A preliminary conceptual scale to discretize the distributed manufacturing continuum

A Preliminary Conceptual Scale to Discretize the Distributed Manufacturing Continuum

Ijaz Ul Haq, Fiorenzo Franceschini

Abstract—The distributed manufacturing methodology brings a new concept of decentralized manufacturing operations close to the proximity of end users. A preliminary scale, to measure distributed capacity and evaluate positioning of firms, is developed in this research. In the first part of the paper, a literature review has been performed which highlights the explorative nature of the studies conducted to present definitions and classifications due to novelty of this topic. From literature, five dimensions of distributed manufacturing development stages have been identified: localization, manufacturing technologies, customization and personalization, digitalization and democratization of design. Based on these determinants a conceptual scale is proposed to measure the status of distributed manufacturing of a generic firm. A multiple case study is then conducted in two steps to test the conceptual scale and to identify the corresponding level of distributed potential in each case study firm.

Keywords—Conceptual scale, distributed manufacturing, firm's distributed capacity, manufacturing continuum.

I. Introduction

THE offering of added value products and services with lesser inputs is always essential for manufacturing companies to remain competitive and able to enlarge market share. Also, the growing emphasis on ecological and social impacts of organizations on the surroundings they operate arise the need of efficient production and improved operations for sustainable offering to the consumers.

In future, customer value will be achieved not only through the realization of a product or a service but also through socially and environmentally responsible and economically efficient manufacturing processes encouraging positive effects for society [41].

The utilization of local resources for customised products and adoption of new production technologies (e.g. additive manufacturing) in a digitized environment make distributed manufacturing attractive for potential sustainability gains. The main advantages of decentralized production structures are a higher flexibility to reflect local customer, lower logistics cost and shorter delivery times [29].

Centralised 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 [16].

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The advantages associated with distributed manufacturing also bring specific challenges and issues need to be addressed to capitalize its prospects and benefits. The opportunities and challenges of re-distributed manufacturing and circular innovation need to be explored by answering the questions about franchise manufacturing, scalability, implications for intellectual property, learning capabilities to use big data, consumer acceptance to disruptive models, management of localised vs. globalised models and retail ecosystems [30].

Reference [35] identified transition of existing businesses and organizations into a distributed manufacturing structure as one of the issues to be addressed. This paper addresses this transition as how a firm can transform its production from centralized to distribute and how can this firm be mapped in the proposed classification.

A scale is developed to measure the status of distributed manufacturing of a specific firm. A case study approach is used and data are collected from a sample of case companies.

The scale is developed through literature review and tested by collecting data from case companies. The scale is then refined after findings and analysis.

The structure of the paper can be described as: Section II consists of literature review. Section III one deals with the development of measurement scale. Section IV discusses the case study companies. And Section V summarizes conclusions.

II. Literature Review

In existing literature, this concept has been described under different notations including Distributed manufacturing (DM) [51], Distributed manufacturing systems (DMS) [40] Distributed production (DP) [22], Distributed economies (DE) [19], Distributed manufacturing based on desktop manufacturing $(DM)^2$ [5] and Re-distributed manufacturing (RdM) [4], [35].

Reference [49] described the evolution of DM concept from decentralized and modular production control of product components to geographically dispersed flexible and reconfigurable production units of a single enterprise to a network of collaborative organizations complementing each other in skills and resources. Reference [56] argued that the term DM was interpreted in two different contexts. The first interpretation is related to the concept of value addition at geographically dispersed manufacturing locations of one enterprise. The second interpretation is in the context of DMS, defined as a class of manufacturing systems, focused on the internal manufacturing control and characterised by common properties (e.g. autonomy, flexibility, adaptability, agility, decentralisation).

Currently the research [20], [28], [46], [54], [59] is focused on DM to explore its potential as a manufacturing methodology that employs geographically dispersed and decentralised production facilities in consumer proximity with customized product development. This contrasts with centralised manufacturing concept having conventional mass production with associated supply chains to deliver end products to consumer over various destinations. A few definitions of DM are listed in Fig. 1.

Reference	Definitions
(Johansson et al. 2005)	"With Distributed economies (DE), a selective share of production is distributed to regions where a diverse range of activities are organised in the form of small-scale, flexible units that are synergistically connected with each other and prioritise quality in their production"
DeVor et al. (2012)	"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"
(ESPRC, 2013)	"Technology, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location and scale"
(WEF, 2015)	"Distributed manufacturing turns on its head the way we make and distribute products. In traditional manufacturing, raw materials are brought together, assembled and fabricated in large centralised factories into identical finished products that are then distributed to customer. In distributed manufacturing, the raw materials and methods of fabrication are decentralised, and the final product is manufactured very close to the final customer"
Kohtala (2015)	"Distributed production includes a wide range of current and emerging practices where private citizens have increased capacity to effect what is produced, from product personalisation to personal fabrication"
Rauch et al. (2016)	"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"

Fig. 1 Definitions of DM from the Literature [19], [5], [35], [9], [22], [41]

DM has a set of characteristics discussed and explored in workshop studies and literature. Due to the novel nature of the concept an explorative research design is often declined of analysing case studies and conducting joint study and brain storming sessions.

Reference [35] listed outcomes of ESPRC (engineering and physical sciences research council) workshop on RdM which identified four core fields i.e. geographies of manufacturing, enabling production technologies, new models of economics, business & investment and quality, regulation & legislation, as potential research topics. For addressing manufacturing quality issues references [10] and [11] proposed a selection criterion for performance indicators and subsequent design of a performance measurement system.

Reference [43] described DMS as a possible approach for sustainable manufacturing due to its adaptable and decentralized characteristics and listed a set of trends towards the development of DMS.

Reference [49] conducted a cross-case analysis, consisting of six case companies to identify the patterns and landscape of DM. This case study analysis identified five dimensions of DM.

In another study, [51] explores the characteristics of RdM 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.

Reference [30] defined a set of characteristics for the RdM in finding similarities between the drivers of RdM and circular models of production and consumption. Reference [38] explores the interplay between circular economy and RdM and identifies opportunities to combine makespaces with circular economy through RdM. An analysis of conceptual dimensions of DM paradigm considered in Literature is listed in Fig. 2.

The literature review indicates some distinct characteristics of DM. The following dimensions are considered for the development of a conceptual scale to measure the different stages of DM:

(a) Manufacturing localization
(b) Manufacturing technologies
(c) Customization and personalization
(d) Digitalization
(e) Democratization of design

III. Development of a Conceptual Measurement Scale

The next step is the development of a conceptual scale to evaluate the development level of DM in firms. As a first step, we propose the use of an Ordinal scale to measure the level of the five DM dimensions, identified from literature. These dimensions are described in detail below:

A. *Dimension 1 (D1): Manufacturing Localization*

The different forms of DM based on decentralized structure utilising local resources are discussed in literature.

Reference [29] divided the DM into eight forms: (i) standardized and replicable model factory, (ii) modular and scalable model factory, (iii) flexible and reconfigurable model factory, (iv) changeable and smart model factory, (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. The first four forms represent individual evolution stages of decentralized model factories, whereas the remaining four forms illustrate other special forms of DP.

Reference [40] described the five forms - micro production networks, contract manufacturing networks, mobile factory networks, production franchise networks and collaborative cloud manufacturing - of DM as business model clusters.

These five forms of DM are used 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.

