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Global Production Networks: Design and Operation

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In the course of the ongoing globalization, companies of all sizes are nowadays acting in global production networks (GPNs). However, a comprehensive scientific overview and understanding of those networks is still missing. To close this gap, a framework for designing and operating GPNs is introduced which structures the most important influencing factors, challenges, enablers and outlines the need for decision support systems. The state of the art in designing and operating GPNs is reviewed. Furthermore, three trends are identified that will help to transform rigid and historical grown networks into changeable and efficient GPNs with a focused network footprint. In conclusion, a prioritized need for future research in forming the production strategy, designing the network footprint and managing the network is given.

Production, Network, Global Production

1. Introduction

Globalization has led to profound changes in the economy in recent decades [39]. Nowadays, companies of any size operate globally in the form of global production networks (GPNs). GPNs are one of the most critical form of organization in the manufacturing sector [266] and already account for nearly 80% of global trade [240].

1.1. Phases of globalization (macroeconomic view)

The global expansion of companies and their GPNs was shaped by different economic temporal phases including different corresponding motives (see Figure 1). The shift from rigid and centralized production plants towards a production in networks dates back to the 1990s. The first phase of global expansion was driven by the increasing internationalization of large companies with the aim of exploiting favorable factor costs [238,239]. Other drivers were the development of new sales markets and the development of local just-in-time delivery systems [189]. The first phase of globalization benefited from the global reduction of trade barriers under the General Agreement on Tariffs and Trade (GATT) [5], the sharp decline in international transaction costs in transport and communications [109], and the progressive integration of Central and Eastern European as well as Asian countries [27]. The second phase of global expansion began in the 2000s. It can be traced back to the increasing internationalization of small and medium-sized companies. As suppliers of large companies, they were under pressure to follow their customers into global markets. At the same time, the opening of markets also enabled them to enter new sales markets. High domestic competitive pressure can be cited as another reason for small and medium-sized companies to internationalize. It forces local adaptation of products due to the increasing trend towards individualization [177]. On the other hand, it enables the operation of product service networks, which represent an integration of goods and services in one market offer and require a local market presence [161]. Another current driver of global expansion is access to a skilled workforce [110]. Since 2005, both international direct foreign investment and the volume of international trade

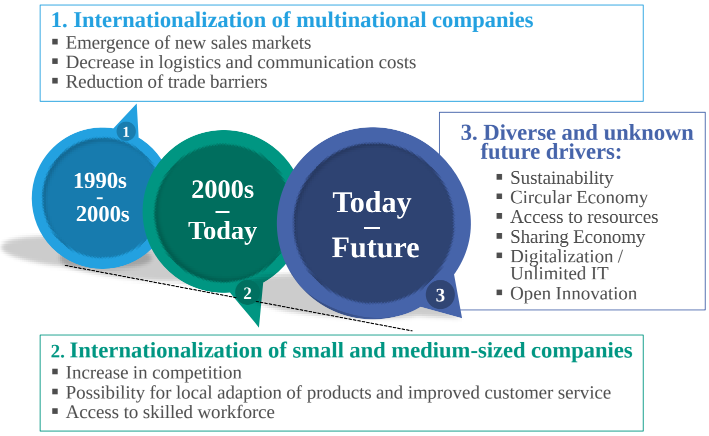


Figure 1. Motives for the global expansion of companies.

more than doubled [241]. Future drivers of global expansion are uncertain and diverse. Globalization processes typically have a geographically uneven nature [102]. Yet, the expected increase in global trading volume of finance, products, and services will rise from $ 15.8 trillion in 2016 up to $ 66 trillion in 2025 [153,265]. One economic motive that will gain even more importance is the need for increased local presence. It is facilitated by trends such as required sustainability, scarcity of resources and the emergence of a sharing economy. In particular, new developments in information technology, such as digitalization, social media, and open innovation will further influence the development of GPNs. However, it is uncertain whether the global expansion of companies will continue without halt. Backshoring of once offshored production capacities to the home base and dissolving of production networks are phenomena, that may also gain importance [128].

1.2. Expansion of networks over time (microeconomic perspective)

The phases of globalization changed existing paradigms of manufacturing. Although export from traditional centralized production had a number of advantages, the opening of market as well as decreased transaction costs forced industries to move towards distributed production networks (see Figure 2) [158]. As a first step, industrial companies started to establish sales departments abroad, aiming at sensing the needs of foreign markets and global demand. In this way, companies could operate on an international basis, expanding the limits of their businesses [174]. As a step forward, companies started to seek production environments in developing or developed countries, enabled by location-specific factors such as low-cost labor or highly-skilled personnel [34]. In addition, the increasing need for customized products forced industrial companies to open assembly or production plants in foreign markets, aiming to deliver targeted products at low cost and short delivery times. Simultaneously, industrial companies followed the new coming trend of “glocal” production [226]. It combines the development of global market and the successful fulfilment of the local requirements by establishing Research and Development (R&D) departments close to their production facilities abroad. Glocal production enables the analysis of local markets, the design of new targeted products or the (re-) design of existing products meeting local requirements.

A successful example of a production network expansion from domestic appliances industry is Arçelik A.Ş.. The Turkish company started with its first production plant in Turkey in 1955. Today, Arcelik has more than 18 production plants in six different countries. It has sales, marketing, and R&D departments in 19 countries, offering its products in more than 100 countries over the world [6]. The successful expansion of Arcelik’s production networks was not only achieved by developing new production units in different countries, but also by acquiring brands and their production plants in targeted markets.

By globally expanding their business, companies like Arcelik do not only remain competitive in their home market but are also capable of delivering targeted products addressing individual and local requirements through a sustainable production network. It must be emphasized that globalization and global expansion of production networks is characterized by a continuous and evolutionary growth in most industrial cases. Therefore, production nowadays includes inefficient structures that are difficult to plan and operate [65,70,231]. This is the main motivation for this keynote paper.

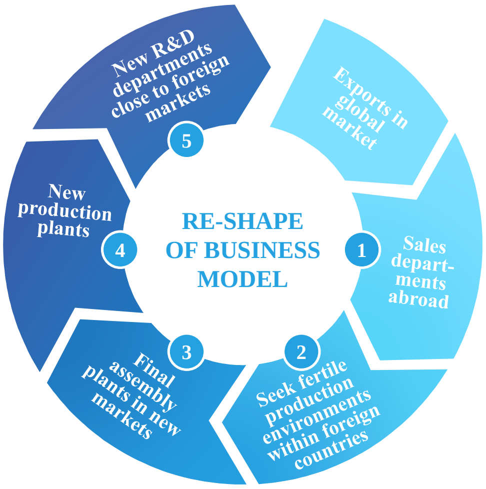


Figure 2. Expansion of production networks over time.

1.3. Structure of the paper

This paper presents the current state of the art in the field of designing and operating GPNs. At the beginning, macroeconomic phases that boost globalization (subsection 1.1) as well as typical steps in the global expansion of industrial companies (subsection 1.2) have been introduced. The outline is presented (subsection 1.3). Following, the term global production networks is defined (subsection 2.1), three core tasks of designing and operating GPNs are described and their related subtasks are introduced (subsection 2.2). Moreover, phenotypes of GPNs are presented and supplemented by industrial examples (subsection 2.3). Subsequent to these fundamentals, a framework for GPNs is introduced. It structures the most important influencing factors (subsection 3.1), challenges (subsection 3.2) and enablers (subsection 3.3) and outlines the necessity of decision support systems (subsection 3.4). Following the framework, the state of the art in forming the production strategy (subsection 4.1), designing the network footprint (subsection 4.2) and managing the production network (subsection 4.3) is reviewed. Furthermore, the most important methods and models that are deployed for decision support in research are reviewed (subsection 4.4). After deriving the most important research gaps (subsection 4.5), a look into the future is taken. Three main trends that will impact the formation of a production strategy (subsection 5.1), the design of the network footprint (subsection 5.2) and the management of production networks (subsection 5.3) are described. Based on these trends, a prioritized need for research is outlined (section 6) and a single conclusion (section 7) is given.

2. Fundamentals

2.1. Definition of global production networks (GPNs)

Products and related services are provided by global production networks (GPNs), which are complex man-made systems operating in the ever-changing fabrics of the economy, society and the ecosystem. GPNs are intrinsically dynamic, open and overlapping systems, as their structure is carved out of dense nets of interrelated actors whose activities are united in the ultimate goal of providing customer value [244]. For defining and characterizing GPNs, this keynote takes the perspective of companies operating globally, driven by some specific business purpose, mission, and strategy [99,106]. Hence, in contrast to the upcoming idea that production networks are not designed and planned but rather emerge, a purposeful, deliberate approach is taken (see also [106,129,183]).

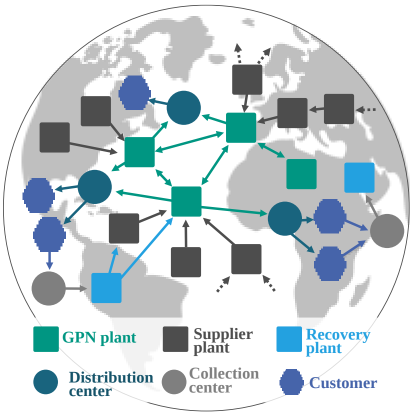


Figure 3. Structure and environment of GPNs.

Accordingly, a GPN consists of geographically dispersed production entities, which are interlinked by material, information and financial flows. GPN are designed and operated by humans. All production entities perform direct value-adding activities under a common strategy of a company. The overall network structure and the relationships within are relatively stable. This essential core of production – just in the interest of reaching markets and customers efficiently – is typically completed with distribution centers and networks [183]. If the companies' notion of value integrates economic, ecological and social aspects as well [106,245], they have to measure up to more and more demanding requirements of sustainable and circular production [234]. In this case, collection centers and recovery plants may add a new functional and structural layer to GPNs [163,254]. Figure 3 depicts the generic structure and environment of GPNs, where links between the nodes stand for material flows. It is assumed that information flow is bi-directional between any connected nodes.

Any production node in a GPN can be supported by some, or even a multi-tier system of suppliers who, however, do not operate directly under the drive of the GPNs strategy. For instance, in a supplier's role a provider of semiconductor components or packaging materials serves different industries simultaneously. Channels of forward and reverse logistics are operated by logistics service providers who are typically (but not necessarily) legally independent of the GPN. Of course, there is a way of governance as for example a company can force its upstream companies or third-party logistics service providers to engage with its sustainability initiatives [223].

In a GPN, the nodes do have a definite – occasionally, very high-level – autonomy and are often in a competitive situation. Hence, even though the GPN is driven by a common strategy, the particular business interests of the members are not necessarily aligned, just as their access to resources and information is partial and asymmetric [245].

