2019; Toimiklis & Makatsoris, 2019). Centralized manufacturing lacks these sustainability benefits associated with distributed manufacturing 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 (Gwamuri et al. 2014).

Distributed manufacturing has been discussed in literature as a potential approach to achieve sustainability objectives i.e. sustainable production in emerging markets (Rauch et al. 2016), environmental sustainability of distributed production (Kohtala, 2015), distributed manufacturing potential to contribute to a sustainable and resilient city (Freeman et al. 2017) and sustainable product-service system implementation through distributed manufacturing (Petrulaityte et al. 2017). However, little research has been completed to demonstrate how manufacturing companies can measure their capacity to adapt distributed manufacturing as a production methodology to avail the sustainability benefits associated with it. The opportunities and challenges of distributed manufacturing need to be explored by answering the questions about learning capabilities of organizations and management of localised production models (Moreno and Charnley, 2016). The transition of existing businesses and organizations into a distributed manufacturing structure is one of the issues which needs 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). Two research questions are investigated in this study:

RQ1: How can the existing distributed manufacturing capacity of a manufacturing company be represented?

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

For this purpose, a preliminary conceptual scale is developed to represent the distributed manufacturing capacity and positioning of a manufacturing company in the distributed manufacturing continuum. This capacity measurement and positioning of company are helpful for decision makers to identify and address the relevant areas in the process of distributed manufacturing adaptation. The scale is developed through identification of distributed manufacturing dimensions from literature and the empirical data collected from Italian mould manufacturing sector. The scale is based on distributed manufacturing reference profiles and the distributed manufacturing capacity of a firm is measured by the comparison of its positioning with the reference profiles. The structure of the paper is described as: 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: distributed manufacturing, distributed manufacturing dimensions and research gaps.

2.1 Distributed Manufacturing

Distributed manufacturing concept has been discussed in Literature under different notations including distributed manufacturing (DM) (Srai et al. 2016), distributed manufacturing systems (DMS) (Rauch et al. 2016), distributed production (DP) (Kohtala, 2015), distributed economies (DE) (Johnson, 2005), and re-distributed manufacturing (RdM) (Pearson et al. 2013). The distributed manufacturing (DM) term has been used in different contexts and evolved over the period. Seregni et al. (2015) described the evolution of distributed manufacturing 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, Zah and Wagner 2003, Buckley and Ghauri 2004, Reichwald et al. 2005) to a network of collaborative organizations complementing each other in skills and resources (Wiendahl and Lutz 2002, Camarinha-Matos 2009, Mourtzis el 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 Distributed manufacturing systems (DMS), defined as a class of manufacturing systems, focused on the internal manufacturing control and characterised by common properties (e.g. autonomy, flexibility, adaptability, agility, decentralisation).

Distributed manufacturing concept is being researched to explore its potential as a manufacturing methodology that employs decentralised 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 centralised 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 (incorporating customers demand to produce high variety products) to distributed manufacturing (offering personalised and bespoke products) (Mourtzis and Doukas 2012; Srai et al. 2016). This transformation is being facilitated by advancements in novel production technologies (Durao et al. 2016), digitalization by cyber-physical systems and internet of things (Yew et al. 2016) and an emphasis on local economies for sustainable development (Freeman et al. 2017). Distributed manufacturing is thus characterized by location, flexibility, production technology, customization, digital technologies, 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 distributed manufacturing, presented in literature, is given in Table 1.

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

2.2 Dimensions of Distributed Manufacturing

For the identification of distributed manufacturing dimensions / characteristics, the literature has been explored. The research databases like Scopus, Emerald insight, Google Scholar and Science Direct have been searched with key words distributed manufacturing, re-distributed manufacturing, distributed production and distributed manufacturing systems to look for the relevant material about dimensions of distributed manufacturing. In Table 1 gives a summary of papers published in distributed manufacturing research area. It highlights different contexts addressed in these research studies. Distributed manufacturing 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), sustainability (Rauch et al. 2016; Kohtala, 2015), circular innovation & economy (Moreno and Charnley, 2016; Prendeville et.al 2016), supply chain (Srai et al. 2016b), 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 1, detailing a set of conceptual dimensions of distributed manufacturing paradigm, have been discussed below.

