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Production Networks

Synonyms

Supply Network, Supply Chain Network, Value-Creating Network

Definition

Products and related services are provided by **production networks** where autonomous enterprises are linked by relatively stable material, information and financial flows. A production network typically includes nodes of suppliers and manufacturers involved in direct value-adding activities, distribution centres and logistics service providers, as well as facilities and channels for reverse logistics. The network concept puts emphasis also on the fact that enterprises operate within the fabrics of economy, society and ecosystem: they have to respect not only their customers' and own interests but also those of other stakeholders, including the social and natural environments.

Theory and Application

Architecture of production networks

It is widely acknowledged that production networks are one of the most complex and dynamic man-made systems. Their general **architecture** includes a number of tiers of external suppliers as well as manufacturers of intermediate and finished products. The products usually get to the customers through distribution centres. Some enterprises in this forward process assume multiple roles (e.g., supplier and manufacturer), and may participate in a number of networks at the same time. For instance, a producer of semiconductor components or packaging materials may serve even different industries simultaneously. Figure 1 shows a general network architecture with flows and buffers (i.e., inventories) of material between nodes. Inventories are inevitable to provide service at the customer-requested level and to enable local resource optimization, even though keeping stocks incurs costs and involves risks (due to perishable or potentially obsolete items). The network often includes also lateral links that facilitate cooperation of partners of the same type, typically in form of inventory balancing or consolidation.

Recently, as more and more attention has been given to repair, recycling and remanufacturing, **reverse activities** have become integral parts of the general production network architecture (Melo et al. 2009). The reverse logistics includes facilities like collection centres and recovery plants.

Throughout the whole network, the flow of multiple commodities is in general accomplished by **logistics service providers** who operate via different modalities such as inland surface (rail, road, waterway), sea, and air transportation, or even pipelines.