The perspective above distinguishes a GPN from a supply chain which focuses on the step-by-step provision of a defined set of products and services to customers via the vertical sequence of procurement, production, delivery, use, maintenance, collection and recovery activities [216]. In a supply chain – or, actually, supply network – management emphasis is on the inter-organizational planning and controlling of the consistent flow of material, information and financial assets along the entire value-added chain of specific products and services [262] from suppliers up to consumers or even recovery.

In contrast, the design and operation of strategy-driven GPNs involves core tasks that can be grouped into three main categories: (1) the formation of the production strategy, (2) the design of the network footprint, (3) and the management of the production network (see Figure 4). In this context, the design subsumes the formation of the strategy, footprint design and definition of planning procedures. The planning of the corresponding actions as well as the controlling of their execution shapes the operation of a GPN.

2.2. Core- and subtasks of designing and operating GPNs

The core tasks of designing and operating GPNs can be further specified into different subtasks (see Figure 4).

Subtasks related to the production strategy include long term strategic decisions related to the market, the product service portfolio and sustainability aspects. The subtasks related to the network footprint design refer to mid-term decisions related to the geographical location of production plants, distribution centers and recovery plants. The subtasks of the network management consist of tactical-operative decisions that deal with the control and management of the company's production network.

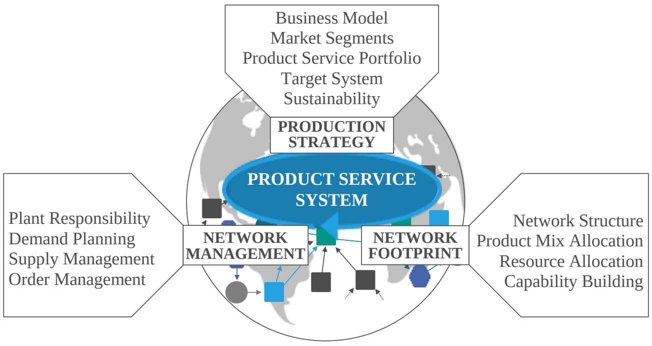


Figure 4. Core tasks and subtasks of designing and operating GPNs.

The core tasks and subtasks of designing and operating GPNs form the structure of this keynote paper. They will be explained in more detail within the illustration of phenotypes (subsection 2.3) and the review of state of the art (section 4).

2.3. Phenotypes and industry examples

Following the different core tasks production strategy, footprint design and network management, three widespread *phenotypes* for designing and operating GPNs are presented and illustrated by real industry cases. Phenotypes capture typical patterns of structure and behavior of GPNs in the eye of the observer and describe general ways in aligning GPNs. They serve as an orientation for both industry and research when dealing with the topic.

2.3.1. Phenotypes on production strategy level: A classical typology of subsidiary

Strategic tasks in the management of GPNs include long-term decisions that guide the implementation of the company's business strategy. One of the probably best-known and most influential phenotypes for a strategic task is the role model for alternative strategies of foreign subsidiaries of multinational companies described by Bartlett and Ghoshal (1986) (see Figure 5) [12,197]. The definition of the strategy of a foreign subsidiary involves tasks such as the definition to supply a specific market, to serve a customer division or to manufacture a product line for a specific market segment. For assigning a role to the subsidiary, Bartlett and Ghoshal suggest two dimensions: The strategic importance of the local environment and the level of competences of the subsidiary. The strategic importance is assigned based on the current market size, a predicted market growth or the technological pioneering role of a market. The level of competencies refers to autonomous decision-making in sales, marketing, production and other supporting activities [12,141,197]. Building on the two dimensions, four roles are distinguished such as Strategic Leaders, Contributor, Implementer and Black Hole. A Strategic Leader is a subsidiary operating in a strategically important local environment being equipped with high competencies. It actively implements a strategy and makes decisions such as the responsibility for a product or a value-added function [12,197]. A Contributor is a role describing subsidiaries that operate in a less important environment but have capabilities that exceed necessary actions to maintain business. Therefore, the Contributor has competencies that meet some of the needs of the primary multinational company [12,197]. An Implementer is a subsidiary operating in a less important market and being equipped with the competencies to maintain its local operation. Therefore, an Implementer has a balanced portfolio of strategic importance as well as competencies and strives for the implementation of a strategy defined by the primary multinational company [12,197]. An unfavorable role of a subsidiary is the Black Hole. In this case, a subsidiary is not equipped with the necessary competence that the strategic importance of the local environment requires. Therefore, the mother company must find a solution to develop and equip the subsidiary with competencies to manage its way out of it [12,197].

Industrial companies and their production networks can be classified according to the above phenotypes.

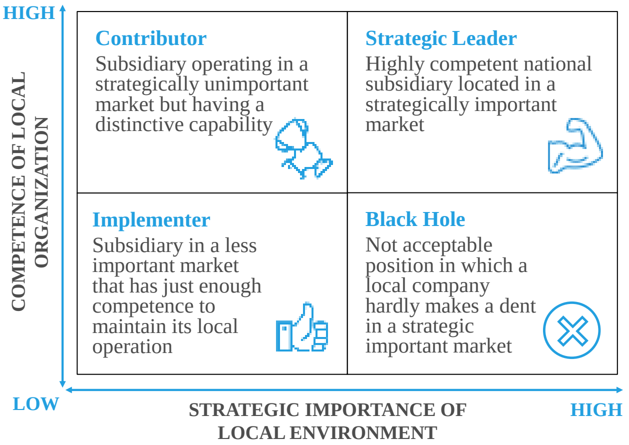


Figure 5. Phenotypes for subsidiaries of GPNs by Bartlett and Ghoshal [13].

One example is the medium sized technology company Zahoransky AG, which has its origin in the Black Forest in Germany. Zahoransky develops injection molding tools, automatization solutions, packaging machines, as well as tufting and trimming machines for brushes. Each of the five production plants belongs to a subsidiary and offers a defined product, assembly and parts spectrum being selected on core competences, market proximity and costs. The subsidiary being located in Germany is responsible for the development of all new products. It therefore undertakes the role of a Strategic Leader. Contrary, the subsidiaries and the production plants being located in Spain and India offer certain products for local and global markets but also deliver components to the Strategic Leader. Therefore, the role of a Contributor can be assigned to them.

Another example that could be classified being a Black Hole subsidiary in the past was the Chinese subsidiary of the Festo AG & Co. KG. Earlier, Festo manufactured its pneumatic and electric driving systems such as spindle axis exclusively in Germany. The Chinese subsidiary of Festo located in Jinan could not satisfy growing customer requirements of Asian markets such as rising market demand, large-scale orders and short lead-time requirements. Therefore, an adaption of the GPN was proposed within the EU funded project RobustPlaNet (NMP 2013-609087, Shock-robust Design of Plants and their Supply Chain Networks (RobustPlaNet)) that upgraded the role of the Chinese subsidiary towards the role of a Strategic Leader [114,171].

2.3.2. Phenotypes on network footprint level

Tasks related to the design of the network footprint include mid-term decisions related to the geographical location of production plants as well as their resource, capacity and technological facilities. A well-known scheme of phenotypes for designing the network footprint is the one presented by Abele et al. (see Figure 6) [1]. Abele distinguishes five network types namely World Factory, Local for Local, Hub and Spoke, Chain and Web Structure. They vary from a centralized to decentralized architecture and differ in their ability to use economies of scale and scope as well as the importance for local adaption and the exploitation of low transaction costs. Within the phenotype World Factory, production takes place at only one production plant which supplies worldwide sales markets. A World Factory can realize maximum economies of scale on the one side. On the other side, the possibilities to adjust production and products to local market requirements and supply opportunities are low and transaction costs such as logistics and management costs are high. A centralized production at one location was common at the beginning of the globalization but the relevance of this phenotype has decreased within the last decades. The phenotype Local for Local is the contrary to the phenotype World Factory. Within this phenotype, different production plants produce for their own local market. The plants have relatively low interaction and are characterized by high flexibility, short lead-times as well as the possibility to adjust products and production to market-specific characteristics. Drawbacks of this phenotype lie in the unfavorable cost position as excess resources are provided several times within the network. The third phenotype, which is called Hub and Spoke, strives to combine the possibility for economies of scope and scale with the possibility for local presence. Therefore, production steps that are costly or knowledge-intensive are concentrated at one or a few production locations. Other production steps, such as simple assembly steps, are executed at a number of close to market locations. These plants are also referred to as satellite production plants. The phenotype Chain puts even more emphasis on the advantages of each single production plant. Every production step is concentrated at a different location in order to maximize the economies of scale and scope of each individual production step. This phenotype is accompanied by logistics costs even higher than of the World Factory. This phenotype is valid for high-tech industry such as electronics and semiconductor industry where the product value density is high. The fifth phenotype, the Web Structure, is characterized by the fact that all production plants are able to manufacture all products being offered. Using this phenotype, local adaption as well as the utilization of economies of scales are low on one side. On the other side, due to excess resources and capacities, the production network can breathe in case of volatile demand, and capacity utilization can be smoothed. This is a unique feature which makes the Web Structure superior in terms of flexibility and agility. As it combines the benefits of centralization with benefits of high capacity utilization and close-to-the-market production, the Web Structure is propagated as being the future phenotype for industry. Even today, it is the most common phenotype on the level of footprint design [1,203].

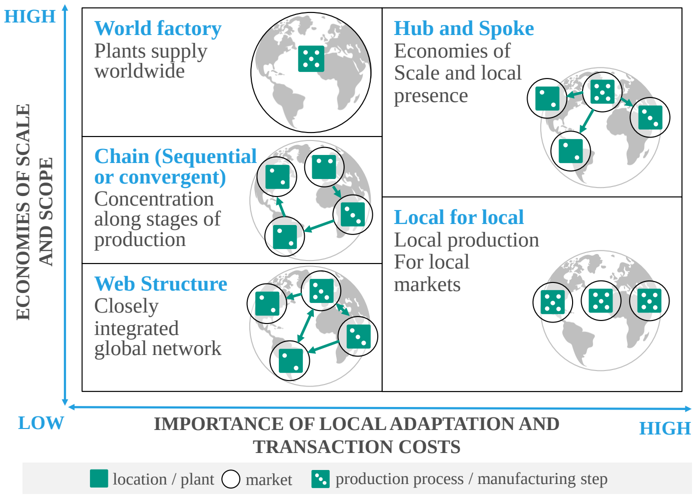


Figure 6. Phenotype for footprint design of GPNs by Abele et al [1].

Abele's phenotypes for footprint design of GPNs have been picked up by several authors [199,244,245]. The concept can be applied easily to industrial use cases as well.