Johansson et al. (2005) presented the concept of distributed economies for sustainable industrial growth which described the transformation of centralised large-scale production units to decentralized small-scale, flexible and connected units. The proposed distributed economies 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 scales 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 mass customization offers personalised 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 distributed manufacturing 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, distributed manufacturing is considered as a potential strategy for sustainable manufacturing operations. Rauch et al. (2016) discussed distributed manufacturing systems (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 distributed manufacturing systems. These trends include sustainability, rising logistics cost, mass customization, democratization of design, market/consumer proximity and regionalism & authenticity. Kohtala (2015) conducted an integrated literature review about environmental sustainability of distributed production 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 distributed manufacturing 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 ESPRC (Engineering and Physical Sciences Research Council) workshop on re-distributed manufacturing. The workshop identified four core fields i.e. geographies of manufacturing, enabling production technologies, new models of economics, business, investment & quality and regulation & legislation as potential research themes in the context of re-distributed manufacturing. Srai et al. (2016) performed a cross-case analysis, consisting of six case companies, to identify the challenges and opportunities associated with distributed manufacturing in terms of customization, digital infrastructural developments (Internet of things, big data), and new production technologies. This analysis concluded distributed manufacturing as a new paradigm having decentralized, autonomous, flexible and customer driven production activity in its proximity opposed to centralised, large-scale, forecast-driven manufacturing of products in large volumes. In another study, Srai et al. (2016b) explored the characteristics of redistributed manufacturing systems within the context of emerging industry supply networks (EI SNs) through cross case analysis of six industrial systems (defence aerospace, maritime cluster, built environment, industrial biotechnology, photovoltaic, 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 re-distributed manufacturing and circular innovation drivers. It was concluded that integration of digital intelligence has leveraged the decentralised, re-distributed and circular models of production and consumption through distribution of knowledge, structure, ownership and different customisation levels. The case studies were then analysed against the criteria defined for re-distributed manufacturing 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 redistributed manufacturing (smaller-scale, localised, customizable production units) and identified opportunities to combine makespaces with circular economy through redistributed manufacturing. The modelling techniques were also used to assess the potential of distributed manufacturing in consumers goods industry. To demonstrate the use of re-distributed manufacturing and product-service system (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 re-distributed manufacturing. 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 (SD) modelling in which data-driven decisions have been used to simulate different re-distributed manufacturing scenarios. In another study of business model development to support the diffusion of distributed production, Seidenstricker et al (2017) used business model engineering approach and designed a business model for distributed manufacturing systems (DMS) based on four core elements (value proposition, value chain & processes, revenues and technologies, competencies & key resources) and a three level (designing, planning, 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 distributed manufacturing model. Zaki et al. (2017) investigated the role of big data in facilitation of redistributed manufacturing in consumer goods industry and proposes a conceptual framework – based on literature review and qualitative analysis of case studies – illustrating interrelationships among big-data, co-creation and redistributed manufacturing. Soroka et al. (2017) conducted an exploratory survey about the customer and product data generation, storage and analytics for re-distributed manufacturing model implementation by manufacturing SMEs (within the United Kingdom). 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 re-distributed manufacturing. Besides big data analytics and digital intelligence, the diffusion of distributed manufacturing methodology into organizational and operational structure of companies requires the development of new business models. The prospects of distributed manufacturing for sustainable food production have also been explored. Gimenez-Escalante and Rahimifard (2018) developed implementation models for distributed localised 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 re-distributed manufacturing for establishing sustainable and localised 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 re-distributed manufacturing 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.

Distributed manufacturing, as discussed in literature, is a manufacturing paradigm 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 represent the localized characteristic of manufacturing and taken as first dimension of distributed manufacturing 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 distributed manufacturing 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 is then analysed 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 distributed manufacturing. The involvement of customer in product development process at design stage to perform co-creation or co-innovation activities enable high customization. The standard product designs produce standard products while democratization of design, enabled by digital technologies, produce 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:

(1) Manufacturing Localisation

Manufacturing localization indicates the presence of manufacturing facilities close to the point of consumption utilising local resources (energy, labour, material etc) for manufacturing operations. This characteristic of distributed manufacturing is listed in all reference studies under different notions of flexible and small-scale production (Johnson et al. 2005), decentralized production (Mourtzis and Doukas, 2012), on or near site manufacturing (DeVor et al. 2012), localisation (Moreno and Charnley, 2016; Srai et al. 2016), localised manufacturing (Pearson et al. 2013), local networks (Prendeville et al. 2016), geographical dispersion (Srai et al. 2016b) and regionalism (Rauch et al. 2016). Manufacturing localisation is taken as first dimension of distributed manufacturing.

(2) Manufacturing Technology

Distributed manufacturing 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; Veldhuis et al. 2019), flexible and autonomous operations (DeVor et al. 2012), reconfiguration of processes and resources (Srai et al. 2016b), diffusion of new technologies (Prendeville et al. 2016), multifunctional processing & 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 distributed manufacturing.

(3) Customisation and Personalisation

Distributed manufacturing is characterized by offering personalised products by incorporating customers specification into product development process. The potential of offering highly customised products prepared on customer orders (bespoke production) using flexible reconfiguration processes and new production technologies, makes distributed manufacturing adaptable to new mass customization (MC) trends. This characteristic is mentioned in the reference studies as mass customisation (DeVor et al. 2012; Rauch et al. 2016; Moreno and Charnley, 2016), customer-oriented processes (Mourtzis and Doukas, 2012), bespoke fabrication (Kohtala, 2015), customised / multi variant products (Pearson et al. 2013), mass & late customisation (Srai et al. 2016b) and personalisation technologies (Srai et al. 2016; Prendeville et al. 2016; Gimenez-Escalante and Rahimifard, 2018; Veldhuis et al. 2019) and is taken as third dimension of distributed manufacturing for the development of conceptual scale.

(4) Digitalisation

Digitalization represents the usage of digital technologies in distributed manufacturing operations which facilitates the information flow between process operators, suppliers, customers etc. The advancements in digital infrastructure (Internet of things, cyber-physical systems 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 et al. 2016b), 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) in literature and is taken as fourth dimension.

(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 et al. 2016), integrated design & innovation (Johnson et al. 2005), co-innovation (Veldhuis et al. 2019), co-creation (Zaki et al. 2017), collaborative & open innovation (Prendeville et al. 2016), multi-user participation (Srai et al. 2016) and integrated design (Srai et al. 2016b) 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 distributed manufacturing concept has been evolved from a network of decentralized and geographically dispersed production units for distributed economies to small scale, flexible and localized production facilities for the provision of personalised 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, distributed manufacturing also brings various challenges (of operation, organization, resources etc) for the companies. Despite the benefits distributed manufacturing systems (DMS) 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 ESPRC workshop identifies availability of skilled labour, sustainable resources, transition from existing businesses, organization & socio-legal structures and establishing of digital infrastructure as emerging issues related to distributed manufacturing 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 organisational structures. The transition from existing business can be initiated once the understanding of company's capability gaps is known. Distributed manufacturing offers a means for organisations 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). 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 distributed manufacturing 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 distributed manufacturing capacity of manufacturing companies and discussed in detail in the next section.

