Logist. Res. (2012) 5:113–121
DOI 10.1007/s12159-012-0085-x

REVIEW ARTICLE

Decentralized manufacturing systems review: challenges and outlook

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Received: 3 August 2012 / Accepted: 23 August 2012 / Published online: 4 September 2012

Abstract During the last three decades, the economic landscape has abandoned its local characteristics and evolved into a global and highly competitive economy. The market demands toward high product variety, the low human labor costs in specific locations, the evolution of Information and Communication Technologies, and specific social and political forces are the principal reasons toward globalization. The main trend currently outlining the development of manufacturing paradigms is the ever-increasing tendency in the direction of decentralization of manufacturing functions toward decentralized entities. This has caused a fundamental reorganization process of the manufacturing organizations in order to cope with this trend. Several critical issues rise in the control and management of such organizations. These criticalities are further compounded by the need to achieve mass customization of industrial products, as this greatly complicates the manufacturing and supply activities. Moreover, the modalities for the configuration and implementation of each of the distributed manufacturing typologies are identified. The purpose of this paper is to specify the main trends, issues, and sensitive topics that characterize the behavior and performance of these production systems. Based on this review, a discussion over existing production concepts is performed.

Keywords Decentralized manufacturing · Globalization · Production concepts · Mass customization

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1 Introduction: globalization and economical facts

The economic landscape has drastically altered during the last three decades. The local economy has evolved into a global and highly competitive economy. Industries started to operate on a global basis expanding the limits of their business. The export of finished goods to foreign markets has been the dominating theme in the international trade up to the 1990s, and gained even more attention the last decade. Moreover, location-specific factors such as low-cost labor and highly skilled personnel in specific locations enabled the globalization. Enterprises started to seek for fertile production environments into developing or developed countries [1]. A number of developments have fueled the effectiveness of global production (Fig. 1). The advent of the Internet and the increasing computational power enabled globalization [2]. The widespread application of Information and Communications Technology (ICT) in the 1970s boosted the development of cooperative and collaborative structures [3, 4].

The transportation costs for intercontinental transports also keep dropping significantly. This allows manufacturers to distribute their products at dispersed production sites and markets in massive volumes. The amount of freight traffic kilometers presents a high annual growth rate and is envisioned to triple in the next 20 years [8]. The world Gross Domestic Product (GDP) grew at a Compound Annual Growth Rate (CAGR) of 5.1 % over the years 1990–2006. International trade has outmatched this trend with a CAGR of 7 %. The strong growth in trade volume further increased over the last 10 years. While for 1950–1992, the trade volume grew 1.5 times faster than the GDP, this ratio increased to 2.6 for the time period 1992–2008 [9]. The growth in trade volumes indicates that trade intensive production setups are of increasing