One real world example for the phenotype World Factory is the production network of C. Josef Lamy GmbH. Lamy is a world leading producer of writing instruments such as fountain pens, ink roller and other kinds of pens. The company carries out its business in premium-market segments and strives for high-quality products. Therefore, all Lamy pens are produced at one production plant in Germany that bundles all competencies. The production depth is more than 90%.

An example for a Local for Local production is the continuous production company LafargeHolcim Ltd. LafargeHolcim is a leading global company building materials and solutions with the headquarter being located in Switzerland and operation in more than 80 countries. The company is organized in four business segments Cement, Aggregates, Ready-mix Concrete as well as Solutions & Products. It serves masons, builders, architects and engineers. The operations have a wide geographical footprint. Especially in the cement, concrete and aggregates business, the manufacturing is located close to the final customer. Due to the required short lead time after production as well as the low value density of the products it is not economical to ship products over large distances that involve more than about one hour of traveling time. Therefore the production network is designed according to the Local for Local network phenotype with issues of sustainability and corporate social responsibility being of high importance

An example for the phenotype Hub and Spoke is the production of hydraulic tubes by the automotive supplier TI Automotive GmbH. All continuous production steps such as soldering and coating of the tube are carried out at high-tech production plants. Other production steps such as the separation, deburring, assembly and bending of the tubes take place at production plants being located close to the customer, which typically is an automotive car manufacturer. Applying this phenotype, TI Automotive combines both the benefits of economies of scope and scale as well as local adaption and low logistics costs.

2.3.3. Phenotypes on network management level: Plant roles

As the discussion in the previous section makes it clear, different production units in a companies' global network perform different technical and managerial tasks. It is essential to define the roles and responsibilities of each production plant in the companies' global production footprint. A well-known phenotype providing guidance is Ferdows' concept of plant roles (see Figure 7) [59].

Ferdows six generic strategic roles for manufacturing plants are based on two variables: the primary reason for the location and the current level of plant competency (measured by the type and extent of the activities beyond pure production carried out at the plant – for example, procurement activities or product and process development tasks). These six roles are Offshore, Source, Server, Contributor, Outpost, and Lead (see Figure 7). Offshore and Source Factories focus on cost-effective production of products or components. In contrast to Offshore Factories, Source Factories have the expertise to further develop products and processes, to plan production and to set up their own supplier and distribution networks. Server and Contributor Factories focus on serving specific geographical, often national or regional markets. The usual reasons for a Server Factory is to bypass trade and customs barriers, benefit from low taxes or subsidies, reduced logistics costs and serve their immediate customers better due to closer proximity. The Contributor Factories do all that plus more. They modify product design for their markets, improve process technology, develop a supplier base and procurement and logistics systems that can be used in other parts of the companies' production network. However, the ultimate responsibility for developing new production knowledge for the company is born by its Lead Factories. Lead Factories are usually located in close proximity to companies' R&D organization, outside research centers, and, if possible, industrial clusters. While these factories are the custodians of new production knowledge for the entire network, Outpost Factories have less expertise. Their main task is collecting information, which is why they are often located in industrial clusters, next to critical suppliers, competitors, and customers.

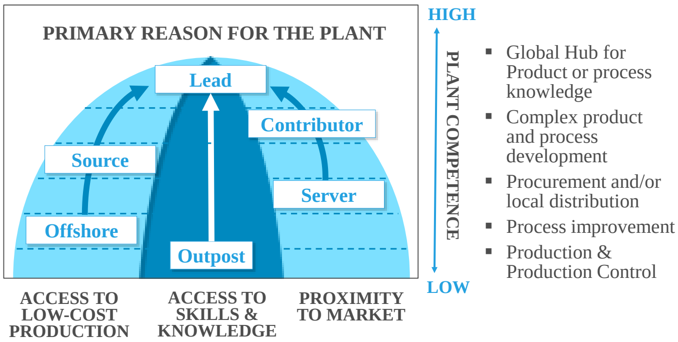


Figure 7. Phenotype for plant roles in GPNs by Ferdows [60].

A production plant may have more than one of these generic roles. Furthermore, as discussed in subsection 4.3.1, these roles are likely to change with passage of time. Ferdows' plant roles have been tested by Vereecke & van Dierdonck [247] and served as a starting point for numerous research activities related to GPNs [54–56,160,247].

A good example for Ferdows' plant roles is the production network for surgical medical devices and medical technology by Aesculap AG. There are several globally distributed plants, including Germany, Poland and Malaysia. The plant in Germany bundles competencies for research, development, production and marketing of various product groups and thus takes over the role of a Lead Factory. The strategic goal of opening further plants in Poland and Malaysia was to exploit low production costs. As the plants source local vendor parts and perform simple process customizations on their own, they serve as Source Factory according to Ferdows' phenotypes. For Aesculap, no matter at which global production plant the product was manufactured, the shipment of all products to the customer takes place via one central logistics center being located in Germany. Therefore, market proximity plays only a minor role for Aesculap. As a result, the plants are neither Server nor Contributor Factories.

On production network management level, several new phenotypes have recently gained interest.

New Speedfactories bring products much faster to the market and allow to adjust products flexibly and individually according to the customer's wish. One example is Adidas with its two Speedfactories located in the Bavarian city Ansbach and in Atlanta, Georgia (GA). They produce highly customized sports shoes and strive to reduce the time from the design of the shoe to the customer delivery from 18 months to a few hours. The production of the Adidas Speedfactories employs novel production techniques such as computerized knitting, robotic cutting and 3D printing [18,230].

Another new phenotype is Urban Factories production in cities. An Urban Factory is a production site located in an urban environment. It is actively utilizing unique characteristics of the surroundings towards value creation in areas such as operation, technology, environment, society, and mobility [101]. The concept of the Urban Factory is important for the automobile production plant Ingolstadt of the Audi AG. Audi's location in Ingolstadt is historically located in close proximity to inhabited urban areas. Due to limited space availability, layout planning of the future plant will consider switching from the original horizontal material flow to a vertical material flow. This is suitable, for example, for the production areas Body Construction and Assembly [19,101].

The change of traditional take, make and dispose mentality to a sustainable lifestyle decouples economic growth from resource consumption and leads to the new phenotype of Circular Economy Production Networks [234]. Circular Economy Production Networks include reuse, repair, remanufacturing or recycling production activities that return products at least to its original performance or convert their material into a new product [234]. An example is the automotive supplier Knorr-Bremse AG which remanufactures calipers of trailer disc brakes at its plant in Aldersbach using the same production line as for the assembling of new calipers. Despite the reverse logistics flow, reconditioning and quality control, greenhouse gases are 70% less compared to the production of new parts [132].

3. Framework for designing and operating global production networks

The following section introduces a framework (see Figure 8), which condenses the most important aspects of designing and operating global production networks (GPNs). The framework was developed collaboratively by the authors of this keynote based on a literature review and their expert knowledge. It shows influencing factors, challenges, enablers and decision support systems when designing and operating GPNs. The influencing factors affect decision-making when forming a global production strategy, designing the footprint or managing the production network. While the challenges hamper decision-making, the enablers help to deal with the challenges. Decisions support systems are methods and tools that help to interpret data, to model systems and to find the best-possible solution in decision-making.

Designing and operating production networks involve decisions that can be grouped into core and subtasks related to a companies' production strategy, the network footprint and the network management (see subsection 2.2). All decisions should be made with regard to the product service system. The product service system consists of the physical product and a related service that is produced and offered in order to fulfil a need in a market place. The offering of services, for instance, involves the change from simply providing intermediate or final goods to apply some additional competencies with benefits for the customer. Every product service system has its own features designed according to the market requirements and the product life cycle [135]. Services in particular allow partners of production networks to differentiate from competitors and generate additional turnover [32,44,52,161].

3.1. Influencing factors

When deciding on tasks of designing and operating GPNs, multiple influencing factors as well as risk and dynamic in their behavior have to be taken into account.

As the demand for a product and related services are decisive drivers in the design and operation of GPNs, markets and their developments have to be considered when managing global production networks [1], [145].

Location-specific cost factors play a crucial role in GPNs. Cost factors can be broken down into several categories such as labor costs, capital costs, material costs, energy costs as well as coordination or communication costs. Even a sustainable and green production is not free of charge but generates costs [1]. Depending on the company's cost structure, importance can vary among the different cost categories, but generally, labor costs are the largest costs for most manufacturing industries.

As GPNs are spread globally, the significant influence of logistics becomes evident. Besides logistics costs, lead time restrictions impact the network footprint and demand for a high ability to deliver [1]. Logistics costs are an integral part of the total costs of a product and can be divided into transportation and inventory costs [30].

When deciding on setting up a production abroad, differences in people and cultural factors need to be evaluated. Varying language and mentality lead to difficulties in communication within the humans operating the GPN as well as difficulties in communication towards markets and customers [127]. Moreover, staff turnover and differing qualification levels make it hard to find adequate personnel. Domestic professionals are temporarily sent to foreign locations as expatriates to support design and operation of the production network.

In terms of legal factors, aspects such as the legal system, the importance of the rule of law, the level of corruption, and the possibilities to protect intellectual property as well as company-specific know-how have to be mentioned [1].

Other factors influencing the network are political and governmental factors. Taxes, subsidies and standards in terms of wages as well as safety or environmental regulations influence companies in their decision-making. Besides, especially trade barriers consisting of tariffs and non-tariff trade barriers have a significant impact on global production [111].

The considered influencing factors are not static. Their behavior is more or less characterized by uncertainty and dynamics which challenge the design and operation of GPN [1].

3.2. Challenges

Decisions on designing and operating production networks are hampered by main challenges including uncertainty, complexity, sustainability and disruptive innovation. Decision makers have to be aware of these challenges.