Distributed Manufacturing Analysis Dimensions						
Moreno and Charnley (2016)	Localisation	Customization	Distributed Knowledge	Distributed Structure	Distributed Ownership	
Pearson et al. (2013)	Localised Manufacturing	Cloud Manufacturing	Customised / Multi variant Products	Flexible & Agile operations	Inter organizational reconfiguration	Resource Efficiency
Rauch et al. (2015)	Regionalism/Authenticity	Lower Logistics Cost	Mass Customisation	Democratization of Design	Market / Customer Proximity	Megatrend sustainability
Srei et al. (2016)	Localisation	Digitalization	Personalisation	New Production Technologies	Multi User Participation	
Prendeville et.al (2016)	Open Digital Networks	Collaborative and Open Innovation	Diffusion of New Technologies	Personalisation and Customisation	Prosumption	Local Networks & Social Interactions
	Sharing practice, knowledge & skills	Reshoring of Manufacturing				
Srei et al. (2016) (EISN)	Geographical dispersion	Mass and Late Customization	Integrated Design	Customer interaction in product development	E-commerce driven remote sales	Reconfiguration of products & resources

Fig. 2 List of DM Conceptual Dimensions considered in the Literature [30], [35], [43], [49], [38], [51]

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 detail description of these levels is given below:

1. Basic: Centralized Manufacturing

The centralized manufacturing facilities produce large production quantities and use supply chain network to deliver these products to the customers.

As compared to decentralized network of factories, the centralized manufacturing set up offers the advantages of higher production capacity, operational cost reduction and less organizational complexity [29].

This centralized production facility has the characteristic of mass production i.e. manufacturing low variety products in large volumes. Mass production allows low cost manufacturing of large volumes of products with limited variety, enabled by dedicated manufacturing systems [31].

2. Low: Decentralized Model Factories

This model offers decentralised and geographically dispersed manufacturing facilities in the customer and 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.

Reference [31] developed 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. Medium: Contract Manufacturing

This model defines the hiring of a specialised manufacturer in the desired location instead of establishing company's own DM unit. This arrangement saves the investment of company and provides collaboration opportunities to the locally distributed manufacturers to become a part of globally extended value chain.

Reference [23] described the use of integration mechanism to manage the uncertainties in contract manufacturing relationships. One of the case companies in this study is Electronics Co, a globally operating electronics manufacturer having production facilities in Europe, Asia and Americas.

4. High: Production Franchise and Mobile Model Factory

This design form shows DM facilities operated independently in various defined regions as franchises. These Franchise production networks adopt changeable and flexible manufacturing systems to meet the specific customer requirements in the allocated region or area.

Reference [32] 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.

Reference [43] demonstrate operation of a mobile factory in which a small production cell was developed and installed at the construction site to avoid long transportation due to bending in Scotland, machining and pre-assembly in Italy and finally installation in UK.

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 additive manufacturing technology and transferring of product data to distributed locations instead of physical product.

The transferring of product data and the use of advanced printing and assembling technology at the distributed facility by skilled staff, make the production of highly customised and resource efficient products possible.

Reference [6] used an applied research approach based on designing, implementing, and testing a DM scenario for spare parts.

Production of the bottom part of pneumatic cylinder is conducted in this scenario. 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 is to analyse organizational and process impacts in different use cases.

The different levels of manufacturing localization dimension are shown in Fig. 3.

Manufacturing Localization						
Name	Centralized Manufacturing	Decentralized Model Factories	Contract Manufacturing	Production Franchise	Mobile Model Factory	Collaborative Cloud Manufacturing
Scale Level	Basic	Low	Medium	High		Advanced
Level Description	Mass production of high volume and low variety products at one location	Manufacturing standardize products in dispersed facilities	Manufacturing products from specialized manufacturer	Outsource flexible manufactu-ring systems	On site manufact-uring facility	Product data transfer & Advance manufacturing techniques

Fig. 3 Scale Levels of Manufacturing Localization Dimensions

B. Dimension 2 (D2): Manufacturing Technologies

The second dimension of DM is manufacturing technologies. These manufacturing technologies evolved over time in last few decades incorporating computer aided designs and manufacturing, information and communication technologies, flexibility and modularity, control and automation, robotics, cyber physical systems and additive manufacturing.

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" [1].*

> *"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" [33].*

> *"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" [37].*

The Advanced manufacturing technologies are categorized into further sub-groups. Reference [52] listed sets of dimensions on which AMT classification is based in literature. It includes:

- engineering techniques, manufacturing techniques and business techniques
- direct, indirect and administrative
- integrated AMT and non-integrated AMT
- direct, indirect and communication
- hard technologies and soft technologies
- design, manufacturing and administrative
- stand-alone, manufacturing cells, integrated manufacturing
- stand-alone, moderate and high complexity
- basic technology and artificial intelligence

Reference [15] 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.

Reference [36] 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.

Reference [27] 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.

The manufacturing technologies have been progressed over the years and the timeline of advanced manufacturing technologies (AMT) development can be attributed to four zones.

Fig. 4 listed four time-periods and the corresponding technology topics generally dominated in that period. For the development of a Manufacturing technologies ordinal scale, this dimension is divided into four levels i.e. basic, low, medium and high, based on the evaluation of AMT over time.

In each level the extent of Manufacturing technologies is defined by estimating the performance of firms under the six sub-groups of advance manufacturing technologies (AMT) proposed by [37]. This categorization of [37] is taken to define manufacturing technologies dimension levels as it encompasses all the sub-categories of manufacturing technologies like design (CAD, 3D modelling), network (LAN, Internet of things) and control technologies (SCADA, Machine learning).

The required performance merit against these six sub-groups for each scale level is shown in Fig. 5.

Technology Development	Time Span
Statistical methods & Metrology techniques for Quality control	1980 – 1990
Information & Communication technologies for manufacturing	1990 – 2000
Factory automation and Flexible manufacturing systems	2000 – 2010
Industry 4.0	2010 – Present

Fig. 4 Time Span of Dominating Technology Topics in Manufacturing [52]

Manufacturing Technologies Classification	Manufacturing Technologies Levels			
	AMT O (Basic)	AMT 1 (Low)	AMT 2 (Medium)	AMT 3 (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 / testing 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	Machine Learning and Artificial intelligence

Fig. 5 Levels of Manufacturing Technologies Dimensions [37]

C. Dimension 3 (D3): Customization and Personalization

DM 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.

Reference [22] conceptualize the DP landscape in four dimensions i.e. mass fabrication, mass customization, bespoke fabrication and personal fabrication.

In this landscape, mass fabrication and mass customization define DP at large scale while bespoke fabrication and personal fabrication at small scale. Also, mass customisation and bespoke fabrication are categorized with digital manufacturing while mass fabrication and personal fabrication are listed with peer-to-peer production.

For the development of the scale, Customization and personalization dimension is categorized into five levels of mass production, mass customization, bespoke fabrication, personal fabrication and peer production.

1. Basic: Mass Production

Mass production includes production of economically smaller batch sizes, lean manufacturing of high-quality products, mass customization through portfolio of product families and mass personalization in form of distinctive feature associated with consumers such as labelling consumers name on the products [3].

The term mass production relates to high volume production rates with very low product variety. Reference [55] 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.

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 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 [12].

Reference [13] presented a relationship between authority and economy 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 authority refers to the freedom for consumers to give inputs into design and production of products and economy refers to the availability of low cost products with shorter delivery times for consumers.

