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REVIEW ARTICLE

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Servitization of manufacturing in the new ICTs era: A survey on operations management

Abstract Servitization of manufacturing has become one of the main pathways for transition and upgrade in the manufacturing industry. New information and communication technologies (ICTs), such as the Internet of Things, Big Data, and Cloud Computing have enabled the servitization of manufacturing in terms of value creation, resource management, and supply chain management. This study presents a comprehensive review on the servitization in operations management in the era of new ICTs. A new value chain framework is proposed under the business model that revolves around servitization, which showcases the new activities and ways of implementation in the era of new ICTs. The virtualization, configuration, and evaluation of integrated manufacturing and service resources are analyzed. In particular, the methods used in new ICT-supported resource management platforms are surveyed. Problems in the supply chain management in manufacturing services (including the selection of partners, as well as the coordination, planning, and scheduling among members) are presented. This study concludes with a discussion on state-of-the-art servitization in operations management in the era of new ICTs.

Keywords servitization, service-oriented manufacturing, value chain, resource integration, supply chain, ICT

1 Introduction

Over the past decades, significant changes have been witnessed in the supply and demand in the manufacturing industry. In terms of supply, manufacturing firms have faced fiercer competitions against the background of technological progress and emerging economic booms. In terms of demand, customers' preferences have been in the midst of the transition to personalization and customization, with an increasing focus on the use of products or the results offered by the products, rather than the products themselves. In fact, the purchase of a product is not a customer's ultimate goal (Agrawal and Bellos, 2017). Instead, a customer's real goal is the results offered by the product, as Theodore Levitt once famously stated, "People do not want to buy a quarter-inch drill. They want a quarter-inch hole!" To dovetail with changes in the supply-and-demand markets, manufacturing firms have attempted to provide more and more services to satisfy individual demands and to facilitate the use of their products. The transition — from supplying merely physical products to providing an assemblage comprised of products and services, along with the functionality of those products and services (Örsdemir et al., 2019) — is known as servitization.

A considerable number of examples of servitization in various manufacturing industries have been reported in the literature. The highest proportion of those examples is attributed to the equipment-manufacturing industry, whose industrial features such as complexity, and technology- and capital-intensive nature accentuate the importance of services to their customers (Yang et al., 2018). Lay (2014) has examined servitization in various European manufacturing sectors (e.g., aircraft, automotive, plant engineering, air compressors, and machine tools). Examples can also be found in other industries such as cloud computing (Sultan, 2014), defense avionics (Batista et al., 2017), and heavy trucks (Gaiardelli et al., 2016).

Although the prevalence of servitized manufacturing firms tends to be higher in developed economies than in

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developing ones, most manufacturing firms in China have become cognizant of the importance of services and servitization. For example, a general manager of an oil-equipment firm proclaimed during our interviews that "there will be no market share if we do not provide relevant product-centric services." An overwhelming proportion of firms have made the transition toward services: 95.6% of Chinese listed high-end equipment manufacturing firms offered services. For example, Shaanxi Blower, Taiyuan Heavy Industry and Shanghai Zhenhua Port Machinery Co., Ltd. provide customers with equipment and associated services such as installation, testing, training, and even solutions for using the equipment.

In recent years, the emergence of new information and communication technologies (ICTs), such as Internet of Things (IoT), Big Data, Cloud Computing, and Blockchain, has facilitated the implementation of servitization (Culot et al., 2019; Opresnik and Taisch, 2015; Rymaszewska et al., 2017; Wu et al., 2018). ICTs also have huge effects on operations management (Olsen and Tomlin, 2019). For example, Big Data has enabled firms to provide new services such as preventive maintenance, advanced pricing and consulting (Huxtable and Schaefer, 2016). Big Data also plays an important role in modern operations management, such as customer-driven supply chains, agriculture supply chains, and service operations (Singhal et al., 2018; Choi et al., 2018). Moreover, the IoT and Blockchain enable remote and real time monitoring, diagnosis, control, and optimization within factories and across geographically dispersed assets (Babich and Hilary, 2020; Olsen and Tomlin, 2019). Besides, new ICTs have promoted the integration of manufacturing and service sources through cloud manufacturing service platforms (Rabetino et al., 2017).

Therefore, several new questions have arisen from servitization in such an era of new ICTs. First, from a value chain's perspective, servitization aims to create more value. The traditional value chains in manufacturing firms' are bound to be reconfigured under the business model of servitization in this era. However, what is the framework of new value chains? What are the new activities and new methods used to implement these activities? Second, from an operational perspective, if a firm attempts to adopt the business model of servitization, such a firm must be an integrator of manufacturing and service resources. Manufacturing and service resources should be integrated to provide a total solution, i.e., an assemblage of product and services, or a functionality offered by the product and services. However, what are the effective ways of resource integration in this era of new ICTs? Which approaches are efficient? Third, when the various manufacturing service (MS) resources can be integrated with aid of ICTs, what are the new methods applied in the selection of partners, and the coordination, planning, and control of the MS supply chain in this era of new ICTs?