Uncertainty, for example, is a challenge in predicting the development of the influencing factors [209]. Uncertainty

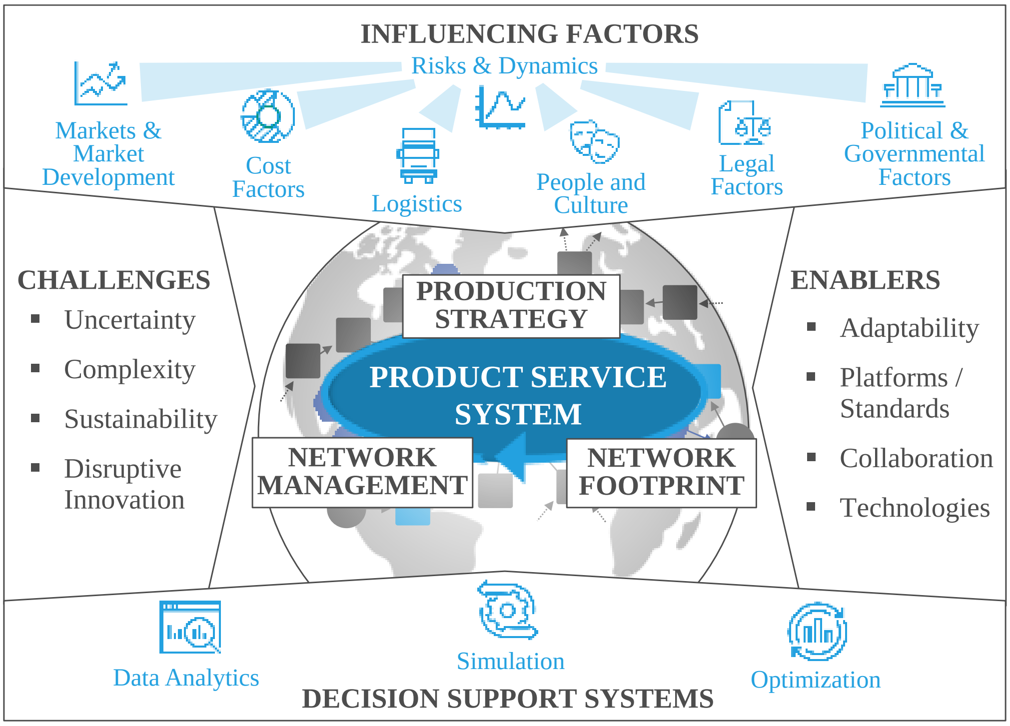


Figure 8. Framework for designing and operating GPNs.

describes the situation where unforeseen external and internal events occur that change the impact of influencing factors or the behavior of the production network, making it hard to take all eventualities into account [165]. Demand is the main motivation for any production. Therefore, the primary challenge for global production is the uncertainty of market demand [245].

Another challenge is complexity. It refers to the high number and the diversity of elements and relationships within influencing factors and the production network itself. On the other hand, it depends on the variability in the progression of time, which is expressed by the variety of behavioral possibilities of the elements and by the variability of the course of effects between these elements [51,205].

Beside uncertainty and complexity, sustainability is another broad and long-term challenge of rising importance. It captures the necessity that partners of production networks have to meet the needs of present stakeholders such as customers or partners without compromising the ability of the ecosystem and future generations to meet their own needs [117].

Also, technological and organizational changes challenge the management of production networks. One challenge is the rise of disruptive innovations which consist of new technological innovations (e.g. 3D printing, Internet of Things (IoT), biotechnology) that change performance metrics or consumer expectation by providing radically new functionality, discontinuous technical standards or new forms of ownerships [180]. One main challenge of the present age, which is prompted by disruptive innovations, is digitalization. It builds up on the digital modification of instruments, devices and machines and compromises challenging implications for industry. These include the fear of loss of control over the customer relationship, the need to engage digitally with suppliers and customers as well as an increased competition and the risk of commoditization of hardware products [169].

3.3. Enablers

On the other side, decisions on designing and operating production networks may be facilitated by new enablers. Adaptability, for instance, expresses the ability of a production network to respond to changes in the environment or the interacting system. Using principles such as universality, scalability, modularity, compatibility, mobility and adaptability helps to overcome the challenges of uncertainty [48,259].

Platforms and standards include requirements and specification for the function and technical structure of production resources and IT-systems. They pursue the objective to build up structures in production networks that are adaptable, flexible and fast reconfigurable [50],

Another enabler that allows to tackle various forms of complexity is collaboration. It describes the interaction of system components in a production network that makes it possible to harness knowledge of other system components to make use of their actions in joint interests [150].

Another key enabler are technologies such as sensors, cloud technology, artificial intelligence (AI), block chain, big data and additive manufacturing. They were already mentioned in the section related to the challenges as they play a dual role. As enabler they integrate physical and computation processes and help to retrieve physical or digital manufacturing services on demand. Both contribute to GPNs by better adaptability, controllability as well as streamlined information sharing and improved capacity utilization [43,134,200,232,251,254,258]. The CIRP community is the worldwide leading reference for production technologies. For this reason, technologies play a superior role in this paper compared to other management and business research communities.

3.4. Decision support systems

The tasks of designing and operating GPNs create a need for decision support systems.

The most important systems fall back on solution methods coming from the discipline of operations research. These solution methods map complex decision problems by using simplified quantitative models and algorithms. For instance, data analytics contains of a set of statistical models and algorithms that summarizes information contained in data and presents it in a way the relevant content becomes more emphasized [77]. Simulation facilitates decision-making by conceptualizing and analyzing complex systems such as GPNs in a dynamic model to pursue objectives such as performance evaluation [115]. Mathematical optimization gives guidance in decision-making as it helps to find the best alternative among a set of options [222].

The use of decision support systems is the subject of much research and can be structured according to the core tasks of designing and operating GPNs presented in subsection 2.2. Following the review of the state of the art, the most frequently applied solution methods in research will be presented in subsection 4.4.

4. State of the art

4.1. Forming the production strategy

This section reviews the state of the art in designing and operating global production networks (GPNs) according to the core tasks and subtasks being introduced in subsection 2.2.

4.1.1. Linking global production strategy to business strategy

Three overlapping streams of research provide the context for how a company's global production strategy should relate to its business strategy [63]. The first stream is the rich literature on multinational companies. In the last three decades, research on the structure and organization of multinationals has shifted from a focus on a hierarchical view of relationships between the company's headquarters and its subsidiaries (including its production and distribution plants) towards a perspective of a web of diverse inter- and intra-company relationships [63]. Theories that have been used to examine these relationships include network theory [42,82,83,91,188,267], evolutionary theory [15,130], learning organization [86,108,182] and knowledge transfer [85,227,248]. A common theme among these theories is that multinational organizations can benefit greatly from transferring people, technical resources and competencies developed in different locations within their company [63]. These approaches provide useful contextual knowledge, but in general, stay at a high strategic level and seldom delve deep into specifically how a company's production network should be organized and managed to support its business strategy [63].

The second stream is the literature on industrial networks [36,88,93,123,124]. The focus here is on the external, mostly vertical, networks in which the companies – especially original equipment manufacturers (OEMs) – operate. Relationships with suppliers, subcontractors, and contract manufacturers, in particular, have received considerable attention in recent years [45,187,215,245]. There is a general consensus that increased data, information, and knowledge transfer in the "extended enterprise" can be beneficial to all parties [63].

This perspective suggests that global production strategy should extend its reach beyond the companies' boundaries and clarify the level of dependence on long-term suppliers, alliance partners, contractors, design labs, distributors, arms-length suppliers, and other key actors in the relevant industrial network [63,173,245]. Presence or absence of such "industrial commons" [186] can alter the options for locating global production plants and extent of vertical integration.

The third stream of research has focused on the intra-company production networks, and as such, has addressed, more directly than the other two streams, the relationship between the companies' business strategy and the design of its GPN. A fundamental question in these investigations is where and how to produce (or source) which product (or component) in order to provide maximum support for the company's business strategy [57,60,63,66,67,70,96,97,123,125,136,144,196,219,220,244,249].

A subgroup of this stream of research uses the network - as opposed to production plants, warehouses, logistical systems, etc. within the network - as the unit of analysis [33,62,164,214,248,261,262]. An important premise here is that intra-company production networks can develop capabilities that go beyond production plant capabilities, and especially with the advent of new technologies (including IoT, AI, blockchain, and big data), companies must pay more attention to building capabilities in production network as a whole, rather than a summation of capabilities of individual units [63,81].

While these streams of research provide valuable insights, they do not offer many practical tools for aligning the design and management of a company's GPN to its business strategy. There are only a few models and frameworks that provide high level guidelines. They are usually based on the characteristics of the company's products, processes, and competitive priorities and most useful for identifying possible mismatches between business strategy and architecture and management of production network such as a discrepancy between level of allocated resources and required capabilities from a unit in the network [59,65,219,220].

Ultimately, the importance of production in the company's business strategy has a significant impact on the strategy for a production network [98]. It plays a significant role, the production plants in the company's production network are likely to have access to requisite resources and are encouraged to develop superior and proprietary capabilities; if not, investment is kept at a minimum and the company relies more heavily on others to produce its products and is less vertically integrated. In short, the observed differences in the GPNs of two companies in the same industry can often be traced back to the differences in the role of production in their business strategy [59,62,70].

4.1.2. Market segments

A voluminous literature in marketing has long established that customers served by a company are not homogeneous and can be divided into segments - usually based on geography, demography, psychography, behavior and image or a combination of them [13,135]. Segmentation allows offering differentiated products and services to each group.

The literature in production has approached this issue from a different perspective. Skinner, in his seminal paper [217] observed that production plants were expected to perform well on often incompatible yardsticks and suggested that they should have a "focus" based on the "manufacturing mission" assigned to them by the companies' business strategy. Since then, other scholars have delved deeper into this proposition [58,98,249] and suggested how the "structural variables" (location, process technology and automation, equipment and layout) and "infrastructural variables" (organization, workforce management, quality systems, production and planning systems) as well as linkages to other functions (engineering, R&D, procurement) should be designed to support the factory's "focus". More recent works have extended the notion of focus to a network of production plants [65].

It is reasonable to expect a relation between a company's choice of market segments and the design of its production and supply chain system. For example, some of the focused production plants can be designed to serve specific market segments - be that quick delivery, low cost, or high level of customization - or to provide a better service to customers in certain geographical markets. In many industries, the location and focus of the companies' production plants reflect their choice of geographical market segments [82,83,267]. For example, many western multinationals set up production plants in China in recent years primarily to enter and serve the growing Chinese market (see subsection 3.1) influencing factor market development) [61]. However, on the whole, the literature does not offer many models or frameworks to relate a companies' market segments to the design of its GPN.

A company's choice of market segments clearly shapes, and is shaped by, its GPN [103]. Market segments based also on other factors than just geography can impact a companies' production network as well. For example, tier 1 suppliers in the automotive and beverage industries often set up plants close to their large OEM customers plants. Or in the apparel industry, many companies have been chasing low cost production around the world, creating footloose GPNs, in order to compete in the market segments that demand low prices [71,73]. However, this strategy has been questioned when considering the total cost of procurement, production, transport and delivery [35,125].

4.1.3. Product service portfolio

The ultimate goal of a production network is delivering products and related services to a defined target group of customers. Hence, the product portfolio is substantially affecting the design and operation of the entire production network [103]. In the context of global production the concept of product service portfolio can have different implications. For instance, mass customization, is often studied to address the inclusion of several product types in the GPN. The performance of centralized and decentralized production networks was studied under heavy customization [41,175,176,199]. The included evaluation criteria were defined as cost, lead time, environmental impacts, annual production rate, flexibility, reliability and complexity. The results show, that decentralized networks, which assign authority to individual production plants or even suppliers, may have advantages over centralized networks, especially in the case of heavily customized products. In an extension of this work, the best network was investigated [177] and challenges in applying production networks for mass customization have been identified such as partner selection, inventory management, capacity planning, product data management and collaboration [173].