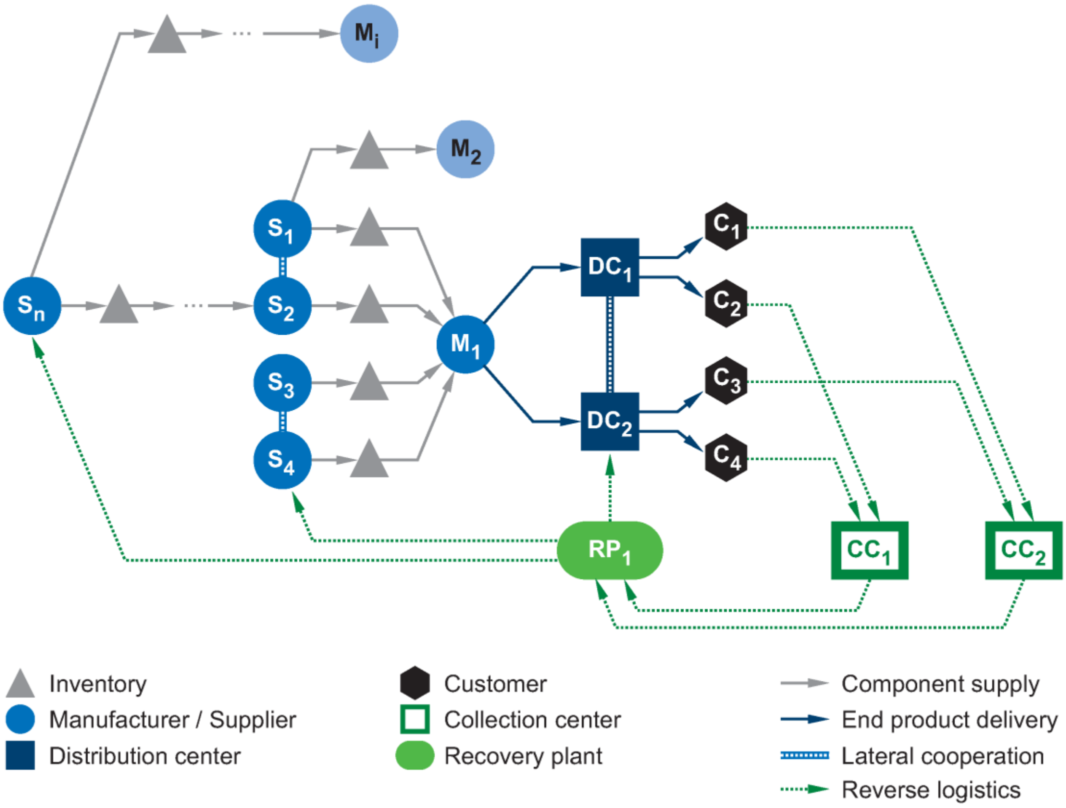

Figure 1: A generic production network architecture.

A common instance of the generic architecture is the **focal production network** where an original equipment manufacturer (OEM) produces a number of different products (e.g., consider M_1 in Figure 1). Since acceptable order lead times are typically shorter than production lead times, production is based mostly on forecasts. Part of the forecast information is shared with the suppliers in order to decrease the well-known bullwhip effect, hence long-term relations and trust are prerequisites for managing the network. Consequently, there are relatively stable relations between the nodes (e.g., key supplier and customer partnering, dedicated warehouses, etc.), and only few and rare newcomers.

Design, management and control of production networks

A production network has a complex, multi-layered, both horizontally and vertically articulated and open-ended structure which is intrinsically coupled with its behaviour. The network is serving some uncertain, changing demand in an environment that is only partially observable and predictable. The network partners, if autonomous, possess local information of future demand, costs and other conditions of business. Their internal operation is driven by individual, almost necessarily conflicting business objectives, logic and decision mechanisms. Some of them are even in a competitive situation. Hence, it is no wonder that due to the complexities, conflicts and uncertainties involved, **designing the structure** and

planning the operation of a production network is realized on several levels of aggregation and corresponding time horizons.

On the **strategic** level, decisions are motivated by the operations strategy of the enterprise reaching the customer base with its value proposition (Simchi-Levi 2010, Holweg and Helo 2014). These decisions concern the number of tiers, commodities and delivery periods. Additionally, issues related to capacities, inventories, procurement, production, routing and transportation modes should also be handled. In case of **global** production networks, financial factors like taxes, duties, exchange rates, transfer prices as well as local investment incentives have also a strong impact on network configuration. In any case, strategic design decisions have to be made under uncertainty. Against all the complexities of production networks, their **performance measures**—at least as discussed in the literature—are surprisingly simple. The majority of indicators relate to some forms of cost, far less to profits, and only few researches tackle multiple objectives like return rate, resource utilization, service level, cycle time, flexibility, robustness or sustainability measures (Melo et al. 2009).

The strategic production network design models are still rooted in the **facility location** problem (Olhager et al. 2015). Some extended formulations include both the aspects of production and distribution. There have been much recent efforts in making fundamental decisions about structure and behaviour by anticipating **inventory management** decisions, too. As for inventories, their points and levels are of primary concern. If multiple commodity, multi-period and multi-layer models are dealt with, their solution poses a serious challenge even if the models are deterministic and have single criterion (Melo et al. 2009). Nonetheless, network design should handle the randomness of some basic model parameters (like demand, various cost factors, exchange rates, etc.) and plausible future scenarios. The deterministic models can be applied in a two-stage design process where the design variables are implemented before the realization of random variables are observed, and then the second-stage usage variables determine the recourses needed to warrant the feasibility of the design (Klibi et al. 2010, Olhager et al. 2015). The numerical solutions typically work with a finite number of possible realizations, or scenarios, which have an essential impact on the future adaptability of a particular network design.