However, given the emergence of servitization as an incipient business model, related problems have emerged such as the MS value chain restructuring, MS resource integration, and MS supply chain management in the new ICTs era. The above questions have remained unanswered. To address them, we conducted a comprehensive survey of considerable literature. To the best of our knowledge, reviews on the operations management (OM) in servitization are scant. In particular, reviews on operations management in servitization against the background of new ICTs are lacking. Therefore, this study represents a pioneering effort to elucidate on the operations management in servitization in the era of new ICTs. We focus on the value chain reconfiguration, resource management, and supply chain management in the era of new ICTs under the business model of servitization. From the operational perspective, we use terms such as MS value chain, MS supply chain, and MS resources throughout this study.

This study is organized as follows. Section 2 presents the MS value chain in an era of new ICTs. Section 3 delineates the MS resource integration and configuration, including the virtualization, configuration, and evaluation, in the era of new ICTs. Section 4 analyzes the MS supply chain management. Section 5 concludes this study and provides suggestions for future research.

2 Value chain reconfiguration

Porter (1985) defined a value chain as "a collection of activities that are performed to design, produce, market, deliver, and support its product", and subdivided a business's activities into two categories, that is, primary and supporting activities. In addition, the value chain as defined by Porter (1985) involves mainly the manufacturing process of physical products, which realizes value addition through the manufacturing assembly. The value chain is threefold: Product research and development (R&D) in its upstream, production and manufacturing in its midstream, and marketing in its downstream (Hu, 2004).

2.1 MS value chain

The increasing number of manufacturing firms create value and foster a competitive advantage through servitization (Gebauer et al., 2012; Spring and Araujo, 2013). Therefore, activities in the value chain and ways of value addition accordingly undergo tremendous changes. In addition, the activities in a traditional value chain are relatively less, in which value addition is achieved mainly through manufacturing-related activities. In the model of servitization, more service activities are observed in the value chain. Firms navigate upstream (i.e., R&D) and downstream (i.e., marketing) to exploit higher-value business activities (Davies, 2004). As a result, the framework of the traditional value chain is unsuitable for analyzing the ways of value addition under servitization, warranting the development of a new framework.

Existing research on the restruction of a value chain and value addition under servitization has been based on the traditional value chain. A value addition-based model for appending related services to products is constructed and used in manufacturing industries to create customer value and foster a competitive advantage (Verstrepen et al., 1999). Additionally, a four-stage value addition-based model is proposed based on the product life cycles. In the first stage (i.e., manufacturing), materials are processed into parts, components, and subsystems; in the second stage (i.e., system integration), parts, components, and subsystems are assembled into the final product; in the third stage (i.e., operation services), operation and maintenance are performed on the service system; and, in the fourth stage (i.e., marketing and after-sales services), branding, marketing, delivery, and after-sales services are offered (Davies, 2003). These two studies characterize the process of value addition based on the product life cycles, but lack quantitative research on the value addition for each stage. Although subsequent research has focused on visualizing the degree of value increment, little quantitative measurement on the degree of value added exist. For example, Ma and Wei (2011) proposed three methods to add value: Primary activities of manufacturers and retailers, introduction of additional services to increase product demand, and provision of services through manufacturers and retailers. However, these proposed methods do not quantify the value added in each way.

In addition, manufacturers should design appropriate value chains corresponding to different product-service system (PSS) portfolios. Shou et al. (2016) argued that, across PSS portfolios, some activities such as the firm's infrastructure and procurement do not differ significantly, whereas others including delivery logistics, marketing, services, human resource management, R&D, and operations do. The authors have combined three PSS portfolios to restructure the value chain and discerned differences between activities under those portfolios. Nevertheless, the authors have adopted the traditional value chain as their framework, thereby disregarding the differences caused by the new activities under the portfolios. In addition, when key activities shift from manufacturing to the upstream and downstream of the value chain (i.e., R&D and marketing), services are offered in each stage of the chain (Han and Wu, 2018), such as providing customized design services during the R&D stage and financial services during the marketing stage. This thus cultivates value addition. Accordingly, it is necessary to construct a new MS value chain.

An analysis of the top 50 manufacturing firms in the Global Financial Analysis Library (OSIRIS) revealed that the types of services they offered could be divided into 12 categories (Neely, 2008). According to the literature and case analyses, 14 more specific service types were proposed (Wang et al., 2018). Through the case analysis, value-adding activities such as spare-parts service, maintenance, training, installation, and solution services were proposed (Matthyssens and Vandenbempt, 2010; Reinartz and Ulaga, 2008). In line with the above discussion, this study structures a framework of the MS value chain (Fig. 1).

At present, research on the restruction of the value chain under servitization has not addressed the limitations of the traditional value chain. Moreover, scant scholarly attention has been given to the new activities in the value chain and the new ways of implementing activities therein. In the future, activities in the MS value chain should be explored.