Likewise, product modularization allows for inclusion of several product and service types in a GPN. Researchers investigated the benefit of finding a set of best design solutions in the context of global production [268]. The results favor the attractiveness of solutions with reduced number of suppliers. Other authors introduced a multi-stage procedure to match the design of the supply chain network and the product architecture for the purpose of increasing the network performance [14]. The product search space included possible components for its modules and accordingly, the supply chain network space includes possible suppliers' configurations. As a result, a system model in the form of a multiple-domain-matrix evolves by investigating on the dependencies among product architecture and network footprint. A comparison between the alternatives for product and network leads to certain assessment values so that the best identified combinations are presented to decision makers. Deciding about the product portfolio is a strategic decision. Existing papers which study concurrent product and supply chain design were reviewed [76]. The main goal was to understand the relationships and interactions between product development and supply chain attributes. The main finding was that most of the reviewed papers focused on architectural attributes on the product side and on detailed ones when supply chain issues were concerned. With the global shift from mass-customization to mass-personalization, the future impact of product service portfolio on GPNs need further investigation.

4.1.4. Target system

The definition of the target system describes the tasks of defining a set of goals that should occur as a result of designing and operating production networks [70]. In production networks, several targets are usually pursued simultaneously, as the production strategy differs depending on the business model, the market segments and the product service portfolio chosen. Cost, quality and time have been identified as key targets [9,10,166,235]. Meanwhile, further targets, such as adaptability, flexibility, access to markets and resources, mobility, learning and sustainability, are important due to increased customer demands and intensification of competition. The diversity of goals and their different scales leads to the fact, that the performance of a production network cannot be represented or condensed by one single target [218]. Therefore, hierarchical multi-criteria target systems are common. They combine sub goals and contribute to the achievement of an overarching goal [185]. A typical example of hierarchical multi-criteria target systems may be a multi-criteria objective function that is used for optimizing the footprint of production networks [145,171]. Another example for a multi-criteria target system are systems of Key Performance Indicators (KPIs) that are used for assessing the operational performance of production and logistics processes when managing GPNs [224].

4.1.5. Sustainability

The main purpose of a GPN is to create value for the stakeholders. However, production as a core function of a GPN should not only be considered as creation of value but also as a process of materials transformation in which environmental change and the organization/disorganization of matter and energy are integral rather than incidental to economic activity [38,40,119]. Value creation will take different forms in different parts of the network such as profits, dividends for shareholders, salaries for workers, which is a key concern in the context of social sustainability. As a result, it is not only for the stakeholders but also how much and what kinds of value are created for the benefit of the local communities that the GPN interacts around the world. However, when the GPN is seen from the material transformation perspective, there are unintentional external effects involved in all GPN activities. In other words, just as GPNs create value it also has the capacity – intentionally or unintentionally – to destroy value in its environment [40]. Therefore, a GPN must not only be in balance, but also have a positive impact in the natural environment and society they operate in. This means that the environment must not be damaged, but possibly even improved. By connecting factories directly to other factories, urban infrastructure, and households, partners can benefit and have symbiotic flows. In this context, solid waste can be exploited by the factory and used for new products, wastewater can be treated, renewable energies can be produced or stored and local emissions can be neutralized [100].

Three aspects of environmental damage are especially important for the future; (i) exploitation of non-renewable and renewable resources, (ii) over-burdening of natural environmental 'sinks' through increased concentration of greenhouse gases in the earth's atmosphere and of toxic materials in the soil, (iii) destruction of increasing numbers of ecosystems to create space for urban and industrial development [40]. These negative externalities have an impact on the ecosystem. The impact depends on the geographical region. It is greatest at the location of the plant itself as well as the neighborhood and declines with increasing distance away from that location.

As a result, a number of researchers has investigated sustainability from the relative sustainability perspective based on the triple-bottom line concept e.g. ecological, social and economic. It was argued that three driving forces; responsiveness, robustness and resilience, can provide global manufacturing companies with a sustainable competitive advantage, which were summarized as triple 'R' in order to help businesses improve their sustainability [137]. Sustainability is also seen by some as a 'megatrend' pushing towards distributed manufacturing and affecting managers' decisions as a result of institutional pressure, companies' competitive values and companies key resources [156,158,191]. Some defined sustainable supply chain networks as networks, which seek on achieving both economic as well as environmental goals. To this end, it was aimed to design closed-loop production systems, having manufacturing and remanufacturing in the same system, in order to avoid the negative environmental impacts [53,87,90,263].

A number of studies have investigated the impact of the triple-bottom line on the supply chain network performance, including supply chain configuration, raw material sources, suppliers, manufacturing plants and transportation [80,94,121,122,170,242]. The results showed that sourcing raw materials and producing locally are better from the relative sustainability perspective.

However, recent work in this context has changed the scope from relative to absolute sustainability and its impact on products and the associated production networks [95,120]. It is clear that ecosystem is no longer an objective that can be traded off against the business objectives; rather it is a constraint than an absolute boundary. This view has recently been reinforced by the United Nations Sustainable Development Goals (SDGs), which will have a huge impact on the GPNs. Further studies will be critical to understand the future impact of these significant changes.

4.2. Designing the network footprint

4.2.1. Network structure

The design of the production network structure describes the geographic distribution of production plants, capacities and technologies. The main goal is finding the optimal structure in terms of production costs, tied-up capital, production quality, lead time and sustainability [9,10,170,235,244,250].

When designing the network structure, three basic views can be distinguished: the supply-chain view including the external value network, the internal production network view, and the single production plant view. Approaches that reduce the design of the network structure to a production plant design problem are described in [163]. Recent contributions move towards consideration of the overall network [29,201,229]. Portfolio-based approaches have been used for integrated design of production, transportation, distribution and service network [202].

Regardless of the level of view, the identification of production network structures was often understood as a static, one period examination that assumes a projection of parameters based on the current situation. In contrast to this traditional view, recent approaches consider the transformation of the existing structure using a migration path. It incorporates multiple time periods. Additionally, the expenses and risks of individual migration steps are taken into account. The goal is not only to define an intended future structure but also to find a risk-efficient path towards the desired future structure [171,210].

When designing the network structure, the uncertainty of influencing factors has to be considered. Many authors addressed the value of changeability [17]. The interplay of strategic management and the changeability of a network was investigated and insights on design for agility were favored [144,165,168].

Complexity was also investigated as being a main challenge in designing the production network structure. With the objective of measuring complexity, approaches identified complexity drivers such as the number of plants, employees, and the product and process distribution structure [208]. Also, the structural complexity of the manufacturing system's layout has been assessed and corresponding models may also be applied to the superior network level [49]. Other approaches focus on the measurement of complexity and utilize the physics inspired information entropy concept [92]. Complexity scores of candidate network structures have also been combined with other performance indicators to select the best structure [133,213].

For managing complexity, several approaches have been proposed. Different models and metrics for evaluating the risks of operating a production network that arise from the complexity of the supply chain have been structured in a framework [184]. The automatic and real-time gathering of supplier information was suggested to respond to complexity [179]. Other authors proposed automatic processing and interpretation of data using intelligent algorithms. Data analytics approaches facilitate the decision-making process when designing the structure of GPNs [47,233]. Using data-mining methods for clustering of product portfolios can also reduce planning complexity and therefore lead to better decisions in production network design [104]. Another concept to deal with complexity is modularization, both in terms of product and production structure. By encapsulating parts of a subsystem and strictly defining interfaces to other subsystems, the influence of variance within the subsystem can be limited to itself without influencing other parts of the enclosing system. Thus, the complexity of the overall system can be reduced. The starting point for complexity reduction in production networks is the facilitation of the product architecture [212]. Decentralization is another concept to manage complexity within production networks which applies to the subsidiarity principle to make decisions at the lowest possible hierarchy level. Research on decentralized decision making in GPN is strongly related to the concept of customization and was already presented in subsection 4.1.3.

Decision making related to the structure of production networks is often supported by using mathematical modelling and optimization. Authors state that up to 40% of the literature related to network structure design incorporates mathematical modelling. This trend is emphasized by other researchers as well [29,183].

For instance, Markov decision processes were used for capacity and investment planning of production systems and production networks in automotive industry. The proposed stochastic and dynamic optimization method enables the identification of possible network adaptions by taking into account costs and different key performance indicators (KPIs) [146].

Other researchers focused on the multi-dimensional uncertainty of influencing factors when designing the structure of GPNs with multi-objective optimization. The focus was especially on the identification of the need for changes in the global production structure and the related point in time of change within a medium to long-term planning horizon [145].

Optimization approaches were also used for facility location decisions within distribution-service systems [2]. With the application of a multi-objective, multi-period, multi-commodity optimization model, facility location decisions were made with respect to forward and reverse value streams. The design of a multi-product, multi-echelon and capacitated close loop supply chain using optimization was also investigated in [116]. Within this approach, product demand, return volume and certain types of costs were considered using fuzzy numbers.

Besides these approaches, an optimization-based software tool named OptiWo was developed in order to address two main challenges of production network design: the high complexity of the solution space of the network structure as well as the lack of time for decision-makers to understand the complexity of this structure. The application of OptiWo consists of two components: the data viewer and the optimizer. Data regarding the products, processes, process chains, resources and production plants define the solution space. In order to obtain possible solutions, dynamic modelling and simulation techniques are used. The optimizer generates realistic scenarios for GPNs. Manual alterations of network characteristics or optimizations of substructures in the network are used as well as sensitivity analyses to include less predictable factors e.g. risks and uncertainties. Lastly, a development roadmap is generated to indicate the differences between the desired and actual state of the production network so that the design of GPNs can be achieved with a minimum level of structural complexity [193,194,206,207].

4.2.2. Product mix allocation

Increased product complexity in terms of variants continues to be one of the main challenges that manufacturing aims to address [51]. In the last decades, companies have adopted the concepts of customization and personalization aiming at integrating their customers in the product design phase [173,176]. OEMs are continuously searching for better approaches to handle the increased product mix and create well-structured and flexible production networks with higher efficiency. In literature, several approaches have been introduced aiming at addressing the issue of product complexity and production networks design. Flexibility [79] and changeability are defined as key enablers for meeting the aforementioned challenges [259]. Changeability has been introduced to the strategic, tactical and network levels investigating characteristics to accomplish early and foresighted adjustments of production plant and network structures [165].