The relationship has been confined in an increasing authority and decreasing economy trend starting from ‘make-to-forecast’ to ‘assemble-to-order’ to ‘tailor-to-order’ to ‘engineer-to-order’ whereas the ‘prosumption’ indicates a scenario of high authority and high economy i.e. customers give input in design process and products are delivered without increased cost and delivery time.

Make-to-forecast methodology deals with the estimation of customers demand and planning of production accordingly while assemble-to-order deals with production of modular components which are assembled in accordance with customer demand.

Make-to-forecast and assemble-to-order methodologies are taken as low level, tailor-to-order and engineer-to-order as medium level and presumption is taken as high level for this dimension of DM.

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.

Reference [22] 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’.

The DM is characterized with Advance manufacturing technologies (AMT) and these AMTs like additive manufacturing enlarge the scope of tailor-to-order and engineer-to-order products [50].

Current embodiments of additive manufacturing technologies are suitable for fabrication of products that feature customized features, low-volume production, and / or increased geometric complexity and also for the satisfaction of individual needs such as collectables, jewellery and home accessories [17].

The bespoke fabrication reduces the inventory cost by producing and delivering products on customer demand. Holding a database of digital designs allows products to be manufactured on demand using AM which can help eliminate or at least minimize inventory waste, reduce inventory risk with no unsold finished goods, with the potential of improving revenue flow as goods are paid for prior to being manufactured [14].

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 [34]. Personal fabrication is fabrication of unique products from shared designs in which design and fabrication are in hands of users [22].

The designers shared their designs with consumers or made customers’ personalized designs. Product designs often shared digitally are realised by the users themselves and, due to their digital form, can be designed together with peers in other locations [24].

These designs are then used to fabricate customized products through consumers owned low cost digital fabrication equipment like 3D printers, milling machines.

This is the form of DM in which firms provide products or services or both to produce personalised items at home or at mini factories. The firms involve in these production activities at any stage of value chain (design, fabrication, distribution) are labelled at High level of mass customization and personalization dimension.

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 [25].

These technological-economic feasibility spaces - in form of free software, open source knowledge sharing platforms like wiki space – are diminishing the traditional factory-based production and moves towards the paradigm of open or peer production.

Reference [2] describes the prospects of open production as the ability to facilitate stigmergy, to self-organize in an open value creation system, facilitates the utilization of emergence in the process where decentralized stakeholders are collectively acting in an intelligent way. The ICT technologies, digitalization and Advance manufacturing technologies are the key enablers of this open or peer production paradigm.

Due to a higher proportion of knowledge in product, the information and communication technologies and the new manufacturing technologies, stakeholders are capacitated to participate in real, global value creation processes in contrast to the conventional development cooperation practices, which were hitherto driven by companies from industrial nations [2].

Many online platforms have been established to facilitate peer production. Reference [44] list 22 such online platforms enabling peer production by offering services of design supply, design hosting, design customization, design crowd sourcing, co-designing, printing, printing crowd sourcing and printer sales to consumers to serve their specific needs.

Customization and Personalization							
Name	Mass Fabrication	Mass Customization		Bespoke Fabrication		Personal Fabrication	Peer Production
Scale Level	Basic	Low		Medium		High	Advanced
Level Description	High volume, Low variety production	Make to forecast	Assemble to order	Tailor to order	Engineer to order	High authority & High economy	Commons based production

Fig. 6 Scale Levels of Customization & Personalization Dimension

D. 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. The advancements 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 [57].

The integration of CPS with production, logistics and services in the current industrial practices would transform today’s factories into an Industry 4.0 factory with significant economic potential [26].

The recent concepts such as the Internet of things, Industrial internet, Cloud-based manufacturing and Smart manufacturing are commonly subsumed by the visionary concept of a Fourth industrial revolution - Industry 4.0 [53].

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 four stages and seven dimensions Industry 4.0 maturity model [18]. Reference [53] developed industry 4.0 maturity model which includes 62 maturity items grouped in 09 company dimensions. These dimensions are strategy, leadership, customers, products, operations, culture, people, governance and technology.

Reference [39] 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 further categorized into five levels (basic, low, medium, high, advanced). 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 7.

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.

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. 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.

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 Data mining and Machine learning.

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 analysis, artificial intelligence and advance production technologies like additive manufacturing.

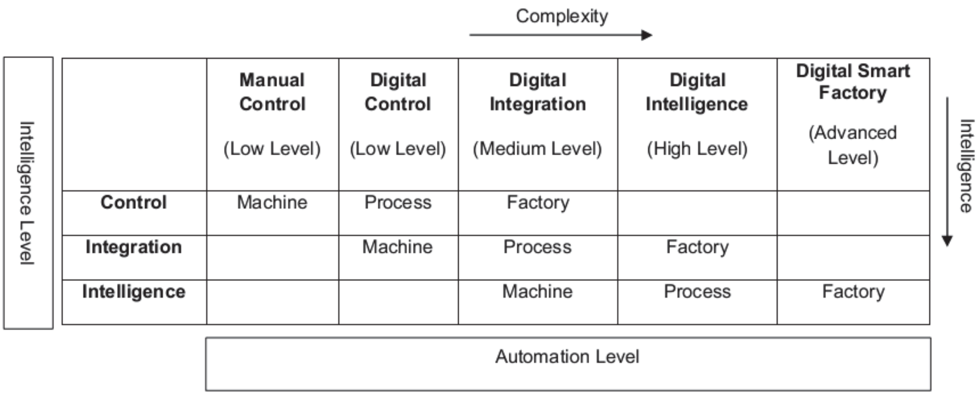

Fig. 7 Digitalization progression adapted from [40]

E. Dimension 5 (D5): Democratization of Design

To meet customer needs in the increasingly discontinuous environment, efforts for customer integration in the form of Open innovation have to be made by utilizing user design and product configurations toolkits in product development [45].

The digitalization of production systems and distributed networks improve the consumer and producer cooperation in product development. This cooperation results in open innovation and co-creation.

Open source innovation is an integrated activity of designer, producer and consumer for co-creation by sharing knowledge and expertise [30]. In open innovation, the consumer itself designs using digital design tools or selecting from design catalogues and produces the product using product development techniques and aids [40].

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 [45]. 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.

Reference [44] 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 ordinal 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

F. DM Scale Construction

The DM conceptual scale is developed in two steps:

1. Step 1

In first step, the construction of the scale levels for each dimension of DM is completed (Fig. 9).

2. Step 2

In second step, we perform the construction of the reference profiles. Each profile represents an element of the DM continuum (Fig. 10).

The scheme of the process to build the DM conceptual scale is shown in Fig. 8.

G.Empirical Study for the Construction of DM Reference Profiles

In second step, we perform the construction of the reference profiles. Each profile represents an element of the DM continuum.

A case study is conducted by taking a sample of firms operating in Italian Mould making industrial sector.

The method of convenience sampling was used. Convenience sampling is a non-probability or non-random sampling in which members of the target population that meet certain practical criteria like easy accessibility, geographical proximity, availability at a given time or the willingness to participate are selected for the purpose of the study [8].

The database of AMAPLAST was chosen to collect the sample. AMAPLAST [47] 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.