2.2 MS value chain in the new ICTs era

New activities are being performed with the opportunities offered by new ICTs (Greenough and Grubic, 2011; Ostrom et al., 2010; Persona et al., 2007). For example, numerous sensors are installed in the products in order to monitor and capture real-time operating data of products (e.g., flow rate, pressure, temperature, and vibration). By transmitting those data back in real time and compare them with normal parameters, it can provide early fault early warning, remote fault operation and maintenance (Li et al.,

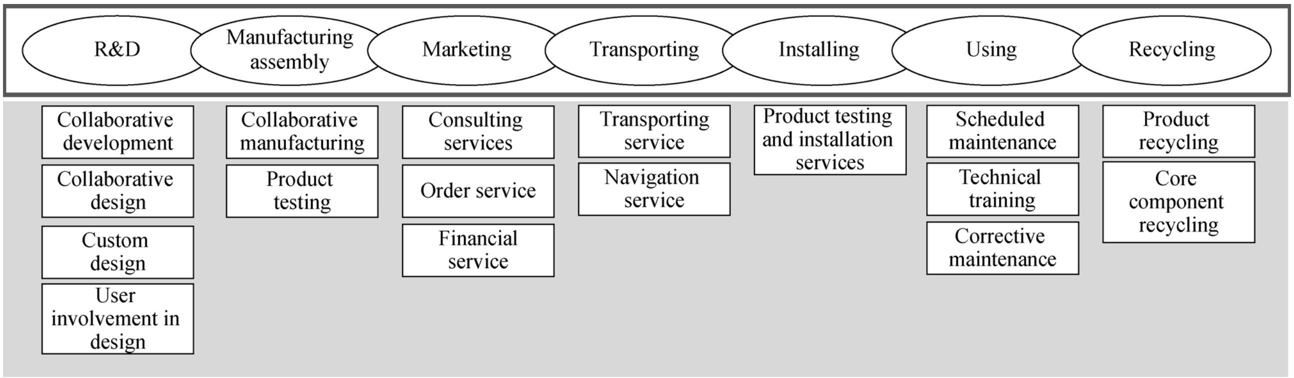

Fig. 1 MS value chain.

2015; Zhang et al., 2017b), thereby allowing customers to take the corresponding measures in time (Greenough and Grubic, 2011). By this way, it can eliminate potential failures and ensures stable operation of the equipment. It is also an effective means to improve reliability and product quality (Muller et al., 2008).

New ICTs can also enable existing activities to be implemented in new ways. Compared with the traditional ways of obtaining customers information, new ICTs such as the IoT and Big Data can offer an unique channel for firms to gain insights into how customers use their products and thus to offer better services (Lim et al., 2018; Momeni and Martinsuo, 2018). Furthermore, understanding how customers perceive and evaluate the quality of services is important to develop and design services that better meet the needs of their customers (Neuhüttler et al., 2019). In addition, integrating customer requirements into product design through the application of customer-related data can improve the extent of customization of the products and shorten the R&D cycle (Xu et al., 2017).

Moreover, new ICTs can achieve product quality monitoring in an innovative manner in manufacturing and assembly stages. Based on the analysis of such product parameters (e.g., configuration parameters, tolerance parameters), it can solve the problem of assessing product quality (Zhang et al., 2017a). It also can explore which factors might have influence on product quality, so that product quality can be improved by optimizing these factors. In addition, mining data (e.g., production history data, production plan, and inventory status) through Big Data can be used to adjust production plans in real time, and compensate for the lag of the traditional adjustment in production plans (Dai et al., 2012a; Zhong et al., 2016).

In summary, the rapid development of new ICTs has reshaped the landscape of product design, manufacturing, and use (Xu et al., 2016). Accordingly, activities in the value chain have changed significantly, in terms of new activities and the new ways of implementing the original activities. However, to the best of our knowledge, there is no complete value-chain framework has been reported. Based on the literature, this study structures the MS value chain in the era of new ICTs (Fig. 2).

Existing research on the restruction of the value chain and value addition has rarely considered their impact of new ICTs on the activities in the value chain. Therefore, an examination is warranted for the new activities in the value