To effectively allocate the products, properly configured and easily adaptable production systems and networks are needed, which would be capable of handling the product program complexity and enormity of the supply chain structures. Distributed and decentralized decision-making during production network design has been proposed to address the highly customer-driven environment [179] and the high product variety demand. More specifically, design of multi-stage manufacturing networks supported by multi-criteria search algorithms [175], metaheuristics [178], and genetic algorithms [177] have been introduced. Another interesting approach regarding the allocation of the product mix in production systems has been presented by [157] investigating the use of axiomatic design of manufacturing networks. Even more than customization, personalization leaves a network footprint of an immense number of possible options, which is hardly manageable. An approach offering a solution for efficient production and delivery of highly-customized and personalized products, while handling the large number of alternative variants at the same time, was proposed by [173].

International outsourcing has been adopted worldwide as a strategy aiming at addressing the challenge of high product variety allocation in production networks in a cost-effective way. More specifically, during the last years, low-cost country sourcing has played an important role in GPN design, re-defining the interface between product and production network design, and realizing low-cost production networks while keeping the product quality levels high [149]. Although outsourcing significantly supports the design of cost-effective production networks, the long term impacts on social, economic and environmental sustainability are still under investigation [170].

Cyber-physical systems will also enable the networking in manufacturing companies, which can be determined as a critical factor in the allocation of products in production networks. The networking will include new organizational paradigms, including clusters and virtual companies, and will enable interconnected partners [25]. Last but not least, the new era of digitalization will lead to the system's complexity reduction, also enabling adaptive planning and control of production systems and networks, building new business models between equipment or component supplier and OEM [147].

4.2.3. Resource allocation

Resource allocation is the task of planning, dimensioning as well as allocating capacities within production networks. By in- and outsourcing of production steps, production networks are able to cope with increasing need for change and agile manufacturing [168]. The combination of resource allocation and production network design by using parallel and synchronous design and evaluation of products has been investigated [155]. The simultaneous extension of production networks, taking future scenarios into consideration, leads to an optimal, robust distribution of production steps within the network [250].

Recent optimizing approaches therefore include the tasks of resource allocation in the planning of production network scenarios [193]. Several methods have been developed to create a specific capacity allocation plan applicable to centralized and decentralized network structures [7,8,151]. Robust capacity allocation regarding key parameters like customer demand and production processes are also considered [198]. Furthermore, a methodology for achieving feasible capacity allocation and flow distribution in networks was proposed by Blunck et al. [16].

Resource sharing has a great influence in the process of resource allocation. Enabled by mass customization, rapid product changes and resource efficiency and supported by the new era of digitalization and cyber-physical systems, companies tend to increasingly exchange and share resources within a production network [118,168]. Different sharing concepts on dynamics and predictability were developed. With this, higher flexibility and efficiency can be generated [67,138].

4.2.4. Capability building

According to a recent survey [89], capability building is identified as one of the three most important priorities by half of the companies, highlighting it as an integral aspect of sustainable organizational performance. With the arrival of the Industry 4.0 era, more and more companies have been recognizing the fundamental role of humans and knowledge as a determinant of growth and a means of building capability and competitive advantage. Knowledge is a complex term, encapsulating in its concept data and information acquisition from all parts and stages of the value chain as well as human intellect and skill.

To be able to sustain the efficiency of a network and to maintain the quality of a value chain, effective knowledge management is indispensable, so that both explicit and tacit knowledge can be seamlessly shared among all the nodes of the network [264]. Decision makers able to ensure quality within their company need to be trained [72]. Highly educated and skilled personnel has to be allocated within the network, so that according to the resource sharing model, they can diffuse technical and managerial knowledge upgrading the know-how level of the least competent nodes, building capability and ultimately increasing the overall network effectiveness. Expatriates are thereby a frequently applied, but – in terms of costs – often underestimated means for diffusing knowledge within production networks [1,11]. Hence, recruiting the scarce highly knowledgeable and qualified human resources is of vital importance. [11]

However, apart from the undeniable advantages that it offers, there are also challenges and risks related to the workforce management in production networks. Effective workforce management has been investigated with regard to its potential in flexibility increase [237]. But cultural dimensions such as language barriers, different cultural mind sets, quality understanding and level of qualification have not been investigated yet.

Moreover, effective knowledge transfer does not only concern human knowledge, but also data and information flow [67,138]. Successfully managing such a complex production network is far from a trivial task and requires a vast amount of production-related data, coming from all actors of all stages of the chain including customers, suppliers, manufacturers etc. [152] and also from the entire product lifecycle [142]. The infrastructure of Industry 4.0, such as cyber-physical systems has made the real-time flow of this valuable data possible, improving flexibility and optimization potential [68,143]. The development of advanced software tools incorporating e-learning and intelligent algorithms, as well as trained and highly educated personnel to use them are needed in order to exploit the available data. Being in an information-based, knowledge-intensive era, companies use the gathered data and stored knowledge to improve their production planning, reliability and network performance [159,172].

4.3. Managing production networks

4.3.1. Plants responsibility

Manufacturing plants usually focus along products, markets or a combination of the two [97] and relate to other plants through the flow of physical goods, information, people, and financial resources [37]. However, given the multitude of variables that can affect their operations, [71,245] their roles and responsibilities can evolve with time and can veer in unintended directions [62]. It is therefore essential to regularly assess and chart the strategic role of the plants in the production network, especially in order to avoid conflicts between central organization and national subsidy.

Ferdows [59] suggested six generic strategic roles for manufacturing plants (see Figure 7). The model can help assessing a plants' current strategic roles, which may be a combination of more than one generic role, and proactively charting a course for if or how they should be changed. While other frameworks have also been proposed [248], e.g. based on flow of knowledge and information among the plants, Ferdows' model has received more attention and scrutiny in the literature. It has been tested, validated, and extended [56,70,74,154,162,247].

4.3.2. Demand planning

As it is planned based on forecasts, the predicted customer demand is vital for decision-making in production networks [221]. However, demand planning with a large number of products and customers makes an accurate customer demand forecast difficult. To improve the accuracy of the forecast, numerous methods and control mechanisms have been developed and applied in the planning process [26,139]. The published literature indicates that improvements in demand forecast accuracy increase the level of responsiveness and cut costs for those members of a supply chain who participate in a demand-driven supply chain [131]. Demand planning in a GPN is depicted in Figure 9.

Generally, customers demand for more customized products, enhanced services and the achievement of perfect logistic quality [131,262]. This demand forces customers to widely get involved in the production supply chain. As customer satisfaction and responsiveness support understanding customer behavior, customer involvement helps companies to reduce development costs, shorten time to market, acquire new ideas, and improve business performance systems [131]. With increasing individualization and customer involvement, traditional demand forecast based on historical data is becoming less important. In the field of fashion, for example, new sources of information such as social networks must be taken into account when collecting market-related data for sales planning. They provide early indications of changing market behavior and new trends. [140,271].

In addition, the wide application of new technologies in the production systems is transforming the demand planning in various aspects. Here, the collection of input data and computation of future data are two important aspects. Internet of Things (IoT) is used to sense and capture the real-time data of demand planning processes, such as customer orders and shipments [255,270]. Such real-time data does not only contribute to the improvement of accuracy in planning the customer demand but also supports the monitoring of process execution as well as information sharing [131,252,269]. Cloud computing as a large-scale distributed computing paradigm thereby helps to improve the efficiency of computation [192,253]. To effectively manage demand, collaboration needs to occur among participants in the demand planning process [131].

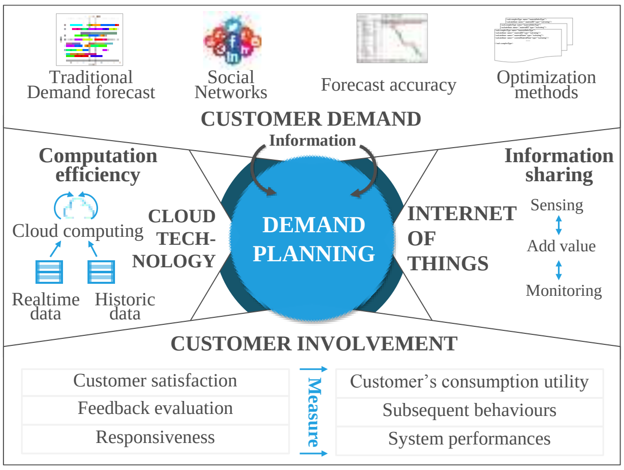


Figure 9. Demand planning in GPNs.

4.3.3. Supply management

In order to reduce the time to market and the total costs, many industrial companies have introduced supply chain management [228]. The main aspects of supply management in GPNs is depicted in Figure 10. Due to the ongoing globalization, supply chains nowadays imply great risks [31,228]. In particular, the sourcing of products from across the global markets has exposed organizations to considerable global sourcing risks, including supply risks, process and control risks, environmental and sustainability risks, and demand risks [107,112]. Meanwhile, a number of obstacles to global sourcing remain such as the lack of buyer-supplier proximity and the incompatibility of just-in-time and global sourcing [228]. Therefore, a comprehensive risk assessment to guide managerial decision-making has been an important research topic. Research on supplier search evaluation and selection based on key performance indicators, for example, has been performed to help managers and researchers select the optimal suppliers [3,4,75].

The development of suppliers is a complex and challenging process, which is a multi-criterion decision problem including both qualitative and quantitative factors [28,148,257]. Organizations increasingly implement supplier development programs in order to maintain high performance bases and in order to remain competitive [167].

The availability of actual - sometimes near real-time - information is one of the key enablers for improving the efficiency of the supply chain, especially in terms of information sharing within the supply chain [126]. Information sharing across entities in the global supply network ensures that the activities and decisions throughout the supply chain can be at high level of coordination. IoT and cloud technologies could provide various advantages in supply chain management operation, such as improved inventory management, increased logistics transparency, business process optimization, and resources saving [190,253].

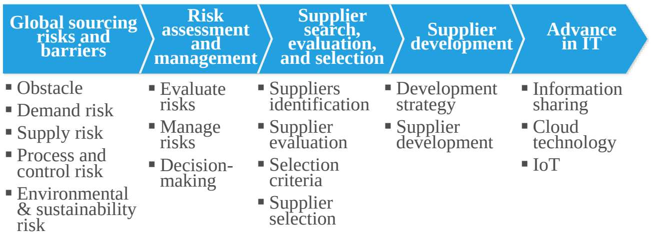


Figure 10. Main aspects of supply management in GPNs.