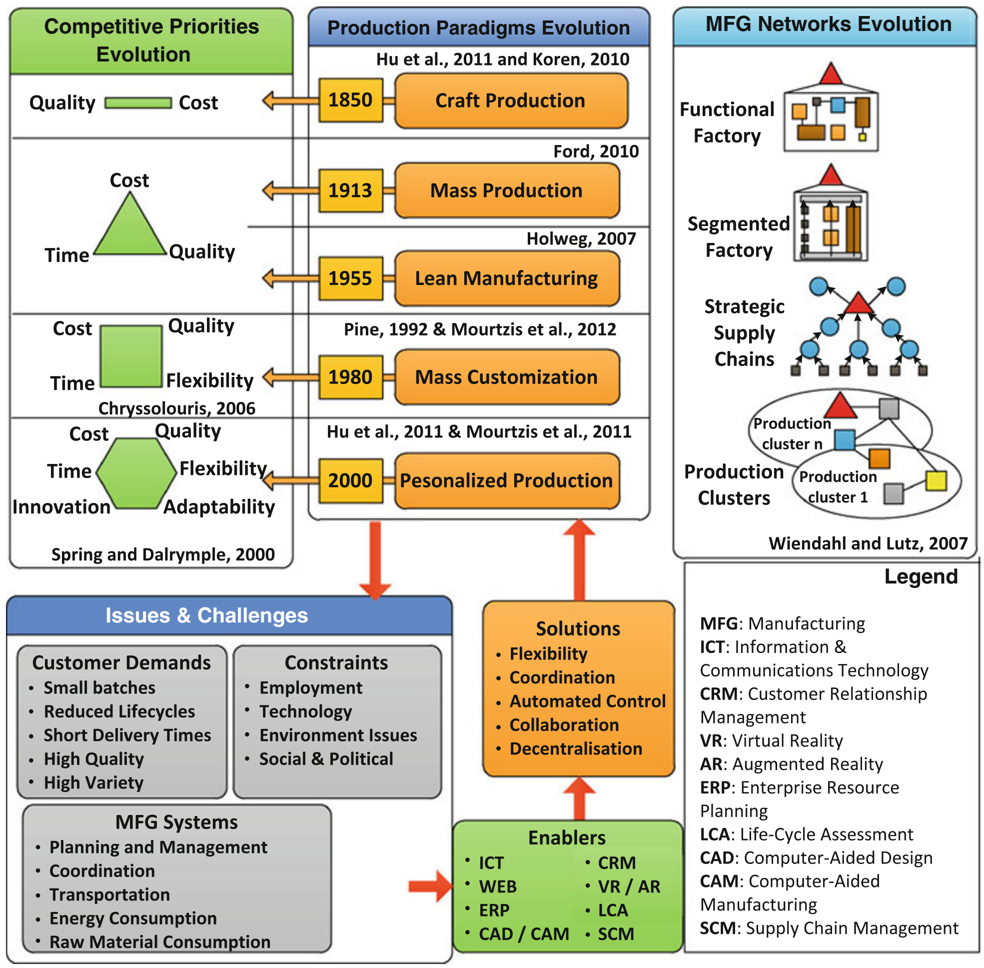

Fig. 1 Evolution of production paradigms, manufacturing networks, and competitive priorities, issues generated and solutions [2, 5, 6, 7, 12, 13, 14, 15, 20]

importance for companies. In recent years, a greater share of companies source parts and components abroad, or re-import finished goods from their manufacturing plants in other countries. In such setups, production equipment and other capital goods are exported to the country of the manufacturing site. Thereby, the trade volume increases substantially compared to the trade paradigm dominant prior to the 1990s.

The manufacturing systems, in order to compensate with these rapid developments, are continuously evolving, leading to the future paradigm. Future manufacturing will be characterized by increased automation, high flexibility, and modularity, focusing on seamless interoperability and environmental friendliness (Fig. 2).

2 Evolution of manufacturing paradigms

Manufacturing is the key driving force of the European economy. In 2010, 34 million people were employed in the EU-27 manufacturing sector, representing 15.9 % of the total employment. Indirectly (with related sectors and activities), manufacturing accounts for close to 50 % of the European economy [10, 11]. Since its birth two centuries ago, manufacturing has evolved through several paradigms, addressing the needs of market and society (Fig. 3). The first paradigm was "Craft Production" that focused on creating exactly the product that the customer requests [12, 13]. In the 1910s, "Mass Production" allowed low-cost manufacturing of large volumes of products with limited variety, which was enabled by dedicated manufacturing systems [14]. In the late 1980s, "Mass Customization" (MC) [15] emerged as a response to consumer demands for higher product variety. Manufacturers offered certain variations of their standard product [12]. Nowadays, high product variety is offered by quite every industrial sector to heterogeneous markets around the globe, via web-based means [16].

In an era of market segmentation and short life cycles, traditional manufacturing methods, like mass production,