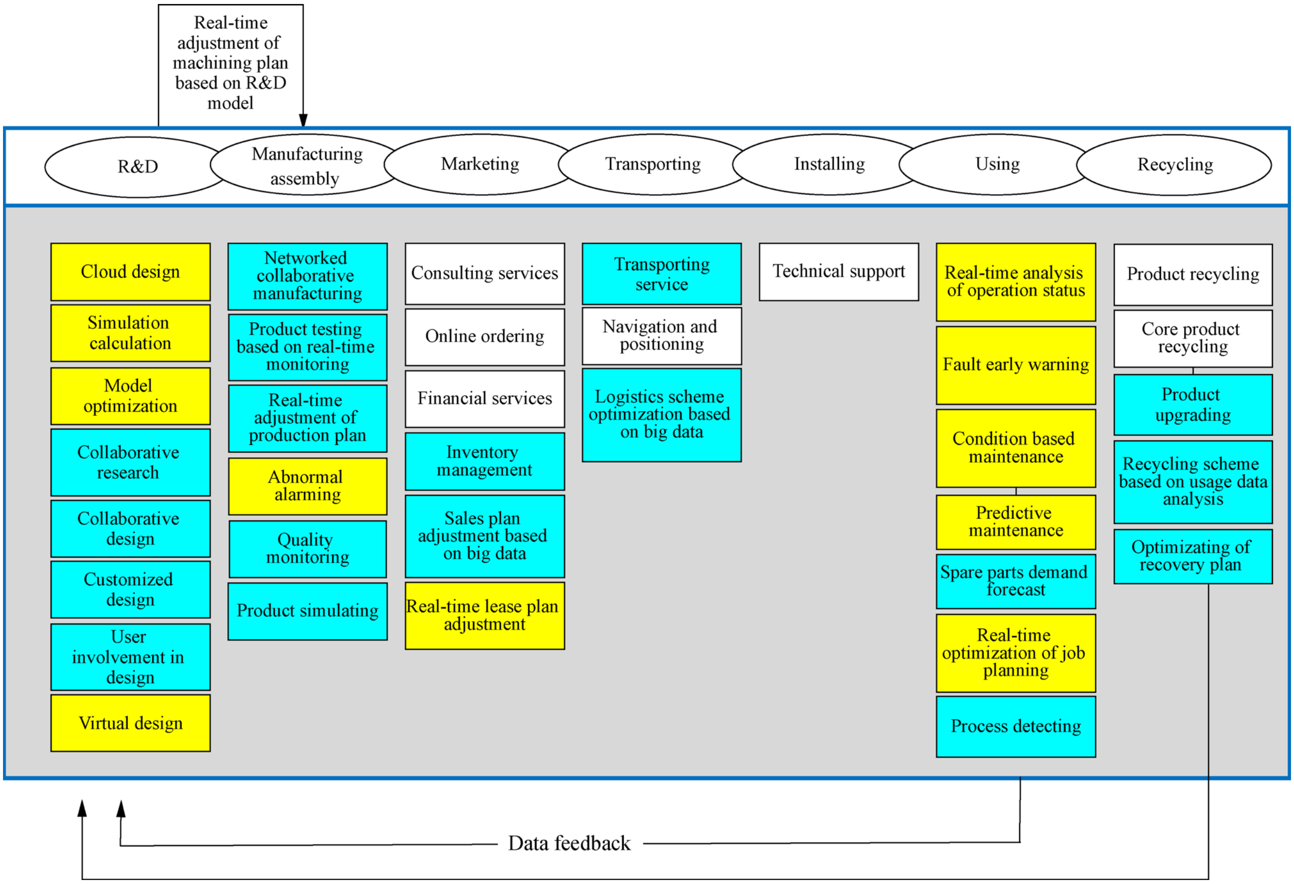

Fig. 2 MS value chain in the era of new ICTs (the yellow parts denote new activities realized by the new ICTs, whereas the blue parts denote original activities realized by the new ways of implementation).

chain, the ways of implementation of new activities, and the new ways of implementation of the original activities in the era of new ICTs.

Increasing number of manufacturing firms have adopted new ICTs to facilitate servitization, which will affect value addition (Lerch and Gotsch, 2015). Numerous benefits have been demonstrated for ICTs: Improving responsiveness (Agnihothri et al., 2002; Kryvinska et al., 2014), reducing service costs (Schroeder and Kotlarsky, 2015), extending machine uptime and enhancing operational reliability (Rymaszewska et al., 2017), and providing customers with new services to gain more added value (Momeni and Martinsuo, 2018). However, quantitative research on the degree of value added is still lacking. In conclusion, more elucidation is warranted in combining qualitative and quantitative means to appraise the value added as a new stream of research.

3 Integration and configuration of resources

3.1 Virtualization

The new ICTs marked by the IoT, Big Data, and Cloud Computing are an important feature of Industry 4.0 and smart manufacturing (Kagermann et al., 2013). The new ICTs not only strengthen the integration of manufacturing and service (Rabetino et al., 2017), but also fundamentally change the process of integration itself. The concept of Cloud Computing has been embraced in the manufacturing industry. Cloud manufacturing is the new model of servitization of manufacturing in the new ICTs era (Li et al., 2011). This new servitization model is implemented by cloud MS platforms.

A cloud MS platform virtualizes manufacturing and service resources, and integrates them through a cloud platform. All resources exist in the form of data. Given the platform with new ICTs, users at both ends of the platform can more conveniently access a wider range of services. Such a platform has stronger information-processing ability. Because of the higher dynamics and complexity of information, it requires higher efficiency of real-time processing, which may not meet the needs of practical application. The core of resource configuration is data processing and fusion to achieve data matching. Underlying the efficiency of configuration of MS resources is, in fact, the efficiency of data matching. The effect of resource configuration is mainly measured by two indicators: The speed and the accuracy of the resource configuration. According to manufacturing characteristics, resource attributes, and new ICTs, Lv et al. (2014) have propounded virtual coupling mapping, access, and corresponding dynamic matching methods of manufacturing resources, which provided theoretical support for resource virtualization. Aiming at the normalized expression and efficient cooperative sharing of massive cloud manufacturing service, Bai et al. (2017) have suggested the concept of Bill of Standard Manufacturing Service for services for product life cycles.