4.3.4. Order fulfilment

The available capacity regarding supply and production must be considered along the whole production network in order to fulfil customer orders with respect to footprint design and delivery times from several production plants. Orders have to be assigned to the production plants before they can be scheduled locally [23]. However, if customer orders are not fully specified at the time of planning, uncertainty regarding order configurations might be considered when assigning orders [21–24,243]. Therefore, demand uncertainty in terms of workload can be modelled through scenarios in order to optimally allocate orders and capacities achieving a desired level of robustness [22,23,198,243].

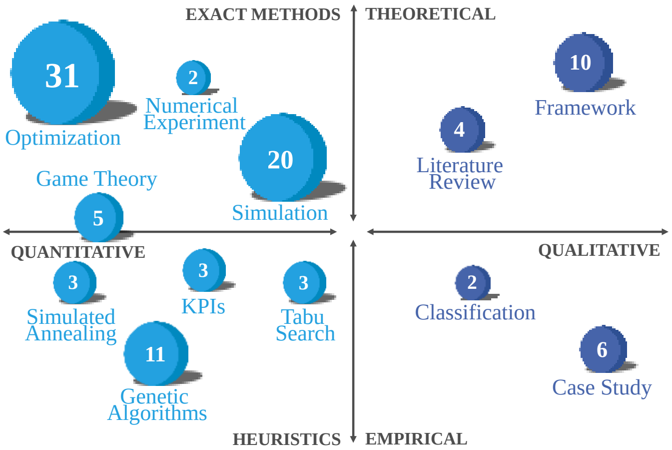
Desired capacity utilization rates at the production plants can be pursued by either central control or by distributed control through agents [16]. In the latter case, auction mechanisms may be applied for negotiation between agents, i.e. companies operating in global networks in order to achieve an optimal planning of orders maximizing their satisfaction [138,225]. Heading for a global instead of a local optimum can be stimulated by providing incentives for cooperative behavior of the network partners, whereby planning reliability can be improved by early sharing information about demand forecasts and incoming customer orders [20,46]. Therefore, discrepancies between forecasted orders and customer orders can be made transparent as soon as customer orders are received [20].

4.4. Most common used solution methods for decision support

Various decision support methods are used to support research in forming the production strategy (subsection 4.1), designing the network footprint (subsection 4.2) and managing the production network (subsection 4.3). As part of the preparation of this keynote paper, more than 150 papers from the three journals CIRP Journal Manufacturing Science and Technology, CIRP Procedia, and CIRP Annals, which have an overlap with the topic of GPNs, were examined for the most common solution approaches and methods for decision support (see Figure 11).

Data analysis is not explicitly mentioned in most research papers. However, it is an important prerequisite for compressing input data coming from Enterprise-Resource-Planning (ERP) or Manufacturing Execution Systems (MES) before using the data in a subsequent optimization or simulation. Data analytics helps to analyze, what events happened in the past (descriptive analytics), why events happened (diagnostic analytics), how likely events will occur in the future (predictive analytics) and what should be done in case of a re-happening of events (prescriptive analytics) [78].

Simulation is another widely used methodology for decision support in the design and operation of GPNs. It is especially suitable as production networks are complex systems where a



*Review of >150 CIRP articles related to GPN or keynote contributions by CIRP members

Figure 11. Most commonly applied solution approaches and methods for decision support in [%].

theory or a formula based modelling is impractical. Simulation facilitates analysis of the system's behavior under a variety of operating conditions. Sub-types are event-discrete, agent-based and continuous simulation [181,246,260].

Mathematical optimization is the most commonly used method for decision support, when designing and operating GPNs (see Figure 11). Optimization tries to depict relationships by a model consisting of at least one objective function and constraints. The model is solved with regard to optimality. Optimization can be further specified by the nature of the objective function (linear vs. non-linear), the number of objectives (single-objective vs. multi-objective) and the nature of the input variables (integer vs. mixed-integer). Optimization relies on simplifying assumptions. Finding optimal solutions is ambitious for real-life problems due to their complexity. The method can only be applied when the network is well understood and can be described analytically [222].

Besides data analysis, simulation, and mathematical optimization, solution methods such as heuristics and qualitative decision support tools facilitate decisions making in GPNs. Genetic algorithms or Tabu-Search as instances of heuristics cannot warrant the optimality of a solution. However, they provide short-term, easy-to-use, and feasible results in decision-making situations. Qualitative decision support procedures for the design and operation of GPNs include, for example, classifications, frameworks, case studies or literature reviews. These approaches can be further differentiated into theoretical, purely on literature review based approaches and empirical work with real use cases.

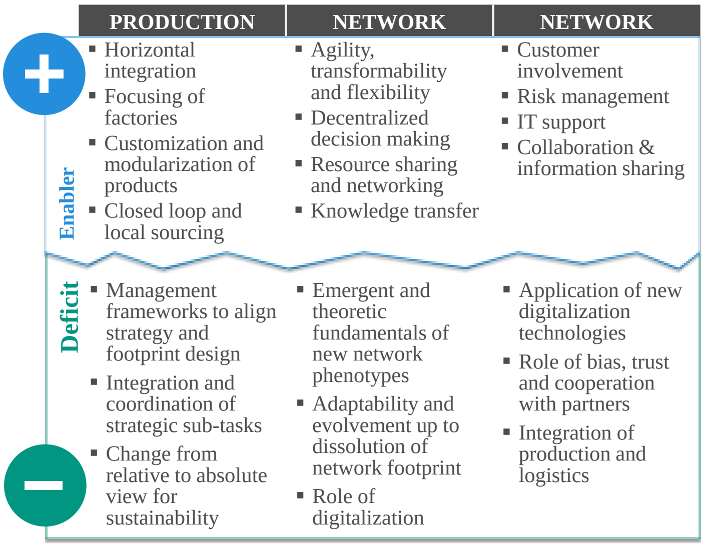
Resulting from Figure 11 it can be seen that the field of decision support in GPNs is primarily addressed by quantitative methods in the CIRP. Less focus has been laid on qualitative approaches. However, they might be promising means which could be emphasized more strongly in CIRP research in future.

4.5. Deficit in the state of the art

The review of the state of the art shows, that designing and operating GPNs was intensively investigated by researchers within the last decades. However, several aspects have not been examined so far. This leads to research gaps (see Figure 12). Within the definition of the production strategy, practical tools for identifying possible mismatches between production strategy and footprint of GPNs exist. However, these tools do not support the alignment of a company's GPN to its production strategy. At this point, easy to use management frameworks are missing. Besides, the future impact of market segment choice and product portfolio definition on production network design are far from clear. Also, approaches that integrate several (strategic) sub-tasks into a are missing. In the context of sustainability, the change of scope from relative to absolute sustainability and its impact on the design and operation of GPNs offers space for future research.

Looking at the core task network footprint design, several new network phenotypes, such as Speedfactories, Urban Factories and Circular Economy Production Networks have emerged in practice. They need to be further investigated from a research point of view. Besides, the concept of adaptability was intensively investigated on production system level. However, this perspective has to be extended to production network level. Especially the constant temporal evolvement of production networks due to merger and acquisition activities, changes in the companies' strategy or emergence of new technologies has to be investigated. The evolvement is on often gradually but it can be drastically and lead up to the dissolution of the production network. Besides, especially digitalization is a new enabler that has shown great benefits when applied to individual production plants. Though, the role and impact on production network design remain unclear so far.

The role of digitalization also needs further investigation within network management. New digitalization technologies may improve forecasting, enable tracking and tracing within the network and lead to an overall improvement of order fulfilment. Therefore, the positive impact of a broader exchange of information on performance and risk management, in general, have to be investigated [236]. Within this aspect, bias, trust, and cooperation among the partners of a production network may play a role. Also, on the management level the integration of sub-tasks needs to be explored in detail. Especially an integrated scheduling of production and logistics processes plays a significant role.



	PRODUCTION	NETWORK	NETWORK
+ Enabler	▪ Horizontal integration ▪ Focusing of factories ▪ Customization and modularization of products ▪ Closed loop and local sourcing	▪ Agility, transformability and flexibility ▪ Decentralized decision making ▪ Resource sharing and networking ▪ Knowledge transfer	▪ Customer involvement ▪ Risk management ▪ IT support ▪ Collaboration & information sharing
Deficit –	▪ Management frameworks to align strategy and footprint design ▪ Integration and coordination of strategic sub-tasks ▪ Change from relative to absolute view for sustainability	▪ Emergent and theoretic fundamentals of new network phenotypes ▪ Adaptability and evolvement up to dissolution of network footprint ▪ Role of digitalization	▪ Application of new digitalization technologies ▪ Role of bias, trust and cooperation with partners ▪ Integration of production and logistics

Figure 12. Deficit in the state of the art in designing and operating GPNs.

5. Trends for change

Building upon the state of the art and the research gaps, the authors of this keynote paper have identified three trends for a need for change in designing and operating global production networks. The trends are depicted in Figure 14 and further elaborated within the next section.

5.1. Harmonization of production strategy and footprint

Fitting the global production footprint to production strategy is a challenge for two reasons. First, the linkage between production strategy and footprint is often unclear. Only very simple production strategies, such as "produce for the local market", "produce where the labor cost is the lowest" or "produce close to the factories of the big customers", have direct implications for the footprint of the production network. However, in practice, even these simple production strategies are almost always modified significantly. For example, location-specific influencing factors –

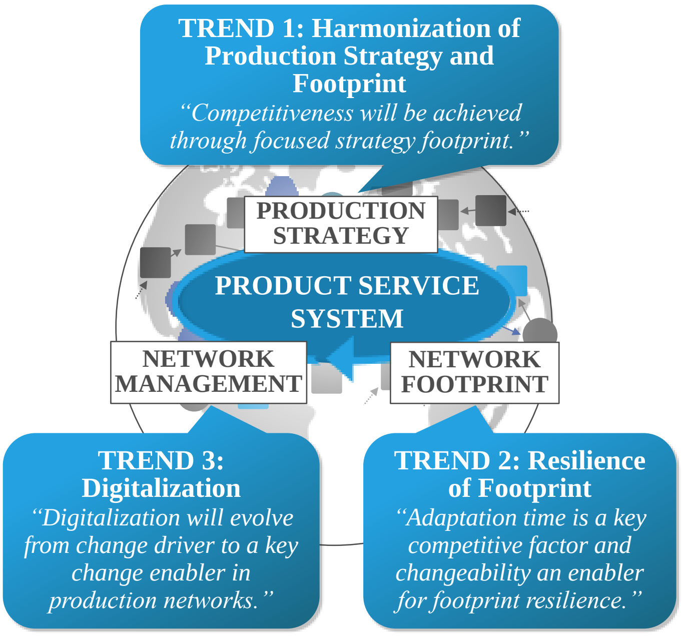


Figure 14. Trends for change in designing and operating GPNs.

local taxes, subsidies, regulations, political risks, etc. – may persuade the firm to put a factory in a location that does not fully fit the strategy [60,63,125]. Besides, production strategies in most firms are fairly intricate with no apparent implications for the production footprint. For example, a firm may choose to put the final assembly near markets served by the factory but produce components in central locations close to the firm's R&D centers or an appropriate "industrial commons" [70,186]. Some of the latter factories may also do final assembly for regional markets, complicating the pattern of flow in the firm's production network. Aside from broad and theoretical generalizations, the literature does not offer specific templates for the production footprint that would support different types of production strategies. In practice, designing a production footprint is still a case-by-case exercise.