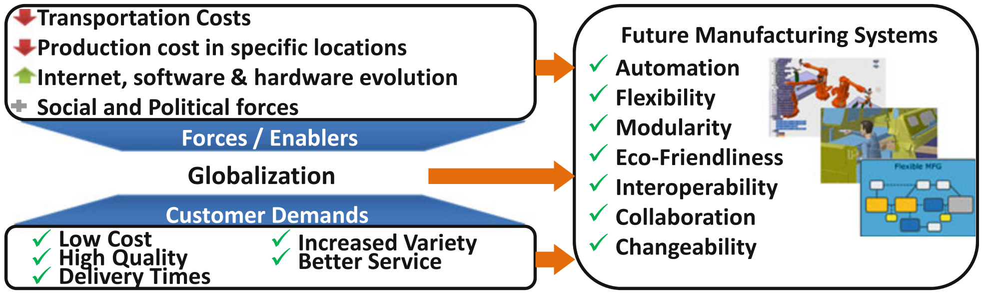

Fig. 2 Forces and enablers toward the manufacturing systems of the future

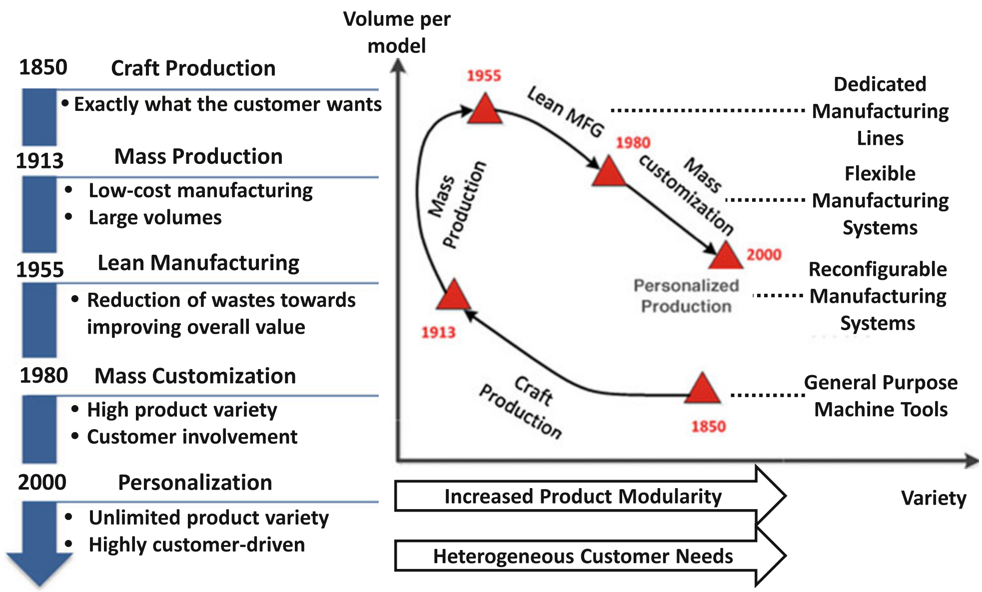

Fig. 3 Evolution of manufacturing paradigms and market needs (adapted from [12, 13])

are incapable of coping with market demand, due to their rigidity and low responsiveness. They are being replaced by the MC paradigm. Decentralized manufacturing approaches replaced traditional centralized practices, showing their benefit in delivery times, transportation costs, and agility [17]. The regionalization of production activities offers great potential to industries toward enhancing their competitiveness. Competitiveness is currently measured by the ability to perform well in dimensions of cost, quality, delivery, speed, innovation, and adaptability to demand variations [18]. To achieve such objectives, industry and academia have focused on the development of systems for control, monitoring, scheduling, synchronization, coordination, and data exchange in decentralized networks [19].

3 Evolution of cooperation structures in manufacturing

Cooperation among industries existed in the past when companies operated in relatively stable market environment where reasonable forecasts were possible and adequately accurate. Inside that "deterministic" environment, optimization was primarily focused on internal processes and manufacturing improvement [20]. However, the architectures of these information systems were fairly rigid. Production concepts that enable faster adaptation to changing market needs were developed over time. Cooperative structures with increased focus on flexibility started forming. Flexibility can be achieved internally through reorganization of structures and processes. To increase flexibility further, companies had to extend their sphere of influence to other companies, so that flexibility could be accomplished externally [21]. A differentiation between intra-firm and inter-firm production concepts with respect to the amount of flexibility becomes reasonable as presented in [22]. In addition, the choice of the building blocks of a cooperation network, the supply chain partners, is based on the analysis of their core competencies and their coherence with the network's needs and strategy. They are evaluated based on their uniqueness in the market, and their ability to provide a variety of products and services toward the satisfaction of the customer demands [20]. According to a study [23], company managers perceive "quality" as the most important attribute for a supplier. However, the same sample of managers assigned more weight to "cost" and "on-time delivery" attributes when actually choosing a supplier. Furthermore, due to increased legal and public environmental conscience, companies integrate environmental criteria into the supplier selection process. Humphreys et al. proposed a framework of quantitative and qualitative environmental criteria that a company can consider during the supplier selection [24].