Cloud manufacturing resources are divided into physical and virtual resources. Physical manufacturing resources span the entire process of product production, which consist of four categories: Hard and soft manufacturing resources, manufacturing capability, and computing resources. Hard manufacturing resources include all equipment such as machining tools, processing centers, computing equipment, simulation equipment, and test equipment. Soft manufacturing resources include various models, data, software, information and knowledge in the manufacturing process. Manufacturing capability includes demonstration, design, production, simulation, experimentation, management, and integration during the manufacturing process. Computing resources include storage, arithmetic and other resources. On the other hand, virtual resources can realize the abstraction and mapping from physical to cloud resources, and describe the virtualization of various attributes of the physical resources, such as their static and dynamic attributes.

Cloud service resources are virtual resources derived from the virtualization of physical and non-physical resources, which are used chiefly to realize users' requirements. With the help of ICTs, data generated in the physical world can be sensed and transferred to the cyber world through IoT and the Internet (Tao and Qi, 2019). In this case, firms can obtain multi-source heterogeneous data from design, manufacturing, marketing, and operating services in real time. Based on these data, firms can perform condition monitoring, preventive maintenance, after-sales service, health management of product life cycles, and other services, which are supported by cloud service resources.

The application of ICTs improves the utilization of resources and promotes the sharing of resources in the manufacturing industry. However, because of the degree of informatization is not high sufficiently in reality, the cloud MS platform cannot meet the requirements of rapid responses; such shortcomings accordingly restrict its application and development.

3.2 Configuration

The existing research on integration of manufacturing resources by data matching has been well-elucidated. Some novel resource-configuration methods based on new ICTs have been proposed: Binary optimization framework (Bertsimas et al., 2014), binary integer programming model (Cao et al., 2015), dynamic 3D depth data-matching policy (Zhao et al., 2015), unsupervised data-fusion model based on joint factorization of matrices and higher-order tensors (Acar et al., 2013), and vertical integration of supply chain (Laili et al., 2012). Notwithstanding the aforesaid research on resource configuration, few studies have hitherto focused on how to improve the efficiency of resource configuration and the specific realization path of resource configuration from the perspective of resource data-processing. Additionally, the aforesaid research has been concentrated more on the manufacturing capability and on the configuration of manufacturing resources for product manufacturing process, without considering service resources.

The configuration characteristics of service resources are different from those of manufacturing resources. Manufacturing resources are storable. In other words, the time consistency of supply and demand for manufacturing resources can be solved through inventory. However, service resources configuration has higher personalized requirements, more information asymmetry and greater information cost, so that the service level and accuracy in configuring service resources are relatively low compared to manufacturing resources configuration. Therefore, acquiring timely and useful information is critical to the configuration of service resources. In addition, the new resources delivery model with Cloud Computing is characterized by pay-per-use and provided resources on demand. Thus, challenges in Cloud Computing research are found, especially in the virtual machine resource allocation. Resource allocation strategy is an important research point in the field of Cloud Computing (Passacantando et al., 2016; Wang et al., 2017). Shin et al. (2014) found that the service fee and stability are the most critical factors for end-user adoption.

From the point of configuring service resources against the background of the development of new ICTs, various service resource-configuration methods based on the cloud MS platform have emerged. Numerous objective-optimization configuration models have been proposed: Virtual machines (Buyya et al., 2009; Ma and Kauffman, 2014), clustering algorithm (Gerasoulis and Yang, 1993), genetic algorithm (Wu et al., 2014), chaos-control algorithm (Huang et al., 2014), bee colony algorithm (Lartigau et al., 2015), particle swarm optimization algorithm (Izui et al., 2013), and comparison scale assignment algorithm (Su et al., 2003). .

Existing literature has focused on the matching model and algorithm application of cloud platform-based service resources configuration. Studying the problem from the perspective of either manufacturing resources or service resources alone may lead to the failure in the allocation and sharing of the manufacturing and service resources. Therefore, it is necessary to study the matching of manufacturing and service resources under the new ICT environment in order to optimize the allocation of such resources.

From the perspective of integrating manufacturing and service resources, the new ICT platform has massive virtualized information of such resources. These resources result in different resource-combination schemes. In this regard, how to choose the optimal scheme from the numerous combination schemes and allocate the manufacturing and service resources reasonably become the key problem. Methods proposed in considerable literature have hitherto solved such a problem by establishing resource portfolio optimization models and selecting optimization algorithms.

Using topology and business process specifications, Su et al. (2003) established a bill of material for new products that combined manufacturing and service capabilities. Tao et al. (2011) designed a cloud MS management prototypical system, which included a task-and-requirement parser, and various aspects of cloud service (i.e., search and matching, comprehensive evaluation, optimization and composition, allocation and call request, allocation management, and monitoring management). Most related research assumed only a single management center for all manufacturing and service resources in a manufacturing cloud. However, this assumption could compromise the efficiency (e.g., scheduling time) and service quality (e.g., response time). Accordingly, Lin et al. (2017) proposed a multi-centric optimized configuration method of manufacturing resource and capability.