Alternatively, one can define a pragmatic mapping between key network features or decision variables, such as demand volatility, supply chain vulnerability, necessity for economies of scale, requirements of consistent process quality, proximity of customers, market specificity of products, customer tolerance time, value density (item cost per kilogram or cubic meter), as well as patterns of production networks spanning from centralized to decentralized architectures. Figure 2 shows characteristic network patterns and significant correlations among key decision variables.

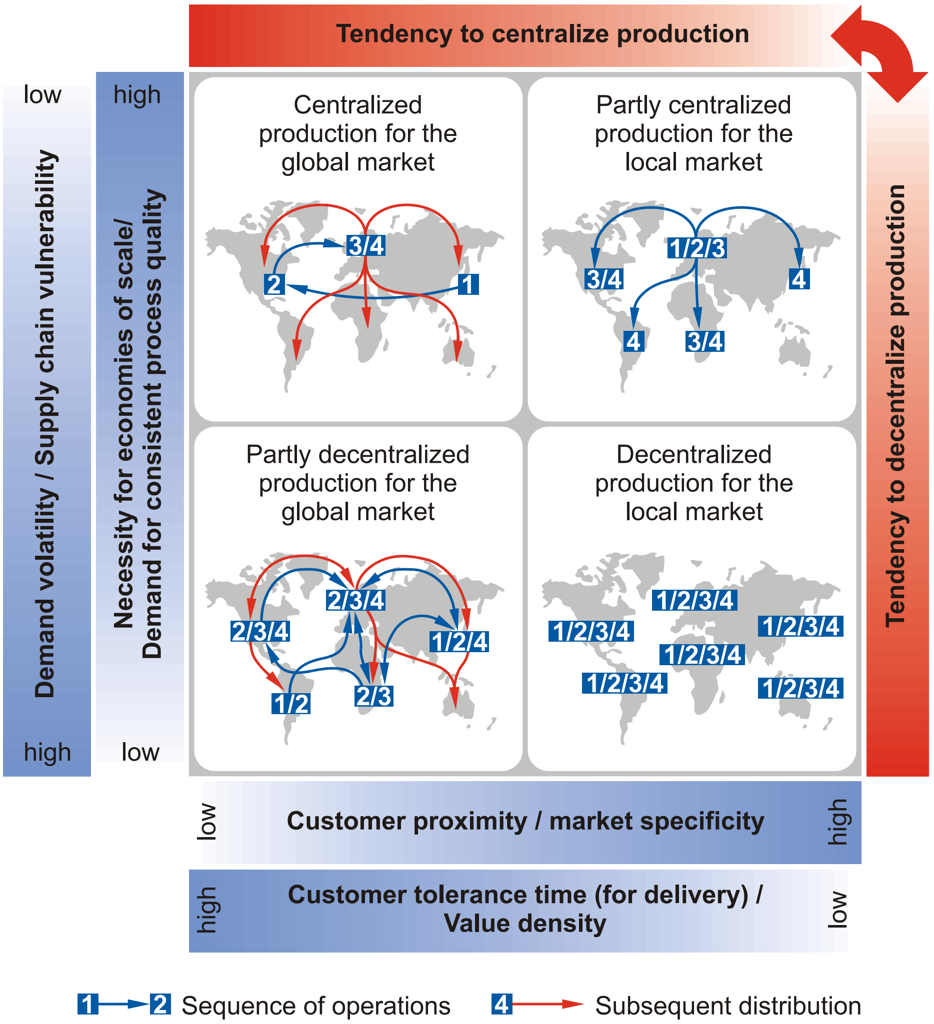

Figure 2: Formation of production networks (Váncza et al. 2011, after Abele et al. 2006).

On the **tactical** level focus is set on achieving strategic goals by advance planning and the coordination of logistics and production operations in the medium term. Here planning is a recurring effort to match future demand with supply by relying on partly asymmetric and uncertain information. Planning necessarily crosses the boundaries of the individual enterprise and integrates procurement (upstream), production, as well as delivery and distribution (downstream) decisions. However, **inventories**, seemingly passive and non-lucrative elements of business can be turned into key factors of coordination.