3.1 Supply chain management (SCM)

In the 1990s, a fundamental transformation took place on the strategic level of the manufacturing domain [20]. Increased complexity led companies to the decision whether to produce or outsource, concentrating only on high added value procedures. Following that, companies started to outsource entire components and modules. The formation of strong bonds between the stakeholders took place, and the networks were linked by logistic companies. This resulted in the establishment of supply chains (SC). Inside a SC, companies cooperate with suppliers over various tiers in order to improve business performance, by reducing the number of self-manufactured components and by substituting them by components from external partners [25]. Such SC networks are commonly led by one central organization, mostly the end-product manufacturer. The company's goal is to add value to its products as they pass through the SC [26], and integrate and coordinate the operational activities with decisions and actions of their external business partners [27]. Moreover, SCs allow the transportation of products to geographically dispersed markets in the correct quantities, with the correct specifications, at the correct time, and at a competitive cost [18]. Enterprise resource planning (ERP) systems were developed over time (Fig. 4) for the management of internal and external resources, and for facilitating information flow.

3.1.1 Centralized supply chain

A centralized supply chain is regarded as one entity that aims at optimizing the system performance [26]. In the first half of the twentieth century, large manufacturers began to study the emerging global supermarkets. They aimed at enhancing their production planning in terms of storing and self-stocking technics. Toyota in the framework of the Toyota Production System (TPS) developed the Kanban subsystem. Kanban aimed at controlling inventory levels, production and supply of components, and in some cases even raw materials [28]. Many systems that follow the Kanban logic have been proposed, depicting the difficulties in applying the Kanban logic in real productive systems or on highly complex and decentralized systems [29]. Different production environments require different SC coordination mechanisms [30].

3.1.2 Decentralized supply chain

A decentralized supply chain differs from a centralized as the entities that comprise the network act independently in order to optimize their individual performance. Although firms throughout the globe realize that the collaboration with their supply chain partners can improve their profits, the decentralization of inventory and decision making is often unrealistic [26, 30]. The need is presented to not only to coordinate the activities of the independent partners but also to align their objectives in order to achieve a common goal. For reducing purchase costs and attract a larger base of customers, retailers and OEMs are constantly seeking suppliers with lower prices. These suppliers, however, may be located at long distances from the OEM sites and retailer distribution centers and stores [32]. A wider integration of the logistics into the supply chain is required [28], in order

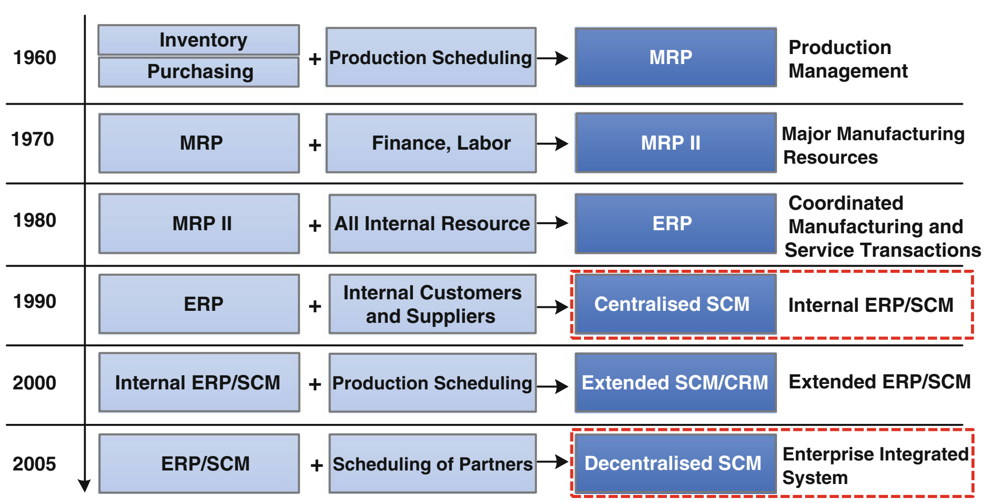

Fig. 4 Evolution of supply chain management and ERP (adapted from [31])

to enhance the performance of the collaborative production network. Globalized transportations entail some risks. A significant proportion of the shipped products are susceptible to defects due to missing parts, misplaced products, or mistakes in orders and shipments [31]. Risk assessment and evaluation models have been proposed, such as chance constrained programming (CCP), data envelopment analysis (DEA), and multi-objective programming (MOP) [33].

4 Decentralized manufacturing concepts and networks

Modularization is a fundamental organizational principle for a successfully operating globalized and decentralized entity [34]. It involves the reforming of the organizational structure into small, manageable units (modules) on the basis of integrated, customer-oriented processes. These units have a decentralized decision-making authority and the responsibility for results. The organizational structures presented below are characterized by a high degree of modularity and non-hierarchic relationships (Fig. 5).