Given the complexity and dynamics of manufacturing and service resources, the practical problems differ in characteristics, and the requirements of matching algorithms likewise differ, the accuracy and run time of matching algorithm are still need to be improved. We should design efficient algorithms based on the characteristics of different problems. For future research, attention should be paid to devising an application-based manufacturing task-allocation system based on a cloud MS platform, optimization of the actual effect of the application of the model, and further exploration of theoretical problems. At the same time, to improve the efficiency of MS resource integration, we can study the optimization of MS module, the rationality of measurements of the MS module, and the coordination of dynamic control and scheduling of the MS module design.

3.3 Evaluation

From the perspective of the integrated evaluation of MS, the efficiency and accuracy of the resource configuration of the new ICT MS platform are critical to the operation of the platform. To allocate cloud resources efficiently, varying important factors such as reliability, performance and power consumption should be considered (Qiu et al., 2016). In this regard, the introduction of evaluative models and algorithms into the new ICT MS platform can further ensure the smooth operation of such a platform. Computing the matching quality of MS resources through a set of evaluation criteria is the main technical means and basis for guiding the integration of MS. The following aspects in appraising MS resource configuration have been researched: Establishing evaluation system, establishing evaluation model, and conducting resource allocation evaluation. In addition, different evaluation indicators correspond to different demand, such as service-quality, trust, capacity assessment (Cao et al., 2017), and utility evaluation (Cheng et al., 2013).

The selection of indicators is the basis of instituting an evaluation system. Based on the characteristics of cloud services, Nie et al. (2011) established the Evaluation Index System of Cloud Services, including security, quality of service (QoS), cost, and reputation. In their study, the weight of each evaluation index was determined by the analytic hierarchy process (AHP). Based on the expert interview method, Godse and Mulik (2009) determined the parameters of software-as-a-service (SaaS) service selection, including functionality, architecture, usage, suppliers' reputation, and cost, and used the AHP to determine the weight of parameters through the method of service expert-led scoring. Huang (2013) established a cloud service evaluation index system including 11 indices: Response time, throughput, accuracy, robustness, mean time among failure, system stability, data-management capabilities, service authentication, authorization and access, scalability, and resource utilization. A cloud service evaluation model was constructed through the attribute-calculation method of QoS.

Zhou et al. (2009) presented a QoS-aware service framework integrating the QoS mechanisms from the manufacturing grid technology and communication networks, and built a QoS Evaluation Model for Manufacturing Grid Systems. Meng et al. (2015) combined direct trust, reputation, and cloud MS platform reputation, and proposed a reputation-based trust-evaluation algorithm. Li et al. (2014) used the AHP and cloud model to model direct trust and friend reputation, and proposed a trust-evaluation algorithm of the cloud MS platform, which combined qualitative analyses with quantitative calculations.

Notwithstanding their contributions of cloud MS evaluation, the aforementioned studies left enough room for further examination. In the future, the MS evaluation index system can be refined to reflect further the ability of the members.

4 MS supply chain management

The MS supply chain is an integral structure of the function grid, which revolves around the focal firm. Given the control for material, service, information, cash, and value flow, the management begins from the input of the manufacturing and service resources, through the participation of customers and the mutual corporation among members (e.g., manufacturing-resource suppliers, service-resource supplier, and MS resource integrators), and finally ends with the delivery of the PSS by MS resource integrators to the customers (Johnson and Mena, 2008).

4.1 Selection of partners

The selection of members in the virtual collaborative network is the foundation underlying the successful completion of tasks. The advent of the cloud manufacturing service model has changed the traditional system of partner selection: The sizable number of partners in the cloud platform necessarily translates into increasingly complex relationships among them. Accordingly, a precipitous increase in the types of partners and the number of evaluative indexes is observed. The (rudimentary) traditional partner-evaluation index cannot satisfy the diversification requirements of partner evaluation in new ICTs era. Therefore, an MS partner selection system is needed to be built and optimized quickly, given that such a system can improve the productivity of manufacturing and service resources.

Dickson (1966) established 23 standards for parameters such as quality, delivery time, and price, which three are considered the main indicators (Weber et al., 1991). In the above studies, only quantitative evaluative indexes have been examined, but in practical applications, qualitative and quantitative evaluative indices should be included for partner-evaluation indicators. Thus, Gilbert et al. (1994) further proposed relevant qualitative evaluative indicators, and highlighted that network infrastructure, compatibility, trust, cooperation, and effective communication are important factors for partner selection. Niu et al. (2012) argued that partners should be selected based on two aspects, namely, qualitative and quantitative. Qualitative indicators include risk and reputation, whereas quantitative ones include cost, time, and quality. However, these indicators do not include evaluation indicators specific to cloud manufacturing, such as the quality of service offered by cloud providers (Alelaiwi, 2017; Kang et al., 2015).