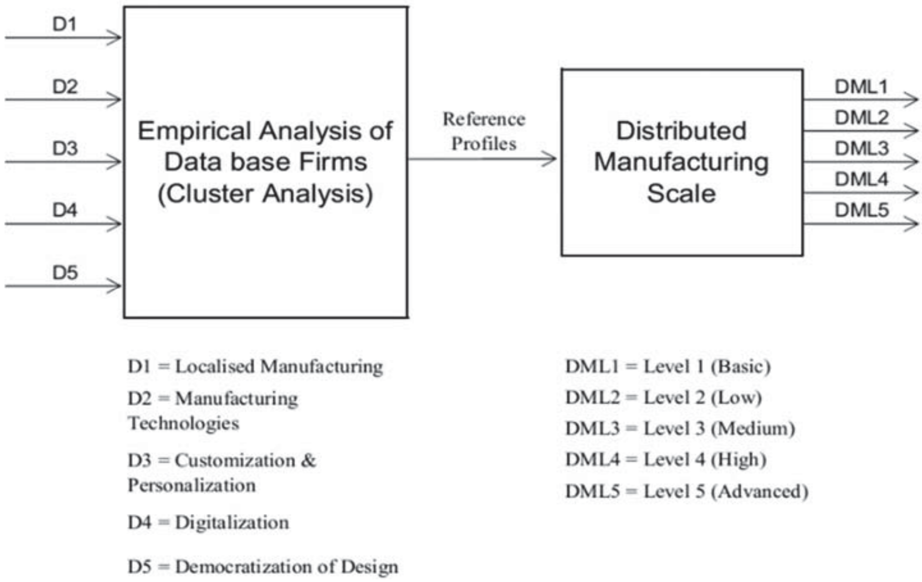

Fig. 8 Scheme of the process to build the DM scale

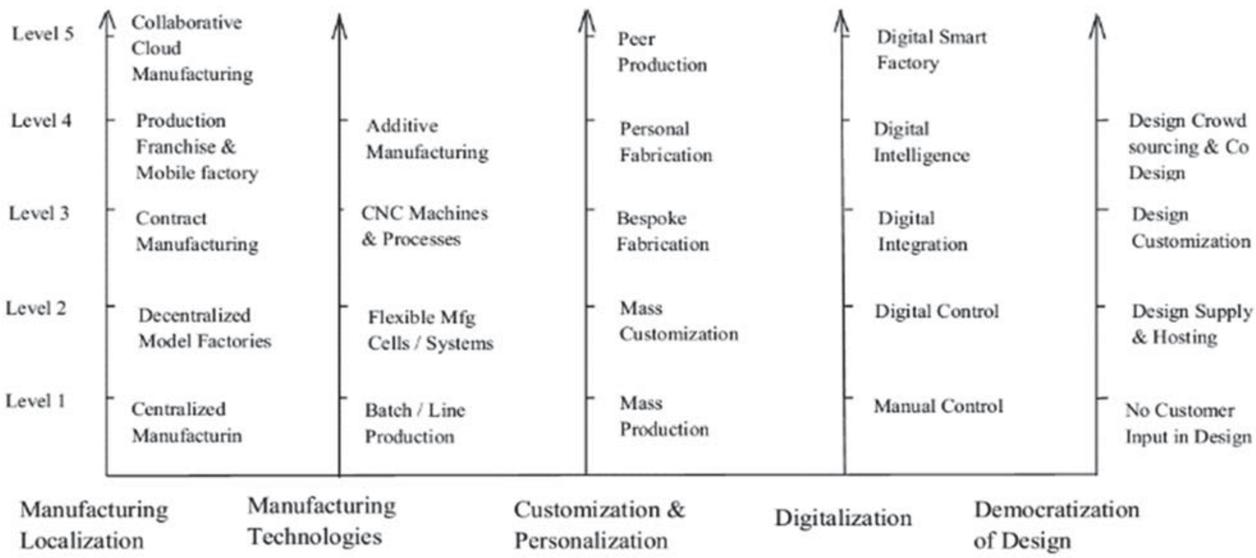

Fig. 9 Conceptual scale for DM measurement

The following are the main groups categorised in the search option of 'machine type':

(1) Plastics machinery
(2) Rubber machinery
(3) Measuring and Control equipment
(4) Machinery parts and equipment
(5) Process control technique and Vision systems
(6) Moulds and Dies
(7) Plastics and Rubber machinery's reconditioners
(8) Others

The group of 'Moulds and Dies' is selected for this study. There are total 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 I) was made to collect the relative information about each case company.

The DM dimensions are 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 dimension.

The following codification is allocated to the five levels of DM dimensions:

Basic: 1, Low: 2, Medium: 3, High: 4, Advance: 5

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

1. Cluster Analysis

The next step involves the clustering of case companies to identify any similarity or dissimilarity pattern. The details of cluster analysis are described in Appendix III.

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

Manufacturing localization: 2
Manufacturing technologies: 3
Customization & Personalization: 3
Digitalization: 3
Democratization of Design: 3

A reference profile built from the levels of DM dimensions obtained in cluster 1 is shown in figure 4.

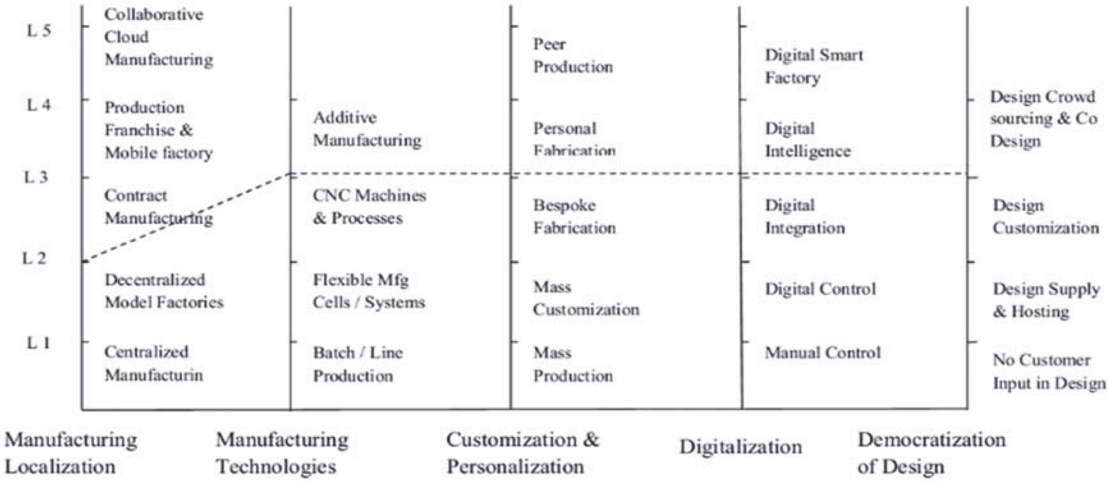

Fig. 10 Reference profile plotted from cluster 1

These five clusters are then plotted on the conceptual scale and resulted in the generation of five profiles as shown in Fig. 11.

These five profiles are considered as reference profiles to measure the status of DM in any generic firm. Each profile represents a specific level (DML1 or DML2 or DML3 or DML4 or DML5) of DM in that firm such that

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

IV. Case Study Verification

A multiple case study method is used to test the DM conceptual scale. A cross case analysis comprising of five case examples for the verification of conceptual scale was performed.

The case example evidence was 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 collected then compared against the DM dimensions levels and a score is assigned to each of them.

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

- Basic level = 1
- Low level = 2
- Medium level = 3
- High level = 4
- Advanced level = 5

The DM status of each case company is then plotted on the conceptual scale and compared against the reference profiles. The following five case studies, representing different sectors, were selected for this analysis.