4.1 Segmented manufacturing

The segmented factory (SF) is modularly organized in small, flexible, and decentralized structures that are self-responsible as well as market- and human-oriented. This organizational structure leads to a reduction in interfaces. Thus, coordination complexity and costs can be reduced, which is extremely important in decentralized organizations and for manufacturing modular products. Inside the company, the segments pursue different competitive strategies. They may also act as customers and manufacturers toward the other segments, which results in very efficient final outcomes [35]. The distance between operational and strategic functions is small, so that information flow is frictionless. The modular architecture and the decentralization of a SF provide the necessary structures for flexibility and changeability. In comparison with the fractal factory, however, the segmented factory has relatively fixed structures because process stability and specialization are realized to a high degree.

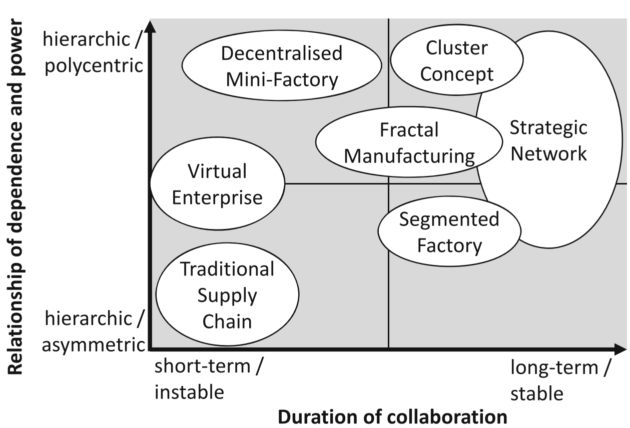

Fig. 5 Categorization of the different production and cooperation concepts (adapted from [20])

4.2 Fractal manufacturing

The Fractal Manufacturing (FM) concept comprises units, the so-called fractals, and is the prototype of the internal and heterarchical organization [36]. A fractal is an autonomous unit, the objectives, and performance of which can be described unambiguously. The FM is for many the European answer to lean production [37]. It has been practiced in many businesses and proven to be very successful [38]. The fractals are characterized by self-similarity, self-organization, and self-optimization features. The constitution of fractals could be interpreted according to the systems theory, in a way that the interior relations are stronger than the exterior relations (flow of material, resources, and information). In case of environment changes, the fractals adjust accordingly. They must fulfill the principle of vitality that is basically determined by their life cycle: conception, realization, maturation, optimization, and deterioration. Insufficient vitality results in stagnating or decreasing revenues and competitiveness. Therefore, a fundamental challenge is to constantly adjust to the exterior requirements [39]. The operative self-organization guarantees fast and flexible reactions and adjustments to changing customer orders. The tactical and strategic self-organization enables the fractals to adjust independently and to cope with highly personalized orders.

The vitality and self-optimization characteristics significantly support the capability of changeability. Fractals can grow and shrink, so that the requirement of scalability and changeability is fulfilled. Additionally, they can separate, dissolute, and restructure, because they are buildup of smaller fractals that can be grouped differently, fulfilling thus the requirements of modularity. The fact that there are functional fractals supporting the others can be added as a further advantage, because in this way, every fractal can concentrate on its core competencies. Functional fractals focus on their supporting functions and producing fractals focus on producing. An additional strength is the strong communication and interaction network between the fractals. The weakness of the FM is the high coordinative complexity. There is no centralized strategic leadership, and consequently, the fractals have to harmonize their objectives continuously. Bionic and Holonic are similar to FM concepts, but are differentiated by the biological or mathematical analogies that they draw characteristics from [40].

4.3 Decentralized mini-factories

The concept of Decentralized Mini-factories (DMF) has specially been developed to support MC. It is supposed to bridge the gap between centralized production, decentralized distribution, and customer contact. A DMF is a scalable, modular, and geographically distributed unit, located in proximity to the customer and connected to other DMFs. The DMF is able to perform distribution, maintenance, and repair service as well as additional services [41]. A central supporting unit for all DMF assures the support with standard components, fundamental product developments, and training for the employees. This central unit, however, has no decision competencies. DMFs can be interpreted as a heterarchical inter-firm network. All the DMFs are independent even though they are all part of one company. The interaction and interdependency among the DMFs are extremely low compared to all the other networks.