Under the cloud manufacturing service model, Kang et al. (2015) used the Grey Relational Analysis model not only to offer cost, reaction time, and quality factors needed by the service, but also to supplement service-related evaluation indicators. Given that previous studies rarely considered the trust relationship between partners in the cloud platform, a new evaluation indicator (the number of past relations) was presented (Alelaiwi, 2017).

The evaluation system is structured based on evaluation indicators. Prior researches have established some mature partner-evaluation systems. Talluri and Baker (1996) suggested a two-phase mathematical programming approach. Despite its consideration of numerous quantitative factors, such a proposed approach overlooked some qualitative factors; thus, the application is limited. To compensate for the inadequacy of the two-phase mathematical programming approach, Chen et al. (2001) and Zhang (2011) established a complete partner evaluation system. A three-stage evaluation model (comprised of filtering, screening, and optimization combination) is established on the principle of combining qualitative analysis with quantitative analysis in partner selection. The evaluation involves first weeding out unqualified partners quickly in the filtering stage, then selecting surplus partners in the screening stage, and finally achieving optimum partners through multi-objective optimization combination in the last stage.

However, under cloud manufacturing service model, the evaluation of the partner selection is dynamic and fuzzy. The prior evaluation system cannot meet the requirements of dynamic evaluation. Thus, a new partner evaluation system is warranted. Given the randomness and fuzziness of the qualitative indicators, the cloud model of qualitative evaluative indicators for partner selection has been established, which forms the foundation for the dynamic evaluation system (Wen and Xia, 2010). Based on indicator selection, the algorithm for dynamic partner selection through the cloud model is chosen. The dynamic and virtual partner selection model for enterprises has been reported, which consisted of the interaction, cloud-agent, application, platform, and storage layers (Zhang et al., 2011). By large-scale distributed storage systems and virtualization of storage technology, existing and prospective partners can be dynamically discovered in real time, and then in the application layer, an intelligent combinatorial optimization algorithm for partner selection can be developed.

Various research methods have been applied in the optimization of the evaluation system, such as the AHP (Lima Junior et al., 2014; Sivakumar et al., 2015), Analytical Network Process (Vinodh et al., 2011), and Data Envelopment Analysis (Toloo and Nalchigar, 2011). Considering that a rough set (based on the rough set theory) is not complicated by prior information of the data set and can better embody the objectivity of the data, a new "rough" method has been suggested to determine the weight of evaluation indicators (Liang et al., 2002). Under the basic framework of AHP, a new fuzzy programming method has also been proposed to evaluate the uncertain weights of partner selection criteria (Lima Junior et al., 2014).

Notwithstanding their contributions, the above methods are associated with shortcomings, such as the subjectivity assigned by experts in the AHP (Nguyen et al., 2015), which may cause deviations in the partner evaluation results. Accordingly, the enhancement of such methods is warranted. In addition, in the face of goal differences among partners, how to deal with the problem of the principle of conforming priority when optimize confront with? To cope with the above two problems, Liu et al. (2018) propounded a method that combined best-worst method (BWM) and VIKOR to establish partner-evaluation methods. On the one hand, BWM can reduce the subjectivity of the evaluation results. On the other hand, VIKOR can not only realize the limited order of the criterion indices, but also consider the experts' subjective preferences. Accordingly, the resultant combination will yield superior results. No solutions to large-scale partner optimization problems have been reported in the literature. Thus, given the anticipated rise in the number of partners in cloud manufacturing service platform, future research should consider the realization of the large-scale partner optimization portfolio when releasing multi-objective optimization.

4.2 Supply chain coordination management

In the MS supply chain operation, many firms cannot effectively share information with their counterparts and fail to meet the responsivity requirements of the supply chain, which in turn leads to their inability to effectively meet customers' demand. To optimize the allocation of resources and to improve the overall competitiveness of the supply chain, coordination is essential among stakeholders in the MS supply chain. Such coordination refers to the cooperation among products suppliers, service providers, MS resource integrators and customers. Through information sharing and organized planning and control between them, coordination enables adjustments in the product, service, information, cash, and value flows in the supply chain. This action is thus crucial to the supply-chain management to realize the goal of the supply chain.

Coordination in an MS supply chain refers to the cooperation based on the service capability. In such a supply chain, MS resource integrators play a dominant role among the members. On the one hand, integrators and resource providers cooperate and provide the demand of service ability; on the other hand, integrators accept service orders from customers and directly provide them with a product-service system. Therefore, MS resource coordination includes the coordination of the manufacturing and service and the coordination between integrators and customers.

(1) Collaboration between manufacturers and service providers

The supply chain virtualizes MS resources with the support of the new ICTs. Such ICTs transform the supply chain from a simple, independent hierarchy to a complex, interwoven and resource-sharing one (Xu, 2012). The management method of the supply chain is more flexible, and it implies more rigorous requirements for dynamic interactions and agile responses of each node in the supply chain.