Table 1: List of distributed manufacturing definition and conceptual dimensions listed in literature

Authors	Year	Context	Definitions	Dimensions
Johnson 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 & open innovation, Flexible & small-scale production, No producer - consumer relationship, Integrated design & innovation, Collaboration & collective spirit, Balance between intra-regional & inter-regional exchange of resources, symbiosis of small- & large-scale production systems
Mourtzis & 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 & 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 et al	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 & Charnley	2016	Circular Innovation	"The shift from centralized to decentralized manufacture with the aim to create a more resilient and connected 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"	Localization, Customization, Distributed knowledge, Distributed structure, Distributed ownership
Srei et al	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	Open digital networks, Collaborative and open innovation, Diffusion of new technologies, Personalization and customization, Prosumption, Local networks and Social

			smaller-scale, localized, customizable production units, largely drive by new additive digital production technologies"	interactions, Sharing knowledge & skills, Reshoring of manufacturing
Srei et al	2016b	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 & 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

3. Development of the Conceptual Scale

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

As a first step, we propose the use of an Ordinal scale to measure the levels of the five distributed manufacturing 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

Distributed manufacturing 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 – eliminate the need of long and complex supply chains (Petrulaityte et al. 2017). To implement distributed localized manufacturing in practice, Matt et al. (2015) presented eight design forms of distributed production units. The first four forms represent individual evolution stages of decentralized model factories i.e. (i) standardized and replicable model factory (ii) modular and scalable model factory (iii) flexible and reconfigurable model factory (iv) changeable and smart model factory, whereas the remaining four forms illustrate other special forms of distributed production which include (v) service model of industrial contract manufacturing (vi) mobile and non-location-bound model factories (vii) production franchise and (viii) additive manufacturing in production laboratories. Based on these design forms, Rauch et al. (2016) defined five models – (a) micro production networks (b) contract manufacturing networks (c) mobile factory networks (d) production franchise networks and (e) collaborative cloud manufacturing – as business model clusters of distributed manufacturing systems.

These five business model clusters are used in this study to define the levels, from basic to advanced, of the localised manufacturing dimension. The basic level indicates conventional centralised manufacturing, low level corresponds to decentralised 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 localised 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 term 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 decentralised 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-optimised and adaptable production system features to these networks. Mourtzis et al. (2012) developed a discrete event simulation models 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% reduced cost, 19.87% reduced lead time and 10.7% 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 distributed manufacturing unit. This arrangement saves investment of company, improve 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 distributed manufacturing 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 et al. (2015b) 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 (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 advanced manufacturing technologies at the distributed facility by skilled staff, make the production of highly customised and resource efficient products possible. Durdo et al. (2016) used an applied research approach based on designing, implementing, and testing a distributed manufacturing 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 analyse organizational and process impacts in different use cases. The description of scale levels is summarized in Table 2.

Table 2: Scale levels of manufacturing localization dimension (Dimension D1)

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 & 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 & Advance manufacturing techniques

3.2 Dimension 2 (D2): Manufacturing Technology

The second dimension of distributed manufacturing 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 (CIM), computer-numerical control (CNC) machines, quality control tools and techniques, 3D drawing environment (3D CAD), information and communication technologies (ICT), cloud computing, robotics, internet of things (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 advanced manufacturing technologies on factory floor improves production efficiency and are considered as a source of strategic competitive benefits which include improved quality, greater flexibility and productivity (Narkhade, 2017). These advancements in manufacturing technologies are driving and facilitating the implementation of distributed manufacturing model and being considered as enablers for this manufacturing paradigm. The connection of machines in a networked environment can provide the basis to establish an integrated distributed production system and additive manufacturing may be considered as a central production technology for deploying this system (Durao et al. 2016). The re-distributed manufacturing 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 Advanced Manufacturing Technologies (AMT) 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 advanced manufacturing technologies are categorized into further sub-groups. Gunawardana (2006) classified advanced manufacturing technologies into six groups – (a) processing, fabrication and assembly (b) Automated material handling (c) Design and engineering (d) Inspection and communications (e) Manufacturing information systems (f) Integration and control. Percival and Cozzarin (2010) divided advanced manufacturing technologies into six categories – (a) design and engineering (b) processing, fabrication and assembly (c) automated material handling (d) inspection technology (e) network communications (f) integration and control. Kapitsyn et al. (2017) classified advanced manufacturing technologies into seven categories – (a) design and engineering (b) production, processing and assembly (c) communication and control (d) automated transportation of materials and parts (e) automated monitoring equipment (f) industrial information systems (g) 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 advance manufacturing technologies (AMT) 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, internet of things) and control technologies (SCADA, big data analytics). The required performance merit against these six sub-groups for each scale level is shown in Table 3.

Table 3: Levels of manufacturing technologies dimension (Dimension D2) based on Percival and Cozzarin categorization (2010)

Manufacturing Technologies Classification	**Manufacturing Technologies Levels**			
	MT 1 (Basic)	MT 2 (Low)	MT 3 (Medium)	MT 4 (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 (CNC) 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

3.3 Dimension 3 (D3): Customisation and Personalisation

Distributed manufacturing contributes in the development of customised and personalised products and services. The decentralised production facilities equipped with advance production technologies (e.g. additive manufacturing) and enhanced user participation in product development possess the ability to deliver customised products and tailored solutions to diversified customer segments (Kohtala and Hyysalo, 2015; Bessiere et al. 2019;

Hannelly et al. 2019). Kohtala (2015) conceptualized the distributed production landscape in four dimensions i.e. mass customization, bespoke fabrication, personal fabrication and mass fabrication. In this landscape, mass fabrication (designing and fabrication of unique products by users) and mass customization (designing and fabrication of modular, personalized products by producer) define distributed production 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) in mass customization 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, mass customization, 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 personalisation 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 individualised product to meet the specific customer needs. The notion 'mass customization' defines production of customized products in relatively large volume. Mass customization 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). Mass customization is a production strategy focused 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 distributed manufacturing.