The basic setting of networked production where decisions are made autonomously at the nodes implies a **decomposition** scheme. Accordingly, the coordination of distributed planning decisions is performed in a top-down, hierarchical way. In the course of so-called **upstream** planning, starting at the downstream party (e.g., OEM), local planning problems are solved in a sequence where the solution of one partner sets targets for the next one (Albrecht 2010). The inevitable sub-optimality of the decomposition approach calls for **centralized** supply chain planning methods which are of theoretical relevance, but hardly applicable under realistic market conditions. The potential loss from decentralized versus centralized decision making in supply networks is referred to as the price of anarchy. The key question of **coordinated planning** is whether it is possible to decrease this price, to circumvent the deficiencies of the decomposition method when there is no opportunity for centralized planning. The autonomy of network partners fairly complicates the answer: each partner takes an individual planning and control approach which fits its specific market, production and supplier requirements. But all partners' operations have to be synchronized with the same planning and control logic to guarantee the achievement of common targets. Though there exists a number of enterprise resource planning (ERP) and supply chain management (SCM) systems that offer technology for information storing, retrieval and sharing within and between the nodes of a production network, these systems are mainly transactional: they do not really support coordinated decision making (Váncza et al. 2011).

Finally, on the **operational** level detailed scheduling of production and logistics activities are accomplished in the short-term. In addition, **tracking and tracing** of the commodities supports near-time control which is responsible for executing the schedules and reacting to unexpected events at the time of realization.

Challenges and Directions of Research

Research of modelling and analysing, as well as designing, managing, planning and controlling production networks is largely multifaceted, diversified and multi-disciplinary in terms of its apparatus. Some recent key issues investigated intensively are the following.

Information and communication technologies

Information and communication technologies (ICT) establish channels for interlinking both enterprises and their customers. These channels are the main technological enablers of globalization (Koren 2010). Since ICT allows members of a network to widen their span of interest and control, the distribution of information and decision rights introduces some new elements of uncertainty. In fact, ICT services invisibly pervade into everyday objects and environments: information access and processing are made easily available for everyone, from everywhere and any time, enabling users to exchange and retrieve information they need quickly, efficiently, and effortlessly, regardless of their physical location. The trends point towards the integration of several technologies like identification and tracking, wired and wireless sensor and actuator networks, the internet of things, and distributed intelligence for smart objects, to name only the most important ones. However, one has to face the challenges of interfaces and interoperability, of handling big bulks of data as well as giving common interpretation to the data. Furthermore, networked communication raises special security and safety issues as well.

Risk management and robustness

Recent research incorporates the management of **risks** in network design and planning. Risks may have a number of different sources, such as uncertain economic cycles and consumer demands, or unpredictable natural and man-made disasters (Simchi-Levi 2010). Of the main risk types supply networks have to face, **demand uncertainty** is investigated most thoroughly, captured by stochastic models (Klibi et al. 2010). Facility location and inventory control decisions together can result in **risk pooling** solutions. Other form of containing risk is based on preventing disruptions by investing into slack capacities, excess inventories or insurance policies.

On the tactical level planning, partners can be made interested in cooperation and truthful information exchange if their **incentive scheme** facilitates the sharing of both the benefits and risks of acting together. Simply said, the partners should laugh and cry together. Such incentives can be formulated in terms of appropriate **contracts** such as the quantity discount and buyback/return contracts, or the application of revenue sharing agreements instead of fixed prices.

Robustness is the general quality of a network to remain effective and efficient in face of plausible future changes of its environment. Robust production networks are set up and run with special concern on mitigating risks: while **resilience** is directly related to the structure and resources of a network, **responsiveness** dampens the impact of changes and uncertainties that relate to the operation and behaviour of a network (Klibi et al. 2010).