Existing literature has centered on product and service supply chains, with somewhat mature research on the MS supply chain model. However, research focused on the management of an MS supply chain specifically against the background of the new ICTs is little. Meier et al. (2010) proposed an integrated product service system (IPSS) for the organizational structure of the network comprised of numerous members such as component manufacturers and service providers, alongside (for industrial product service systems) module providers, integrators, and customers. IPSS redefines the roles and functions of each member of the supply chain. Maull et al. (2014) analyzed the characteristics of services and interactions between products and services, and proposed a product process model of product service supply chains with service providers as the core enterprises.

The development of Big Data has provided the basis for supply chain coordination management, in which supply chain is evolving into digital networks (Sanders and Ganeshan, 2018). In particular, the special issue of *Production and Operations Management on "Big Data in Supply Chain Management"* introduced the Big Data research trends across supply chain management.

(2) Customer collaboration

Given that consumers demand tends to be personalized and market competition becomes increasingly fierce, manufacturing firms should achieve large-scale intelligent customization to meet the individual needs of customers quickly and accurately. Accordingly, it is imperative to improve the operational flexibility of firms, reduce costs, augment added value, reduce the risk of resource acquisition and utilization, and enhance the competitive advantage of firms. To attain such objectives, core firms in the supply chain should allocate and dispatch supply-chain resources rationally and flexibly according to the characteristics of customer's individualized demand (Yao, 2003). Much research has focused on supply-chain scheduling under the mass-customization mode. Yao (2013) established a dynamic multi-objective optimization model and algorithm for the selection of scheduling operators and for optimizing task allocation scheduling. Sahin et al. (2008) and Tormos and Lova (2001) have yielded copious results on varying aspects such as stochastic dynamic scheduling, resource-constrained optimization, and multi-objective optimization. These results offer important referential values for the research of supply chain scheduling optimization under the customization mode.

In terms of value co-creation, Li et al. (2017) proposed a set of methods on firms' implementation of a product-and-service system for customers' needs. Hu and Han (2018) proposed a value co-creation model employing the efforts of both manufacturing firms and user firms. The authors discussed the mechanism of the efforts of both parties to attain two goals: Decrease the total cost of manufacturing firms and enhance the total utility of user firms in different product-and-service combinations. Under constraints for this two-party effort, they proposed a model for selecting product-and-service combination and genetic algorithm for those goals. Zine et al. (2014) propounded that the manufacturing firms and user firms should realize the theoretical framework of the PSS value co-creation through cooperation and mutual benefit.

4.3 Planning and scheduling MS

On the joint management of product quality and operations management, current research mainly focuses on optimizing the preventive maintenance combining with the reliability of equipment. Research on optimizing the policy of maintenance services has revolved around the following: Determining the optimal level of improvement in upgrading and maintenance services (Shafiee et al., 2011), ascertaining the optimal policy in preventive maintenance (Wang et al., 2015), determining the optimal decision-making of product-reliability repairs in periodic preventive maintenance (Darghouth et al., 2015), and optimizing decision-making of different upgrading policies in maintenance services (Öner et al., 2015).

Limited literature has centered on the joint optimization of product design and maintenance services. Liu et al. (2013) studied the unilateral optimization concerning the optimal warranty policies under different product reliabilities. Selçuk and Ağralı (2013) examined the maintenance services in terms of the inventory management of spare parts (a small part in the decision-making therein), and the product reliability. Huang et al. (2007) and Dai et al. (2012b) presented the joint optimization of product quality, warranty coverage, and pricing. It is noteworthy that there were no decisions on the after-sales service in their research and only warranty coverage was a decision variable. However, manufacturer of equipment sells the usage of the equipment in the servitization and ensures their functional performance throughout the whole life cycle. Therefore, the manufacturer does not need to decide on the warranty coverage (in other words, the coverage would be the whole life cycle), but should decide the aspects in the maintenance services, such as the maintenance period and the effort of each maintenance action.

For the maintenance of equipment, existing research has focused on component maintenance, including component-migration technology (Fuggetta et al., 1998) and hot swapping (Appavoo et al., 2003). Future research should consider how to solve the performance problems of the new ICT platform, based on the data, software maintenance, and other aspects of the platform.

5 Conclusions

This study reviews the state-of-the-art problems in operations management in the servitization of the manufacturing industry in an era of new ICTs. Given the advent of Industry 4.0, servitization of manufacturing is crucial in the academia and the industry. The literature reviewed in this study offered insights into the industrial implementation of the servitization strategy. First, after a review of the new (especially, service) activities and new implementation methods of activities under the framework of the value chain, a new MS value chain framework in the era of new ICTs is restructured. The new framework provides an overview of the value-creation activities of servitization in manufacturing, which can be helpful for managers to comprehend the new business model. Second, from the data perspective, the cloud MS platform facilitates the manufacturing and service resource integration and reconfiguration. The methods and approaches applied to virtualization, configuration, and evaluation for such resources are surveyed. These operational-level studies may enlighten managers on the implementation of the servitization model in terms of operation and even projects in such an era of new ICTs. Last, tactical-level problems in supply chain management such as the selection of partners, coordination among members, and planning and scheduling are also surveyed. Such research gives the organizational structure, mechanism underlying the coordinated operations, and control of the manufacturing and service supply chains under the servitization model.

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