3.3.3 Medium: Bespoke Fabrication

The tailor-to-order and engineer-to-order methodologies - which involves design and production inputs from the customers, but production is accomplished in producer's premises – is 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 (2012) 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 personalisation dimension.

3.3.4 High: Personal Fabrication

Personal fabrication is the making of personalised 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 Toffler in 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 personalised 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 distributed manufacturing.

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 personalisation dimension. The description of scale levels for this dimension is summarized in Table 4.

Table 4: Levels of customization and personalization dimension (Dimension D3)

<table>
<tr><th colspan="8">Customization and Personalization</th></tr>
<tr><td>Name</td><td>Mass Fabrication</td><td colspan="2">Mass Customization</td><td colspan="2">Bespoke Fabrication</td><td>Personal Fabrication</td><td>Peer Production</td></tr>
<tr><td>Scale Level</td><td>Basic</td><td colspan="2">Low</td><td colspan="2">Medium</td><td>High</td><td>Advanced</td></tr>
<tr><td>Level Description</td><td>High volume, Low variety production</td><td>Make to forecast</td><td>Assemble to order</td><td>Tailor to order</td><td>Engineer to order</td><td>High authority & High economy</td><td>Commons based production</td></tr>
</table>

3.4 Dimension 4 (D4): Digitalization

The Information and communication technology (ICT) evolution changed the world in late 80s and early 90s 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 cyber-physical systems. Cyber-physical systems (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), cyber physical systems (Verma et al. 2016) and cloud-based manufacturing (Helo et al. 2014), are enabling and driving the distributed manufacturing paradigm.

The induction of digital technologies (internet of things, big data, embedded systems, 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 (Wang et al. 2015). The integration of cyber physical systems 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 (PwC) has developed a four-stages and seven-dimensions Industry 4.0 maturity model (2016 Global Industry 4.0 Survey). 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, 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, 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 (CNC) and integration of machines on factory floor by ERP (Enterprise Resource Planning) or Manufacturing execution systems.

3.4.3 Medium: Digital Integration

The digital integration of digitalization dimension includes of control at factory shop floor, integration of processes and machine intelligence. The example of control at factory floor is the implementation of program logic controls (PLCs) whereas integration of processes can be exemplified by Internet of things 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 Cyber physical systems (CPS) while the process intelligence includes Big data analytics and Machine learning.

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.

Complexity

	Manual Control (Basic Level)	Digital Control (Low Level)	Digital Integration (Medium Level)	Digital Intelligence (High Level)	Digital Smart Factory (Advanced Level)
Control	Machine	Process	Factory		
Integration		Machine	Process	Factory	
Intelligence			Machine	Process	Factory

Intelligence Level

Intelligence

Automation Level

Figure 1: Digitalization progression (adapted from Qin et al. 2016) (Dimension D4)

3.5 Dimension 5 (D5): Democratization of Design

The democratization of design in distributed manufacturing operations is the integration of different design resources i.e. customers design, design catalogues, 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 improve 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 information and communication technologies (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 et al. 2015). Collective innovation as well as the terms crowd sourcing 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) describes the services of these online platforms into following categories: (a) Design supply and hosting (b) Design customization (c) Co-design service (d) Design crowd sourcing. 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 crowd sourcing 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:

Basic: No Customer input in Design
Low: Design supply and Design hosting

Medium: Design customization
High: Co-design services and Design crowd sourcing

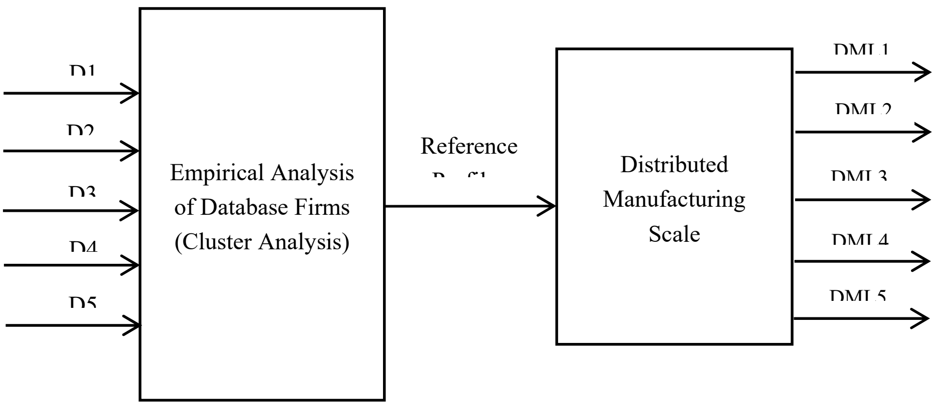
4. Construction of the Conceptual Scale

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

Step 1
In the first step, we define the distributed manufacturing hyperspace composed by the five distributed manufacturing basic dimensions (Figure 3).

Step 2
In the second step, we perform the construction of some reference profiles. Each profile represents a specific scale element (milestone) of the distributed manufacturing continuum (Figure 4).

The scheme of the process to build the distributed manufacturing conceptual scale is shown in the Figure 2 and the way how the reference profiles are built is described in section 3.7.