An advantage that a DMF offers is the facilitation of acquisition of customer information. DMFs foster a better access to "sticky information," through direct interaction with the customer, during the product specification [42]. The proximity to the customer can tie the customer closer to the factory and make a repurchase more probable (economies of relationship) [43]. Economies of relationship describe the potential of cost reduction on the basis of customer loyalty. Because of the small market it addresses, the complexity of a DMF is low and manageable. Another advantage lies in the low initial investment. A DMF can gradually adjust to the market requirements through scaling [44]. The internal organization, however, is not determined at all. Therefore, the potential of changeability cannot be generally assessed and it highly depends on the internal organization of the DMFs. An application of the DMF concept can be found in South Africa at the Automotive Supplier Park [45].

4.4 The strategic network

Strategic networks (SNs) are described by Jarillo as "long-term, purposeful arrangements among distinct but related for-profit organizations, that allows those firms to gain or sustain competitive advantage vis-à-vis over their competitors outside the network" [46]. The efficiency of a SN can be explained by the help of the transaction cost theory. The network is economically efficient if the costs of the extern partners plus transaction costs are lower than the costs of intern production. A necessary prerequisite for this collaboration is a high degree of trust. Such networks are especially profitable for young enterprises without many resources at their disposal. In sectors with high demand for changeability, flexibility, and global competition, the SNs can strengthen competitiveness and help share the risk [47]. The "strength" of a SN is the focal leader; usually the end-product manufacturer. In case the leader or hub firm is missing, the network is called "regional network." Typically, such networks are composed of small and medium enterprises that are often located close to each other.

The key factor of success for a SN is modularization; the modules and components have to be assembled finally to the end product. The end-product manufacturer determines the optimal number of component suppliers, distributes the orders, and coordinates the partners. These formal coordination mechanisms and the contractual ties limit the danger of opportunistic behavior. The long-term cooperation of a SN provides a necessary stable production environment for supporting MC. MC aims for a mass market and longer life cycles of a basic product design. In this production environment, the participating firms can develop their core competencies and specialize over time on the required market niches. Thus, a highly efficient in terms of scope economies network develops. The danger of this mutual reliance is however the strong dependencies of the firms. The firms may rely on the orders of the focal firm and do not interact directly. For this reason and due to the fact that the network is designed for long-term cooperation, flexibility is decreased. MC, however, requires a certain degree of flexibility, supporting the efficient standardization and stability.

4.5 The virtual enterprise

Virtual enterprises (VEs) were developed in the 2000s and presented a new approach to the sharing of tasks between the collaborators inside the supply chain. According to a broadly accepted definition [48], a VE is not a single corporation but a network of many corporations that are perceived by customers as one entity. VEs are set up in order to carry out a single project and after that the bonds between the partners are broken [49, 50]. The VE is extremely flexible and adjustable because its composition can be restructured very fast according to the requirements of a specific order. The problem for MC is, however, that VEs are designed for small market niches. It is optimal to quickly exploit chances that occur for a short time. MC however targets mass markets and not niche markets. VEs are appropriate for fundamentally different orders. The broad range of firms with very different competencies is at disposal to realize any upcoming order, in order to serve personalization. In order to achieve this, collaborating enterprises try to utilize the capacities and competencies of their partners, as there is no constant end-product manufacturer. This is important for the development of a long-term learning relationship and economies of relationship. Therefore, it is possible to conclude life cycle contracts for certain products. However, this does not equal the potential for establishing stable and standardized processes in a long-term cooperation for several products and product generations. The short-term collaboration and the location-independent cooperation provide high incentives for opportunistic behavior. At the same time, the need for trust is very high, because there is no central coordination, which is a problematic contradiction. A main characteristic of VEs is the mutual use of inter-organizational information systems. Typical examples of VE application are low-tech products with very short life cycles like textile and fashion retailing industries [51] and the construction sector [52].

4.6 The cluster concept

The cluster concept (CC) is basically an extension of the VEs. Inside a cluster, we find a heterarchical network of OEMs, end users, suppliers and information, machinery, resources, and materials that are needed for the operation of such a network. The difference between the CC and other production networks is that the different stakeholders may use the same infrastructure, share identical customers, and/or skills bases. Moreover, clusters can include research institutes and the government. Similarly to regional networks, there are regional agglomerations of companies, mostly specialized on one business sector. They provide advantages for both the region and the participating network. Inside the cluster, different (regional networks) can be involved, that is, the cluster itself is composed of smaller clusters. Typically, such a cluster includes large parts of the value chain and is vertically integrated. Clusters often can be found within automobile manufacturing. A prominent example is the motorsports cluster around Oxford in south England, with approximately 200 highly specialized small and medium companies [53]. Other applications of the CC can be found in Canadian maritime industry [54] and Scottish electronics sector [20, 55].