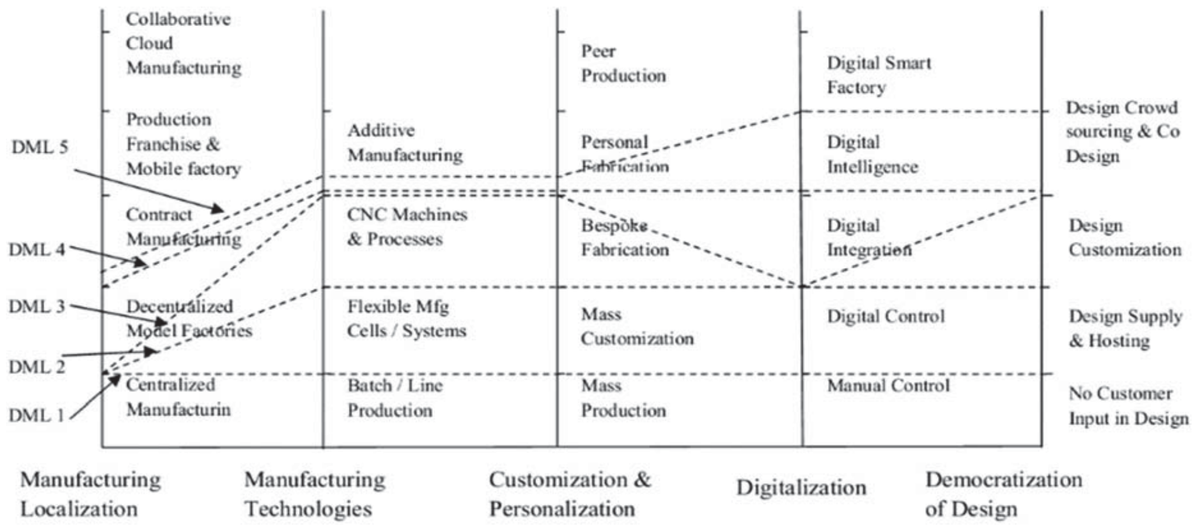

Fig. 11 Reference profiles (i.e. DM levels) for DM measurement

A. Textile Products

This case study focuses on 3D printed textile products. The potential of 3D printing technologies engulfs many industrial sectors and provides the prospects of departure from traditional textile manufacturing techniques in textile industry. Tamicare invented product Cosyflex to 3D print finished textile products. This additive manufacturing technology adoption opens up new business opportunities for Tamicare in fashion, medical hygiene, sportswear, cosmetics and other market segments in business-to-business (B2B) environment.

The company operates a business model deals with planning, designing and commissioning of custom-made manufacturing line. The company offers customized solution in form of product development according to customers' specifications of product, material and application. This customized manufacturing line offering enables the customers of Tamicare to expand their business by producing one or two or more 3D printed products for the retail clothing market. The additive manufacturing technology – Cosyflex – made it possible to print unlimited fabric variations with different combinations of features and patterns by utilizing lesser resources as compared to conventional textile manufacturing line.

This next generation technology to print textile products has the potential to revolutionize the traditional textile industry and its associated supply chains. It makes it possible to fabricate the customized products with a variety of design patterns on customer demand. This technology makes the bespoke fabrication feasible which can reduce the inventory and transportation costs and offer products with high degree of customization. Additive manufacturing ensures sustainable product design as it allows designers nearly unlimited freedom of design and allows for mass customization of consumer goods having desire, pleasure and attachment characteristics [7].

The use of additive manufacturing technology, customized product development in desired location provides a DM solution to ensure the flexibility and capability for diversified market. The DM dimension levels table and profile of case study firm A are shown below:

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 is customer premisis using local resources	2
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		Cosyflex technology for 3D printing of garments	4
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 manufacturing line as per customized specifications	3
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	Automation & Integration of factory floor machines	2
Democratization of Design	Standard Design	Design Cataloges for Selection	Customized Design on Customer Demand	Customer Interface for Design Input		Incorporation of Customer input in design	3

Fig. 12 DM Dimensions Levels for Case Company A

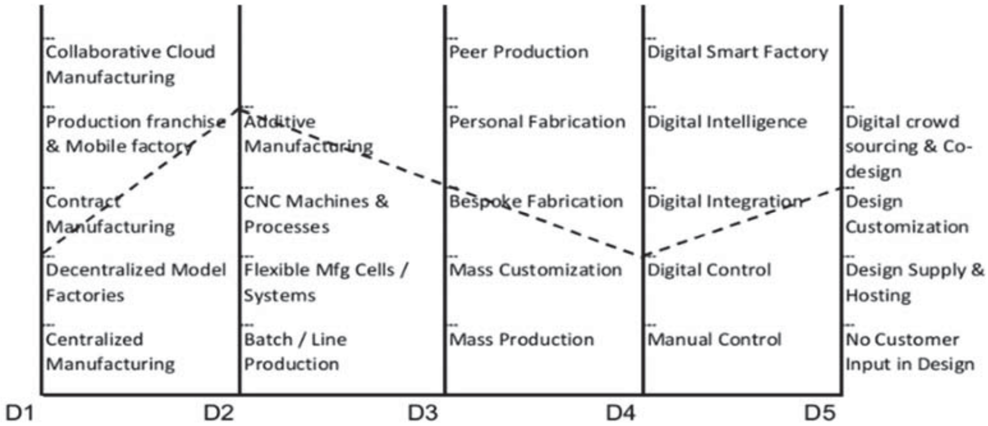

Fig. 13 DM status of case company A

In comparison with reference profiles (Fig. 5), the DM status of case company A is equal or close to DML 3.

B. Furniture Manufacturing

This case study discusses the DM prospects in furniture industry. AtFAB established a DM network of independent digital fabrication workshops and provides personalised furniture products to consumer markets in various geographical regions.

The furniture company fabricates products by transferring digital files of furniture designs to OpenDesk's network of fabricators located in dispersed areas. The company extends its fabrication network by offering 'Design for CNC' manual to the fabricators to assist them in maintaining quality standards in fabrication of finished products. The usage of parametric designs, digital transportation of designs and networked manufacturing enables AtFAB to enlarge its customer base on a global scale with a global community of makers.

Reference [3] defined it as direct digital manufacturing - an interconnection of (decentralised) additive manufacturing equipment and modern information and communication technology (ICT) which allows to match consumer demands and supply capacities in real-time, only limited by physical logistic handling of artefacts. This DM model reduces the dependence of company on energy-intensive global supply chains, middle men and mark-ups. The digitalization and localized network of fabricators results in minimization of waste (energy, material), personalised products offerings and development of a vast consumer market located geographically.

The digitalization and internet of things (IoT) ensure the collection and transmission of product data instead of physical product to long distances. The product data is then converted into physical products by using localized resources.

Reference [21] conducted delphi projections of Additive manufacturing for 2030 and projected distribution of final products will move significantly (>25%) to selling digital files for direct manufacturing instead of selling the physical products.