Collaborative planning and channel coordination

To complement the division of labour among parties in a production network, **coordination** is essential for synchronizing actions so as to achieve some common, system-wide goals (hence, often the term collaboration is used). Members of a production network that are cross-linked by communication channels are not only able but also willing to interact with each other, i.e., exchange information about their products, expectations (forecasts), intentions (plans), and status. **Channel coordination** aims at improving overall supply chain performance by aligning the plans and conflicting criteria of related enterprises. It involves ordering, available-to-promise and inventory planning decisions of the partners. Disparate objectives and the decentralization of decisions may lead to suboptimal overall system performance and be the root causes both of acute material shortages and excess inventories.

As the strong notion of coordination suggests, a supply chain is coordinated if and only if the partners' locally optimized decisions are implemented and result in system-wide optimal performance. This problem can be captured in a **game theoretic** setting: how to find a set of optimal supply chain actions (i.e., production and delivery) that result in an equilibrium from which no partner has an interest to deviate? The game theoretic perspective leads to theoretical contract models that coordinate a supply channel under rigorous simplifying assumptions (Albrecht 2010).

According to the weaker but more realistic notion the supply chain is coordinated if the local, self-interested production and delivery actions result in a better overall performance than the traditional upstream planning. This allows for a broad spectrum of **coordination mechanisms** that have some generic features in common: (1) While keeping the privacy of sensitive cost factors, the partners share information on their intentions (i.e., plans). (2) So as to arrive at a coordinated solution acceptable for all parties, alternative planning scenarios are generated and mutually evaluated. (3) An incentive scheme drives the partners—against their local interests—towards coordinated solutions (Kovács et al. 2013). Typically, potential benefits and risks of coordination should be shared. Note that high-quality and robust local planning and scheduling (see Schönsleben 2012) are indispensable in channel coordination as intentions communicated to other partners are generated by these functions. Robustness to local changes and disturbances prevents the ramifications of those changes through the network and forestalls system nervousness.

Autonomy, competition and cooperation

While any network as a whole is driven by the overall objectives to meet the customer demand at the possible minimal production and logistics costs, the efficiency of operations and the economical use of resources hinge on the local decisions of the autonomous partners. The issue is how to achieve and maintain the right overall behaviour of the network if the autonomous business partners decide locally, based on asymmetric and partially incomplete and inconsistent information. What would drive any partner to sacrifice some of its own goals in the hope of an eventual mutual benefit? Are there any incentive mechanisms that make enterprises interested in cooperation in general, and in sustainable manufacturing and logistics operations in particular? In a network, **cooperation**, an interactive relationship makes it possible to harness knowledge of other partners or to make use of their actions in the service of joint interests. The condition of any form of cooperation is **reciprocity** and **trust** between parties who can decide and act in their own right. Cooperation is the alignment of various, possibly even disparate goals in the hope of some mutual benefit. It can be developed among interrelated parties who have their own identity and discernible interests (expressed in terms of goals, objectives, utility or profit, etc.); who have the faculties for pursuing their own interest, and who admit to the autonomy of other, related parties. Here, **mechanism design** (or inverse game theory) that considers strategic interactions of self-interested agents with asymmetric, private information offers a promising conceptual apparatus for establishing such incentives or institutions that drive network partners towards cooperation (Váncza et al., 2011).

Agent theory and network science

Agent theory and **multi-agent systems**, together with their supporting information and communication technologies—such as networking, software engineering, distributed and concurrent systems, mobile technology, electronic commerce, interfaces, semantic web, cloud computing—have a particularly powerful apparatus for investigating production networks. Agents can capture decentralized, redundant, adaptable, robust and open organizational structures. Agent technology offers (1) a convenient design metaphor that enables one to structure domain knowledge (and system design, accordingly) around components that have autonomy and capability to communicate; (2) a broad array of software engineering models, techniques, formal modelling approaches and development methodologies; and (3) tools and techniques especially suitable for simulating the behaviour of complex systems operating in dynamic environments (Monostori et al. 2006). Agents can make a good service either when building fine-grained enterprise models with sophisticated internal decision mechanisms and inter-firm interactions, or when capturing typically large production networks with many, coarse-grained nodes and a dense net of connections. In the latter case the approach of **network science** can be taken for analysing the structure of networks that conveys rich information on desired properties like efficiency, robustness or resilience.