5 Discussion and conclusions

The review of the existing production concepts is based on a set of key performance indicators (KPIs). The selection of the KPIs is defined on a strategic level. The conclusions support the selection of the most suitable production network structure for the realization of decentralized production that serves a MC model.

Chryssolouris states that "in general, there are four classes of manufacturing attributes to be considered when making manufacturing decisions: cost, time, quality and flexibility" [2]. However, it is not possible to simultaneously optimize all of them because they partially contradict each other. It is rather important to find the optimal trade-off between all of them. For MC, the attributes of time and cost are emphasized. Quality became more important for the German and Japanese manufacturing. Moreover, "flexibility will become a major competitive weapon for the manufacturing industry" [2]. Decentralization of production offers many advantages toward supporting today's turbulent MC and personalization environment. MC is nevertheless a promising strategy providing many opportunities and chances. However, at the same time, its realization is highly demanding. Mass production is so successful, because it can significantly reduce complexity. Complexity is extremely high in MC due to the many variations that disturb the smooth function of the manufacturing systems. Therefore, it is a crucial requirement to master variety and to reduce complexity in order to lower costs and increase flexibility. A key element in complexity reduction is modularization and decentralization of decision making. For the coordination of these decentralized units, it is important to build upon a system of intensive interaction [56]. Communication and the exchange of information and knowledge are highly valuated in decentralized organizations. In this context, customer proximity is crucial for all customized work because it starts with the customer (customized order) and ends with the customer (delivery and after-sales services). For MC, it is an essential KPI not to only make use of Economies of Scale, but also to exploit the potentials of Economies of Scope and Integration in order to improve the performance in the dimension of costs [57]. Finally, there is the requirement that changeability, flexibility, and the responsiveness have to be maintained [19]. Apart from that, time-to-market (quick responsiveness) and customization are relevant for customer friendly customization. These concepts support the attributes of flexibility and time. In Table 1, the level of applicability of the examined production concepts for the defined KPIs is summarized.

The strengths–weaknesses analysis reveals that the examined concepts are generally applicable for the decentralized production of MC products from a strategic point of view. This is attributed to the fact that they were developed against the background of new challenges in manufacturing similar to the challenges of MC. All of the concepts exhibit a relatively high degree of decentralization. Another conclusion that can be drawn is the fact that a certain degree of hierarchy is also beneficial for MC. The least hierarchic and most flexible network, the VE also shows the most disadvantages of all concepts. Similarly, the weaknesses of the fractal factory can be weighted stronger than the weaknesses of the segmented factory. The reason is that MC does not need to be extremely flexible, because the operative flexibility and individualization are confined to a limited space of specification [58]. Furthermore, hierarchic structures decrease flexibility but help to

Table 1 Applicability of production concepts regarding the KPIs, for decentralized mass customization

KPI	Strong applicability	Medium applicability	Weak applicability
Complexity and modularization [2, 34]	Segmented factory	Fractal factory	Mini-factories
	Strategic network	Virtual corporation	
Interaction [56]	Mini-factories	Virtual corporation	
	Fractal factory	Segmented factory	
	Strategic network		
Economies of scale, scope, and integration [57]	Strategic network	Mini-factories	
	Segmented factory	Virtual corporation	
		Fractal factory	
Changeability [19]	Mini-factories	Strategic network	
	Virtual corporation	Segmented factory	
	Fractal factory		

increase the degree of standardization of processes and interfaces. This is very important to guarantee for Economies of Scale so that production costs can be lowered. The long-term development of a learning relationship between the end-product manufacturer and the consumers contributes further to the importance of a strategic leadership. The currently imposed strict environmental regulations consist of further constraints toward the configuration of decentralized manufacturing networks. The carbon emissions have to be kept under control. Moreover, the digitalization of manufacturing is an enabler for the transition from labor-intensive setups toward knowledge-based and automated manufacturing structures. The traditional structure of industrial practice is based on capital and labor; it is evident that the future needs call for structures based on knowledge and capital [59].

Acknowledgments This work has been supported by the EC funded project “A Web-based Collaboration System for Mass Customization—e-CUSTOM” (260067).

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