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	Network of fabrication workshops in different regions	3
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		Manufacturing through CNC manual for Independent workshop owners	2
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	Products based on parametric designs for different regional markets	2
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	Transfer of digital files and computerized control of process	2
Democratization of Design	Standard Design	Design Catalogues for Selection	Customized Design on Customer Demand	Customer Interface for Design Input		Directory of design files for customers	2

Fig. 14 DM Dimensions Levels for Case Company B

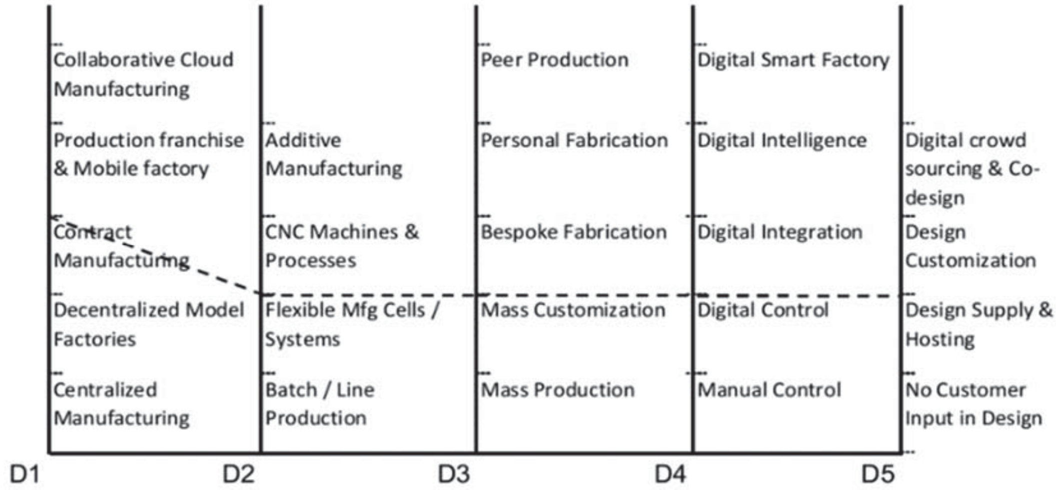

Fig. 15 DM status of case company B

In comparison with reference profiles (Fig. 5), the DM status of case company B is equal or close to DML2.

C. Home Architecture

This case study focuses on housing construction sector. The digitalization and advance manufacturing technologies dimensions of DM add the properties of diversity and innovation to many standardized products without the limitation of scale.

Facit Homes takes this advantage in the housing sector and offers customized houses to the customer by using personalised designs and 3D visualization technology. The 3D visualization of home design enables customers to incorporate or change the design according to their needs before the start of construction. This phenomenon is also referred as cloud-based design in literature. The inherent characteristics of CBD (cloud-based design) are based on cloud computing, virtualization, multi-tenancy, ubiquitous access, software-as-a-service, pay-per-use business model, and so on, it has the potential to become a game changer for the next generation distributed and collaborative design [58].

The company developed hyper-real 3D visualization software to design a personalised home and allows customer to observe their design preference in a 3D environment. The house construction components are also digitally designed and then virtual 3D design components are converted into physical replicas. These replicas are then assembled at the construction site by the build team.

The personalised design approach through the usage of digitalization and 3D components design makes it possible to offer products specific to different markets and geographies. It has become possible to take into account the unique conditions of different geographical areas and develop a product having features compatible with these conditions.

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	The house construction components are converted into physical replica on local site	2
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		3D modeling and CNC machines to fabricate house comonents	3
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	The site specific home design is made to personalize each home	3
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	The execution of house construction through Computerized control	2
Democratization of Design	Standard Design	Design Cataloges for Selection	Customized Design on Customer Demand	Customer Interface for Design Input		A hyper-real 3D visualization software allows users to modify design	4

Fig. 16 DM Dimensions Levels for Case Company C

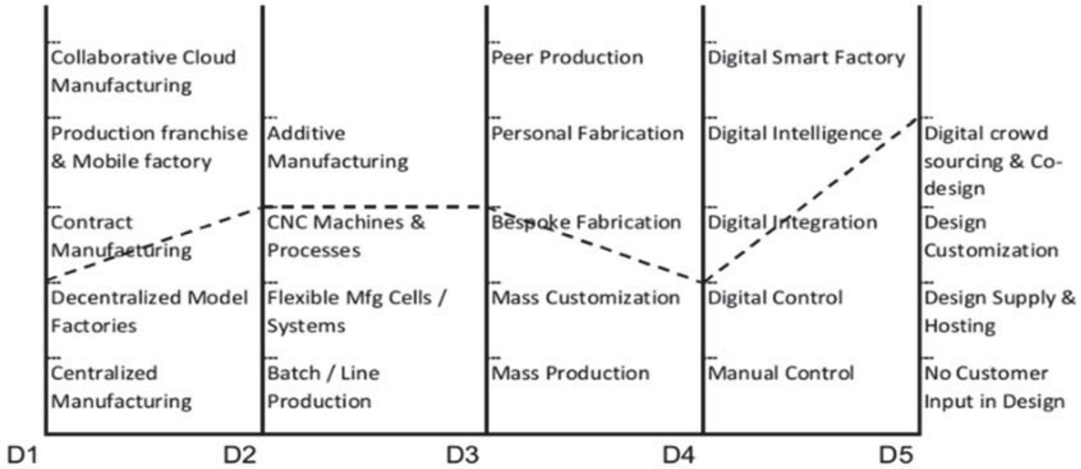

Fig. 17 DM status of case company C

In comparison with reference profiles (Fig. 5), the DM status of case company E is equal or close to DML3.

D.3D Printed Precious Metals

This case study deals with joint ventures of two or more businesses in precious metals sector. One of many opportunities associated with DM paradigm is the collaboration of companies and formation of business models to explore the new markets.

Cooksongold and EOS is an example of such a partnership. DMS, as a modern form of organizational manufacturing concept, could be considered as organization innovation which needs to be adopted by the market and decision-makers in the company [55]. EOS expertise includes the provision of additive manufacturing technology-based solution –Direct Metal Laser Sintering System (DMLS)– together with software applications for data preparation, process and monitoring. Cooksongold is the leading European provider of precious metals in the form of alloys, wire, sheet, tubing, coin blanks and casting grain in gold, silver, platinum and palladium.

The partnership of EOS and Cooksongold made it feasible to provide customized solutions of e-manufacturing to jewellery and watch making industry. The DMLS technology reduces the material waste and makes process cost efficient by using defined cavities to produce small and precise pieces.

The digital designs produced by CAD program provide design freedom for customized products. The digital data is then utilized by DMLS to produce single items or a serial production of products. User-friendly software is also provided to customers by EOS to manage the production process and hence makes the use of additive manufacturing technology simple.

The DM makes it possible the formation of unique partnerships and exploration of new markets emerging from once considered saturated market segments.