Value co-creation and service networks

In the past decades, the landscape of industrial production dramatically changed due to increasing customer expectations that require shorter delivery times, customized and personalized products and accompanying services. In the emerging paradigm of personalized and **co-creative** production, customers are also actively involved in the value creation process, from the decisive moment of the conception of ideas, already in the phase of product design. Co-creation is an emergent process that generates an effective solution, heretofore unattained by any independently acting partner, through interactions (Ueda et al. 2009). Thanks to pervasive connectivity, personalization has been increasingly adopted for consumer products. Through a so-called experience environment, an enterprise can engage its customers in the process of value co-creation. Offerings of the enterprise can go beyond the provision of physical products and involve also sophisticated services. Furthermore, customers may also form communities and interact in a networked environment; the emerging community itself represents a new form of added value. Hence, enterprises must offer a combination of products and services, which gives rise to **industrial product-service** (Meier et al. 2010) and **service supply networks** (Wang et al. 2015).

Sustainable manufacturing in networks

Enterprises have to respect not only their customers' and their own interests but also those of other stakeholders, including the social and natural environments. Hence, they have to take a socially responsible and sustainable approach and be conscious of the parsimonious use of material, energy and human resources. Ecosystems that provide fundamental life-supporting **services** (like purification of air and water resources, etc.) are also capital assets, but relative to other forms of capital (production capacities, inventories, etc.) these are poorly understood, scarcely monitored and may undergo rapid change and degradation. Because these services are not traded in markets, society has no feedback mechanisms to signal changes in their supply. Hence, there is an urgent need of incentive mechanisms that reward the proper management of such assets in combination with the traditional business objectives related to productivity, profitability, and competitiveness (Váncza et al., 2011).

So far, mathematical analysis, simulation studies and experimentation with human subjects have distinguished a couple of basic mechanisms of cooperation among which **reputation** and **trust** are fundamental. In a socio-economic environment where commitment to core values of enterprises—such as integrity, goodwill, respect, image—really matters, reputation has definitely a strong power for encouraging prudent public behaviour. In production, there are already a number of specific examples where one could demonstrate how transparency and reputation could foster cooperation and a sustainable utilization of common resources. For instance, environmental (carbon) footprint, if public, can drive improved ecosystem management. There are methodologies that assess the environmental and/or social impact of production through the entire life-cycle of products. Some recent models measure the energy embodied in artefacts as they are produced by global manufacturing supply chains. There are calls for the development of a supplier code of conduct as well as "smart and green" production—both of which require measures easy to take and communicate. Building and maintaining reputation require two basic capabilities: (1) monitoring ongoing interactions, and (2) ensuring public transparency. Note that in a production network the applied ICT can by and large offer these facilities.

Towards Cyber-Physical Production Systems

Cyber-physical systems are organizations of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet. **Cyber-physical production systems** (CPPS), relying on the newest and foreseeable further developments of computer science, information and communication technologies on the one hand, and of manufacturing science and technology, on the other hand, are meant to lead to the 4th industrial revolution (noted also as Industry 4.0). By definition, a CPPS consists of autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks. Hence, exploring fundamental questions of production networks like design and emergence, autonomy and cooperation, optimization and responsiveness, trust and security should go hand in hand with the evolution of cyber-physical production systems. These investigations require multi-disciplinary research over a broad range of contemporary information and communication technologies, organizational, management and network sciences, cooperation theory, as well as production informatics and engineering.

Cross References

Agent Theory, Supply Chain Management, Industrial Product-Service System, Cyber Physical System

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