D1 = Localized Manufacturing
D2 = Manufacturing Technologies
D3 = Customization & 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

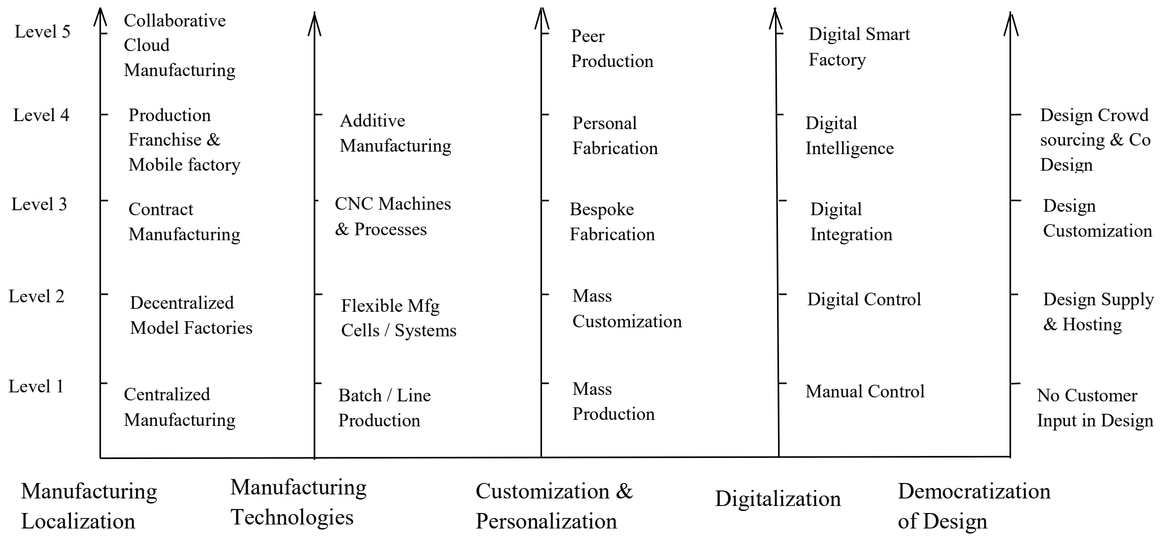


Figure 3: Conceptual framework for the construction of a distributed manufacturing scale

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 distributed manufacturing (DM) basic dimensions, a sample of firms operating in Italian Mould making industrial sector (AMAPLAST, 2017) is analysed 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 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 categorised in the search option of 'machine type':

(i) Plastics machinery
(ii) Rubber machinery
(iii) Measuring and Control equipment
(iv) Machinery parts and equipment
(v) Process control technique and Vision systems
(vi) Moulds and Dies
(vii) Plastics and Rubber machinery's reconditioners
(viii) 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 was collected through secondary resources i.e. website, annual reports and news articles. A questionnaire (Appendix A) was made to collect the relative information about each case company. The distributed manufacturing scale is classified on a scale with five levels i.e. basic, low, medium, high and advance. Each company from the sample is analysed and assigned one level rank against each DM dimension. The following codification is allocated to the five levels of each distributed manufacturing 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 & personalization = L3
D4: Digitalization = L2
D5: Democratization of design = L2

The results of these assigned level ranks with corresponding codification are shown in Appendix B.

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 C.

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

D1: Manufacturing localization = L2
D2: Manufacturing technologies = L3
D3: Customization & personalization = L3
D4: Digitalization = L3
D5: Democratization of design = L3

The reference profile built from the levels of distributed manufacturing dimensions obtained in cluster 1 is shown in Figure 4.

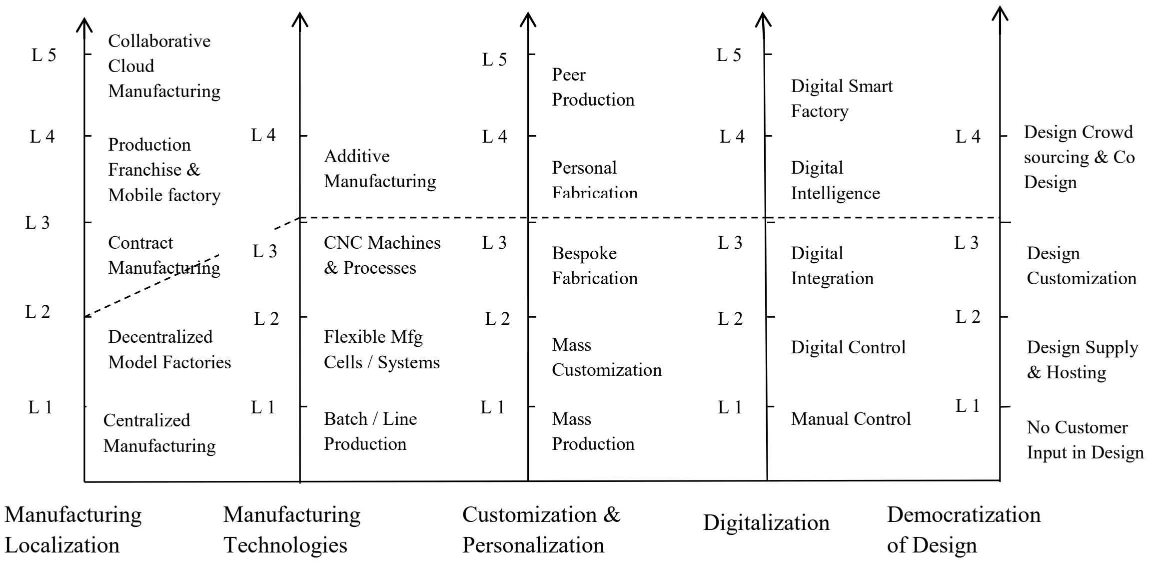


Figure 4: Reference profile plotted for cluster 1

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

These five profiles are considered as reference profiles to measure the status of distributed manufacturing in any generic firm. Each profile represents a specific level (milestone) (DML1 or DML2 or DML3 or DML4 or DML5) of distributed manufacturing continuum. The distributed manufacturing 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 based on the corresponding status of each dimension of distributed manufacturing. The plotted profile is then compared with reference profiles to measure the existing distributed manufacturing 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 distributed manufacturing 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 distributed manufacturing 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.