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		End to end solution for watch & jewellery industy in different regions	2
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			Direct metal laser sintering system (DMLS)	4
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		A combined provision of material & machines for personalized solutions	3
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		Software application for data preparation, process and monitoring	3
Democratization of Design	Standard Design	Design Cataloges for Selection	Customized Design on Customer Demand	Customer Interface for Design Input			Customer input in making digital designs by CAD software	3

Fig. 18 DM Dimensions Levels for Case Company D

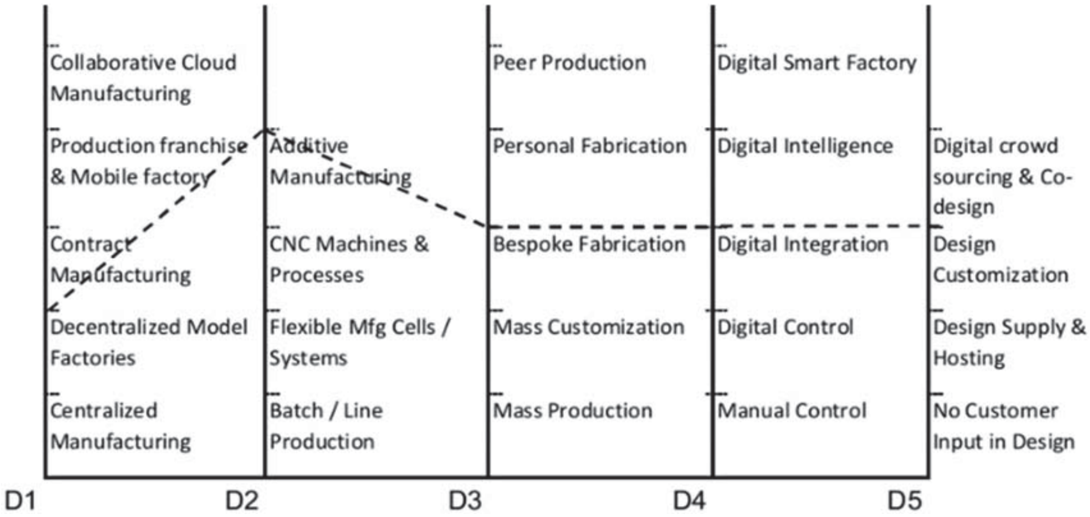

Fig. 19 DM status of case company D

In comparison with reference profiles (Fig. 5), the DM status of case company D is equal or close to DML4.

E. Healthcare

This case study explores the DM applications in the health care sector. The DM methodology makes it possible to introduce personalised healthcare solutions. The long-awaited supply chains can be diminished by producing healthcare products through additive manufacturing at worldwide distributed laboratories and clinics.

Smaller scale precision manufacturing can radically reduce supply chain costs, improve sustainability and tailor products to the needs of patients and consumers. RdM has the potential to improve the citizen wellbeing when applied to products such as medical devices, pharmaceuticals, biopharmaceuticals and regenerative medical products i.e. cell and tissue-based therapies [42].

In Dental applications, the digitalization of design process makes it possible to diagnose patients' requirements and treatment by employing imaging and additive manufacturing processes. A Dental solution provider company BEGO offers 3D printing system which includes in-house developed 3D printer, light-curing device, scientifically tested materials, software tools and services to achieve fast and cost-efficient fabrication of restorations made from resins.

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		Manufacturing of dental products at distributed clinics & laboratories	2
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			3D printing of dental restorations made from resigns	4
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		Patient's skull specific dental treatment	3
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		Software tools to assist scanning & 3D printing	2
Democratization of Design	Standard Design	Design Cataloges for Selection	Customized Design on Customer Demand	Customer Interface for Design Input			Scanning and digital imaging of skull	3

Fig. 20 DM Dimensions Levels for Case Company E

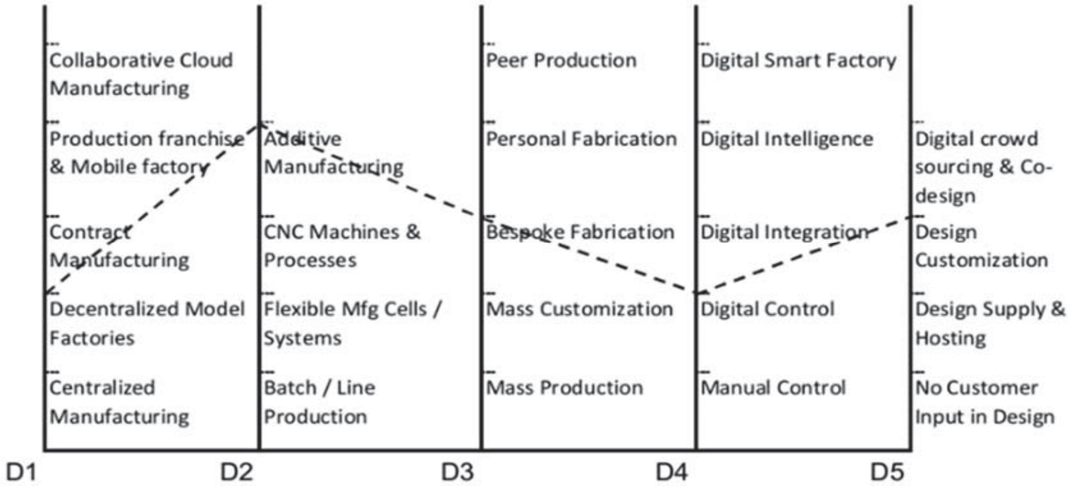

Fig. 21 DM status of case company E

This model makes use of design automation and 3D printing to provide treatment to patients in single laboratory visit and thus improving patient outcomes and cost savings. In comparison with reference profiles (Fig. 5), the DM status of case company E is equal or close to DML3.

V. Conclusion

The growing emphasis on sustainability, resource efficiency and minimal waste, makes DM a promising alternative to overcome the barriers of unresponsive supply chains and wastage of scarce resources associated with centralized manufacturing paradigm.

The literature defines DM and divides it further in different sub-categories. This classification indicates the scope of this production methodology with respect to location, digital and advance production technologies and customer involvement.

For a manufacturing firm 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 manufacturing firm is well understood and precisely documented.

In this paper, we present a conceptual scale to measure the status of DM in a generic firm. In first step, based on literature review, five dimensions of DM i.e. localized manufacturing, manufacturing technologies, customization & personalization, digitalization and democratization of design, are identified. A conceptual scale is then constructed listing each of these dimensions in an ascending order having five levels: basic, low, medium, high and advanced

In the second step, to develop reference profiles on the conceptual scale, a sample of 38 companies operating in Italian mold manufacturing sector is taken and analyzed. These case companies are clustered into five segments on the basis of similarity observed among dimensions of DM.

A multiple case study is conducted and five firms are selected randomly to test and verify the developed measurement scale. The dimensions of DM are analyzed with respect to these five case study firms and their corresponding status is plotted on the scale and compared with reference profiles.

This scale is a generalized scale for the measurement of DM status in manufacturing firms. The data used in this study is collected from secondary resources [48].

Further research work will be conducted by analyzing empirical data from different industrial sectors to consolidate reference profiles in the DM scale.

Appendix I

The 38 companies are selected for the case study. To collect information a questionnaire was built and by going through secondary data the answers of these questions were acquired. These answers are taken as observations to determine the level of DM in case companies.

TABLE I
LIST OF QUESTIONS TO DETERMINE THE LEVELS OF DM 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?
Manufacturing Technologies	Product Data Transfer	Is there any product data (CAD digital file) transfer between the production facilities?
	Design & Engineering	Which design catalogs or software of modeling techniques are being used?
	Processing & Assembly	Which processing technologies (flexible manufacturing, Computerized control, Additive Manufacturing etc) 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 are being 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 are the estimation of customer demand and production planning accordingly being done?
	Tailor to order & Engineer to order	Which channel / method is being 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 (furniture workshop etc) 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?
	CNC Machines & Manufacturing execution systems	What type of manufacturing execution system / enterprise resource planning software 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 product's standard designs are being used for production?
	Design catalogs for selection	Does the company offer its own design catalogues or it uses third party design catalogues?
	Customized design on customer demand	How customer input in 2D/3D design is being incorporated? Do customers provide their own product designs or product specifications?
	Customer interface for design input	Is there any web based customer interface developed to allow customers to design their own products?