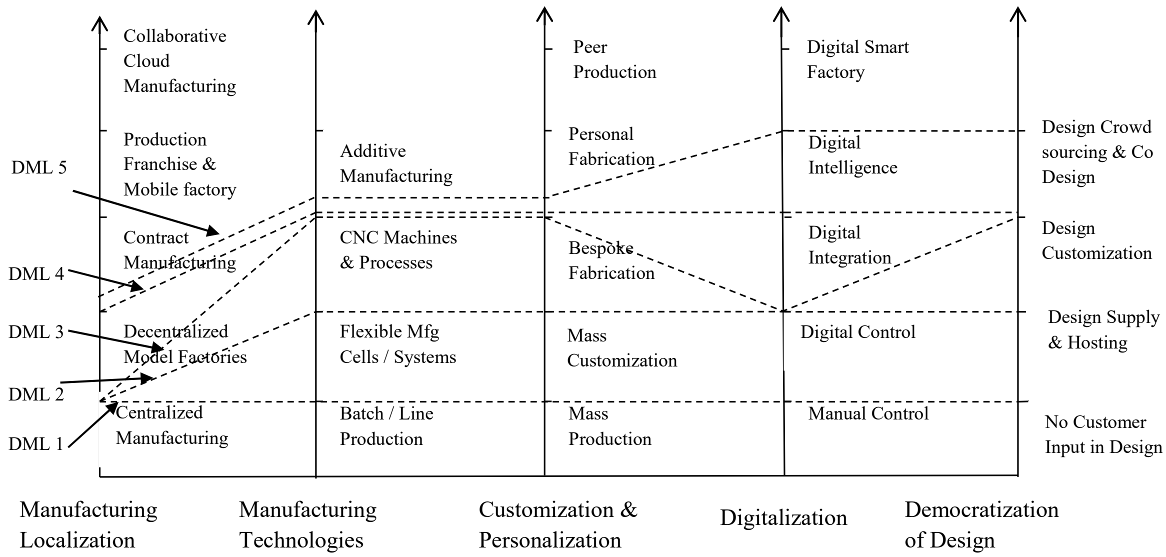


Figure 5: Reference profiles (i.e. distributed manufacturing scale levels) for distributed manufacturing continuum

5. Application Case Studies

With the aim to show the use of the distributed manufacturing conceptual scale, we analyse some application case studies. These case studies are analysed 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 distributed manufacturing.

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 distributed manufacturing 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 distributed manufacturing 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 United Kingdom plastic manufacturing sector, were selected for this analysis.

5.1 Case Study 1: One Plastic Group

This case study analyses 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, 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 & 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 Mouldflow 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 distributed manufacturing solution to ensure the flexibility and capability for a diversified market of plastic products. The distributed manufacturing dimension levels table and profile of case study firm One Plastic Group are shown below:

Table 5: 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 & 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 manufacting systems, Computer aided design, Automated vision based system for inspection	Computerized Numerical Control machines, Deisgn simulation & modeling, Automated sensor based systems for inspection	Additive manufacturing technologies, Rpid prototyping, Virtual / Augmented reality for inspection		Mouldflow process (simulation), Prototyping, Design FMEA, Advanced quality planning techniques	L3
Customization & Personalization	High volume & Low variety	Make to forecast or Assemble to Order	Tailor to order or Engieer to oder	High authoirty & High economy for customer	Commons based production	Delivering injection molded products as per customized specifications	L3
Digitalization	Use of Control Charts	Computerized control & Manufacturing execution systems	Program logic controls, Internet of things & Robotics	Cyber physical systems & Machine Learning	Big Data Analysis & Artifical Intelligence	Automated Injection molding presses and Assembly lines	L3
Democratization of Design	Standard Design	Design Cataloges for Selection	Customized Design on Customer Demand	Customer Interface for Design Input		Incorporation of customer input in product design	L3

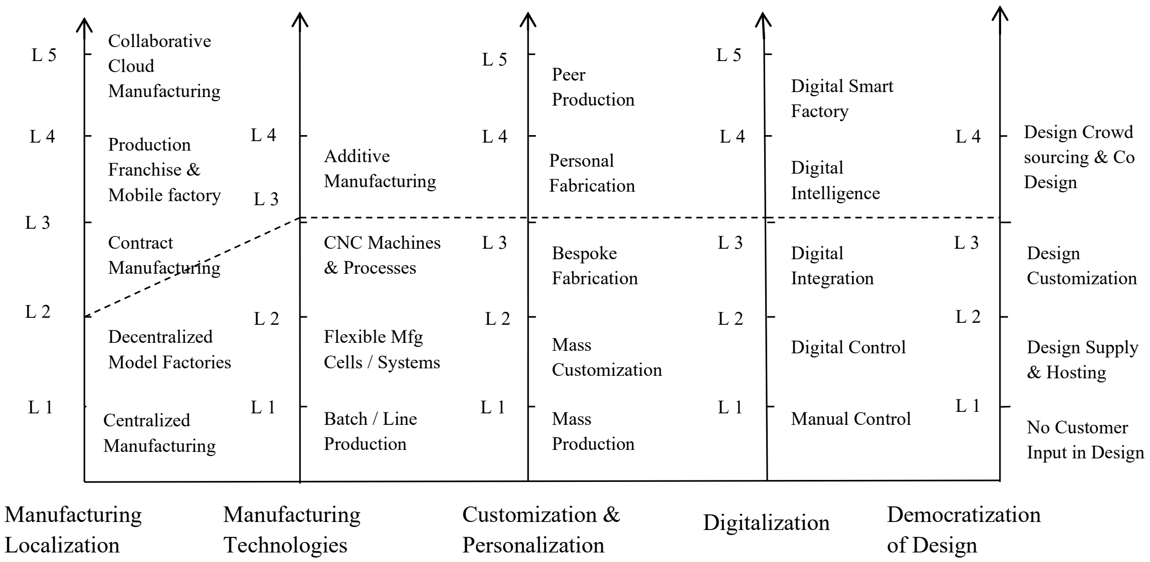


Figure 6: Positioning of firm 'One Group' in the distributed manufacturing framework