TABLE II
LEVELS OF DM DIMENSIONS ASSIGNED TO CASE COMPANIES

	Manufacturing Localization				
	Centralized Manufacturing	Decentralized Model Factories	Contract Manufacturing	Production Franchise & Mobile Factory	Collaborative Cloud Manufacturing
BORGHI		2			
B-TECH	1				
CANTONI	1				
CAPUZZI SYSTEM	1				
CIMA IMPIANTI	1				
CMG	1				
BARUFFALDI	1				
COMAT	1				
DELIA	1				
FRIULFILIERE	1				
GEFIT		2			
HONESTAMP	1				
INGLASS		2			
LTL	1				
GIMAC	1				
MARANGONI		2			
MARA	1				
MECCANICA GENERALE	1				
MECCANO STAMPI	1				
NTS		2			
OMIPA	1				
OMMP	1				
OMS BESSER		2			
PERSICO		2			
PLAXTECH	1				
POLIVINIL		2			
PROFILE DIES	1				
QS GROUP		2			
ROMPLAST	1				
SACMI		2			
SIMPLAS	1				
SIPA		2			
SPM	1				
T2	1				
TECNOMATIC	1				
TERMOSTAMPI		2			
THERMOPLAY		2			
UNION SPA	1				

	Manufacturing Technologies			
	Batch / Line Manufacturing	Flexible Manufacturing Cells / Systems	CNC Machines & Processes	Additive Manufacturing
BORGHI			3	
B-TECH		2		
CANTONI			3	
CAPUZZI SYSTEM	1			
CIMA IMPIANTI		2		
CMG		2		
BARUFFALDI			3	
COMAT			3	
DELIA	1			
FRIULFILIERE		2		
GEFIT			3	
HONESTAMP		2		
INGLASS			3	
LTL		2		
GIMAC	1			
MARANGONI			3	
MARA		2		
MECCANICA GENERALE			3	
MECCANO STAMPI			3	
NTS			3	
OMIPA		2		
OMMP			3	
OMS BESSER			3	
PERSICO			3	
PLAXTECH		2		
POLIVINIL		2		
PROFILE DIES	1			
QS GROUP			3	
ROMPLAST		2		
SACMI			3	
SIMPLAS		2		
SIPA			3	
SPM			3	
T2		2		
TECNOMATIC		2		
TERMOSTAMPI			3	
THERMOPLAY			3	
UNION SPA		2		

		Customization & Personalization			
	Mass Production	Mass Customization	Bespoke Fabrication	Personal Fabrication	Peer Production
BORGHI			3		
B-TECH		2			
CANTONI			3		
CAPUZZI SYSTEM	1				
CIMA IMPIANTI		2			
CMG		2			
BARUFFALDI			3		
COMAT			3		
DELIA	1				
FRIULFILIERE			3		
GEFIT		2			
HONESTAMP			3		
INGLASS			3		
LTL			3		
GIMAC	1				
MARANGONI			3		
MARA		2			
MECCANICA GENERALE			3		
MECCANO STAMPI			3		
NTS			3		
OMIPA		2			
OMMP			3		
OMS BESSER			3		
PERSICO			3		
PLAXTECH		2			
POLIVINIL		2			
PROFILE DIES	1				
QS GROUP			3		
ROMPLAST		2			
SACMI			3		
SIMPLAS		2			
SIPA			3		
SPM			3		
T2		2			
TECNOMATIC		2			
TERMOSTAMPI			3		
THERMOPLAY			3		
UNION SPA		2			

	Digitalization					Democratization of Design			
	Manual Control	Digital Control	Digital Integration	Digital Intelligence	Digital Smart Factory	No Customer Input in Design	Design Supply & Hosting	Design Customization	Co-Design
BORGHI			3					3	
B-TECH		2					2		
CANTONI		2					2		
CAPUZZI SYSTEM	1					1			
CIMA IMPIANTI	1					1			
CMG		2					2		
BARUFFALDI			3					3	
COMAT			3						4
DELIA	1					1			
FRIULFILIERE		2						3	
GEFIT		2					2		
HONESTAMP		2						3	
INGLASS				4				3	
LTL			3					3	
GIMAC	1					1			
MARANGONI			3					3	
MARA		2					2		
MECCANICA GENERALE			3						4
MECCANO STAMPI				4				3	
NTS		2						3	
OMIPA			3				2		
OMMP		2						3	
OMS BESSER		2						3	
PERSICO				4				3	
PLAXTECH		2					2		
POLIVINIL		2					2		
PROFILE DIES	1					1			
QS GROUP				4				3	
ROMPLAST		2					2		
SACMI				4				3	
SIMPLAS		2					2		
SIPA			3						4
SPM			3					3	
T2			3				2		
TECNOMATIC		2					2		
TERMOSTAMPI		2						3	
THERMOPLAY			3						4
UNION SPA		2					2		

A. Cluster Analysis

For Cluster analysis, the Euclidean distance is first calculated between each two companies. Euclidean distance is calculated for the case companies as it is measure of the distance from the centre. 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 given in Fig. 22.

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 Dendogram of cluster analysis is shown in Fig. 23. The clustering of case companies is shown in Fig. 24.

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

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

Fig. 22 Calculation of the Euclidean distance between every two companies of 38 total companies

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

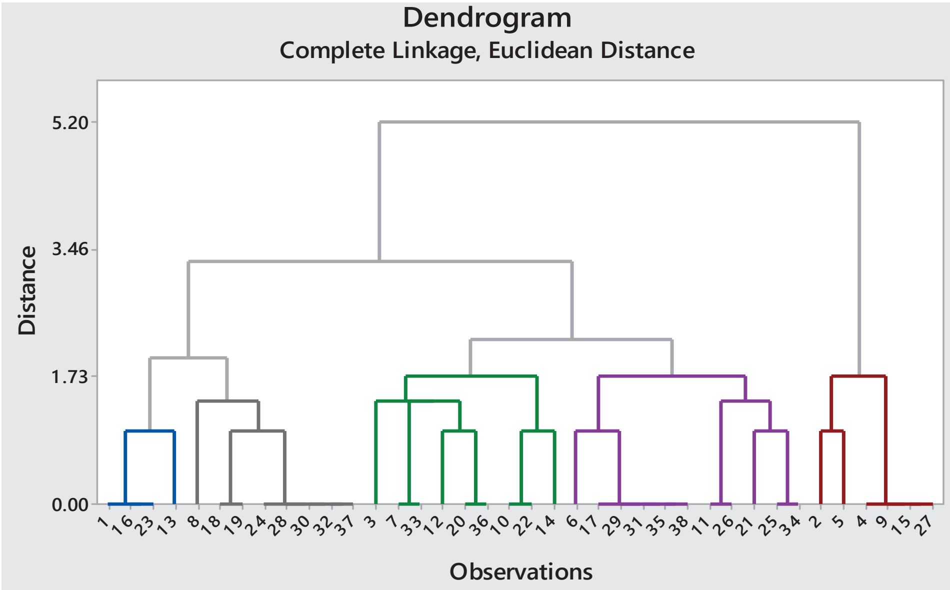

Fig. 23 The dendogram clustering of the 38 sample companies

Amalgamation Steps

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

Fig. 24 Clustering of Case Companies

TABLE III
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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