In comparison with reference profiles (Figure 5), the distributed manufacturing status of company 'One Plastic Group' profile can be associated to to DML 4.

5.2 Case Study 2: Weltonhurst Limited

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

Welthurst made partnerships with third party design services companies to better integrate customers requirement in the design process for customised solutions delivery. These specialised companies offer different services to incorporate customers' specifications in product design. These services include computer aided engineering, simulation software, 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) defines 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 Welthurst to outsource this product development design process to address specific needs of different industrial sectors. Welthurst 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 Welthurst to focus on its core competency of blow moulding process and offer integrated solutions to its diversified customer base. The distributed manufacturing dimension levels table and profile of case study firm Welthurst are shown below:

Table 6: Distributed Manufacturing dimensions levels for case company 'Welthurst'

Dimensions	Distributed Manufacturing Dimensions Levles					Observation	Level Score
Manufacturing Localization	Mass production in one location	Manufacturing standardized products in dispersed locations	Manufacturing from specialized contractor	Outsource Flexible manufacturing & 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 manufacting systems, Computer aided design, Automated vision based system for inspection	CNC machines & processes, Deisgn simulation & modeling, Automated sensor based systems for inspection	Additive manufacturing technologies, Rpid prototyping, Virtual / Augmented reality for inspection		22 diversed size blow moulding machines, Manual finishing & packaging of products, Quality control procedures	L2
Customization & Personalization	High volume & Low variety	Make to forecast or Assemble to Order	Tailor to order or Engieer to oder	High authoirty & High economy for customer	Commons based production	Delivering customized products and bespoke assembly & packaging solutions	L3
Digitalization	Use of Control Charts	Computerized control & Manufacturing execution systems	Program logic controls, Internet of things & Robotics	Cyber physical systems & Machine Learning	Big Data Analysis & Artifical Intelligence	Computerized control blow molding machines, In-house automation	L2
Democratization of Design	Standard Design	Design Cataloges for Selection	Customized Design on Customer Demand	Customer Interface for Design Input		Outsourced design services for customer input integration	L3

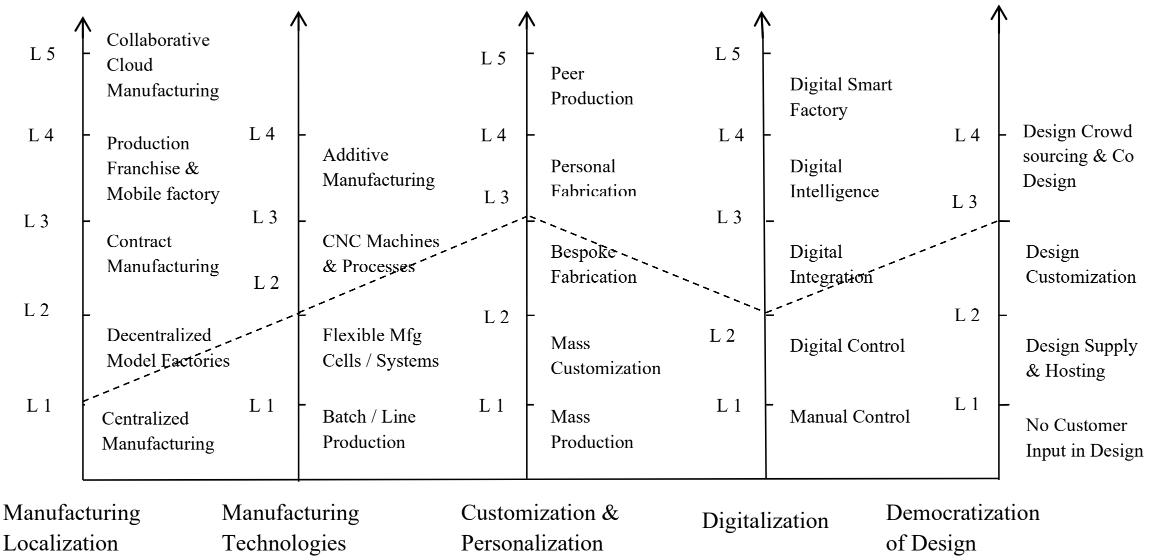


Figure 7: Positioning of firm B in the distributed manufacturing framework

In comparison with reference profiles (Figure 5), the distributed manufacturing status of company 'Welthurst' profile can be associated to DML 3.

6. Conclusion

The growing emphasis on sustainability, resource efficiency and minimal waste, makes distributed manufacturing 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, distributed manufacturing paradigm is being researched as a potential methodology to meet the challenges of competitive advantage and sustainability. Distributed manufacturing enables sustainability by producing products at or near the consumption point in small, efficient, adaptable and customer-oriented production units (Rauch et al. 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 distributed manufacturing in the company is well understood and precisely documented.

The development of a conceptual scale is initiated with the identification and selection of distributed manufacturing dimensions from the literature. This analysis is focused on the scope of distributed manufacturing 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 distributed manufacturing in a manufacturing company is proposed. This conceptual scale is developed in two steps. In first step, a hyperspace, based on five dimensions of distributed manufacturing 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 distributed manufacturing. 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 distributed manufacturing, whereas the DML5 indicates the highest level. The distributed manufacturing 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 distributed manufacturing.

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 distributed production 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 distributed manufacturing. 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 distributed manufacturing 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 distributed manufacturing 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 distributed manufacturing status of case company 1 profile can be associated to DML 4 and that of case company 2 profile can be associated to DML 3. This scale is a generalized scale for the measurement of distributed manufacturing 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 distributed manufacturing. The existing capacity is determined by measuring distributed manufacturing capabilities in terms of localization, manufacturing technologies, customization & 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 distributed manufacturing 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, 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 distributed manufacturing 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 focused upon and helpful for decision makers (company owners, consultants, stakeholders etc) to formulate the required action plans – of design, digitalization, localization technology, personalization – to convert the existing manufacturing operations into distributed manufacturing 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 distributed manufacturing 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. Firstly, the empirical data is 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. Secondly, the capacity of distributed manufacturing 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 focused 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 distributed manufacturing scale.

Appendix A

38 companies are selected for building the 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 distributed manufacturing in case companies.

Table A: List of questions to identify the levels of distributed manufacturing dimensions

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 & 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 & Engineering	Which design catalogues or softwares or modeling techniques are being used?
	Processing & 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 & Control	Which Integration and Control technologies have been installed for process control?
Customization & Personalization	High volume & Low variety	Are there few standard products being manufactured in large quantities?
	Make to Forecast & Assemble to Order	How the estimation of customers demand, and planning of production accordingly are being done?
	Tailor to order & 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 & product manufacturing done from different providers?
Digitalization	Use of Control Charts	Are there statistical techniques being used for process control?
	Manufacturing execution systems & CNC machines	What type of manufacturing execution system / enterprise resource planning softwares are being used on factory floor?
	PLCs, IoT & Robotics	Are Robotics being used in production? Is the production process automated by using Program logic controls?
	Cyber physical systems & Machine Learning	Is there any mechanism employed to collect, transmit and analyze production data from factory floor?
	Big Data Analysis & 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 we- based Customer interface developed to allow customer design their own products?

Appendix B

Table B: Level of distributed manufacturing dimensions assigned to case companies

	Manufacturing Localization					Manufacturing Technologies				Customization & Personalization					Digitalization					Democratization of Design			
	Centralized Manufacturing	Decentralized Model Factories	Contract Manufacturing	Production Franchize & Mobile Factory	Collaborative Cloud Manufacturing	Batch / Line Manufacturing	Flexible Manufacturing Cells / Systems	CNC Machines & 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 & 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		

Appendix C

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 two 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 = Localised manufacturing level of company A

x_2 = Manufacturing technology level of company A

x_3 = Customization & personalisation level of company A

x_4 = Digitalization level of company A

x_5 = Democratization of design level of company A

y_1 = Localised manufacturing level of company B

y_2 = Manufacturing technology level of company B

y_3 = Customization & personalization level of company B

y_4 = Digitalization level of company B

y_5 = Democratization of design level of company B

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 C. The Dendogram of cluster analysis is shown in Figure C.

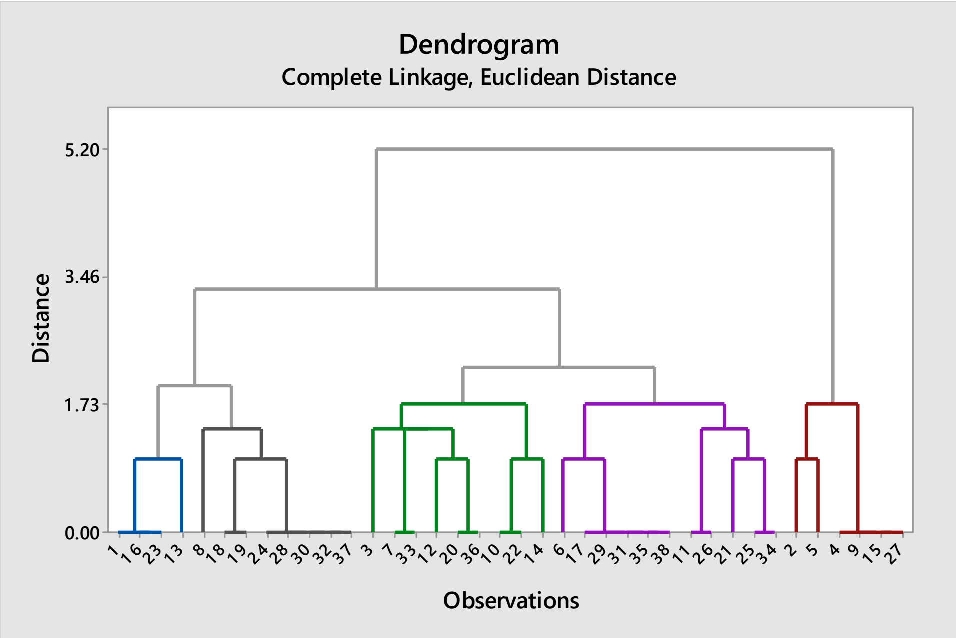


Figure C: The dendogram clustering of the 38 sample companies

Amalgamation Steps

Table C: Clustering of case study companies

Step	Number of clusters	Similarity level	Distance level	Clusters joined		New cluster	Number of obs. 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

Number of clusters: 5

The case companies are divided into five clusters as shown in the Table D. 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.

Table D: Classification of Case Companies in Clusters

	Localized Manufacturing	Manufacturing Technologies	Customization & 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**

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