The second reason, which is even a bigger challenge, is the difficulty of maintaining the fit. Many variables, internal and external to the firm, can make a fine-tuned global production footprint suboptimal for the intended production strategy. The list is long [64]: changes in local taxes, regulations, inflation, labor cost, trade agreements, currency, even addition of new logistics infrastructure, among other variables outside the firm, can make different sites more or less attractive. There are many other variables: a merger or acquisition often requires radical and sudden changes in the production network, competitor's actions, availability of new process technologies (e.g., digitalization), rise of E-Commerce, among others, can mandate a change in production strategy. However, due to the high level of hysteresis present in production networks (e.g., it is not easy to open and close factories quickly), the global production footprints of many firms are likely to be at odds with their production strategies for extended periods [64]. Building agility [168], and more generally "changeability" [17,36,199], in the structure of the production network, as explained in previous sections, would reduce the level of this hysteresis, but can be costly and not go far enough.

Combination of the two reasons – the need for case-by-case approach and the large number of uncontrollable variables that can affect the outcome – suggests that the process for making the decision is critical. In many firms, this is an ad hoc process [1]. Changing the firm's global production footprint inevitably involves substantial financial commitments with consequential legal, labor relations, commercial, and other implications. Many senior managers, including those not directly involved in production, are active in this process. A key predictor of how they would make decisions about changes in the global production network is how they regard the role of manufacturing in the business strategy of their firm [60,98]. Firms that assign a high role place a greater emphasis on the intangible benefits of global production sites than those that assign a low role [15,186]. Conversely, those that do not consider manufacturing to be a competitive advantage usually put more weight on the tangible benefits that are measurable, particularly in short term [60]. Figure 13 shows a list of typical tangible and intangible benefits for sites for foreign factories.

Figure 13. Benefits of global production sites [60].

To summarize, while highly desired, keeping the harmony between production footprint and strategy is a challenge. The solution is not to try to offer theoretical blueprints of optimal footprints for each type of strategy. The combinatorial problem makes that approach futile [64]. A more practical approach is to put more weight on intangible benefits of foreign production sites as they evaluate the options for changing the production footprint. Policies that allow factories to capitalize on the intangible benefits would encourage local managers to build higher capabilities in their factories, preparing them to cope with disruptive internal or external changes more effectively [70,164,247,248]. A production network consisting mostly of such factories would be more robust. i.e., have a higher level of "changeability" [17,36,199], than another with identical footprint but based mostly on extracting the tangible benefits from its factories.

5.2. Resilience of footprint

Management and control of global production networks are highly complex since an almost infinite number of influencing factors has to be considered [244]. Moreover, the complexity is increased by the uncertainty about future developments and the rising volatility within the network. As a result, adaptability has to be provided in order to be able to react to changes faster. However, this adaptability decreases often the average utilization within the network and therefore the price competitiveness [129].

Since a focus on costs is common in production network management [175], the preserved response capacity must be limited and can be overrun by changes that are caused events. The adaptation of the network footprint to this change cannot happen immediately. In fact, from the occurrence of a change to the actual implementation of the adaptation in the network footprint, a certain time passes. This delayed response of the network, the so called hysteresis, can be divided into three parts (see Figure 16): (i) the latency from the occurrence of change until the change is perceived, (ii) the latency until a need for action is identified, and (iii) the planning latency that consists of information gathering, analysis, decision-making and implementation [63]. Resilience describes the capability and ability of the footprint to return to a stable state after a change or disruption. Only companies that are able to react and adapt to changes in due time will be able to persist in times of increasing competitive pressure and dynamics [171]. Short adaptation time becomes a prerequisite for a resilient network footprint and a key competitive factor [129]. In order to create a resilient network, the network footprint management has to be designed in a way that the ability for a constant change is part of the planning process, even though the changes and challenges that might occur in the future are unknown [145]. For this purpose, the latencies have to be shortened. Big data analysis is an enabler to decrease the time span until change in production networks is perceived by identifying outliers in the quantity of influencing factors [84]. A continuous, active management and control of production networks decreases the latency until a need for action is identified [210]. Transparency and standardization in the decision-making process can decrease the time to change from identification to implementation of new, adaptive solutions [211].

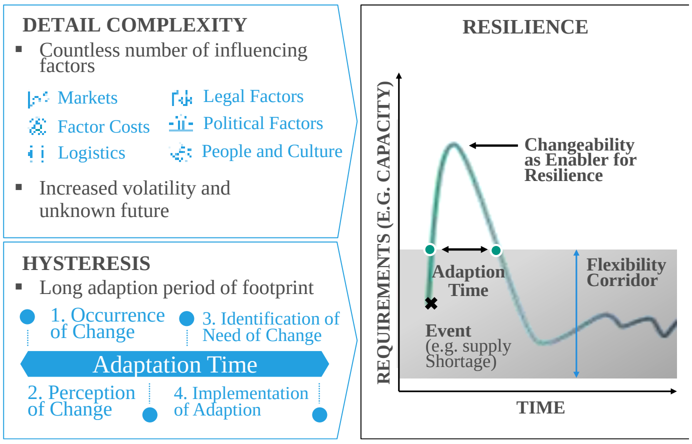


Figure 16. Role of resilience for footprint design.

5.3. Role and impact of digitalization

Within the context of global production networks, manufacturing companies seek to generate high-quality goods with the aim of low cost and less time. Digitalization thereby represents a new level of organization and control in manufacturing landscapes, offering tremendous potentials regarding the improvement of quality, flexibility, and productivity (see Figure 15) [113]. Besides being a technological trend, digitalization is an approach to react to rising dynamics and complexity with digital technologies [105,195,256]. Furthermore, digitalization also offers potential to establish a more efficient, flexible as well as modular production which may help to keep production at high-wage locations [69].

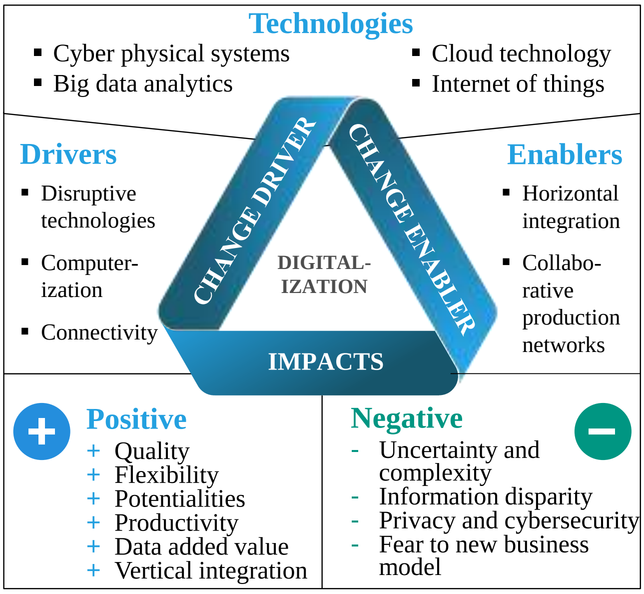


Figure 15. Role and impacts of digitalization in global production networks.

Computerization and connectivity are drivers for the implementation of digitalization [204] as they connect isolated manufacturing resources and technologies used in different manufacturing companies within the global network. The potential success of vertically and horizontally integrated cyber-physical systems, internet of things technology, cloud technology and big data analytics, the role of digitalization is changing (see Figure 15), which can be summarized as follows: learning how to use and interpret the collected data for intelligent decision-making is becoming a higher priority. The horizontal integration of different plants or even different stakeholders of a production network will be pushed by added value of data; isolated plants will be connected into collaborative production networks which allow for flexible and highly responsive reactions. From this point of view, the role of the digitalization is turning from a change driver to a change enabler. This can enhance the ability to realize the reduction of cost and increase in sales.

Despite of the advantages of the digitalization, it is also related to some concerns and issues in the global production networks. For example, because of new value chains created by digitalization, the underlying business models will also change. This means that the business environment will be even more uncertain and complex with an increased number of players including new digital attackers (e.g. Google). As a result, companies have to adapt to the disrupted value chain and proactively push the digitalization of their single production sites. They digitalize the manufacturing processes by means of vertical integration and collect huge amount of data without exactly knowing about the benefit for their company and the overall network (they are driven by digitalization instead of extracting value from it). In addition, the information disparity of production network partners caused by the digitalization should not be ignored. Partners in a production network often aim for diverse strategic goals. These diverse strategic goals hinder an exchange of all available information even if it could be available from a technological point of view. Due to various strategic goals and information disparity, a global optimum when managing global production networks may never be reached. New enabling technologies (sensors, cloud technology, track & trace) will, therefore, increase informational content but the negation of full information exchange may avoid that the full benefits of digitalization show up. Finally, privacy and cybersecurity issues will exist in the future and despite the rapid advancement of information and communications technology. For cybersecurity reasons, business owners will always have privacy concerns and be reluctant to share information and know-how.

6. Future research

The research gaps identified in subsection 4.5 and the three trends for change in designing and operating global production networks (GPN) presented in section 5 lead to a prioritized need for future research. These directions of research condensed in Figure 17 have to be explored intensively. For the core task production strategy, simple frameworks and tools will help to fit real-world network footprints with production strategy. The frameworks and tools must account for the intangible benefits of a global production. Within the core task network footprint design, the role of adaptability for the network footprint has to be addressed. In future, production networks may have to be dissolved. The goal is to reduce the footprint hysteresis in the event of changes and disturbances, facing uncertainty and complexity inherent in global production networks. The potential of increased transparency and standardization must be examined in particular. Digitalization shapes the need for research within the core task of network management. The potential of digitalization and respective new business models for network management have to be shown more intensively in real world applications. In particular, privacy and cybersecurity concerns must be overcome. Based on this, algorithms for automated decision-making, negotiation and balancing of interests have to be developed. Focused research will help to further increase the relevance of GPNs in practice. However, research must not lose sight of future drivers of globalization, such as circular economy, access to resources and sustainability (see Figure 1). Depending on how strongly they are gaining in importance, research must also be geared towards these drivers. Only the combination of research needs and research on the drivers of globalization will help to explain, clarify and predict GPNs in a globalized world.

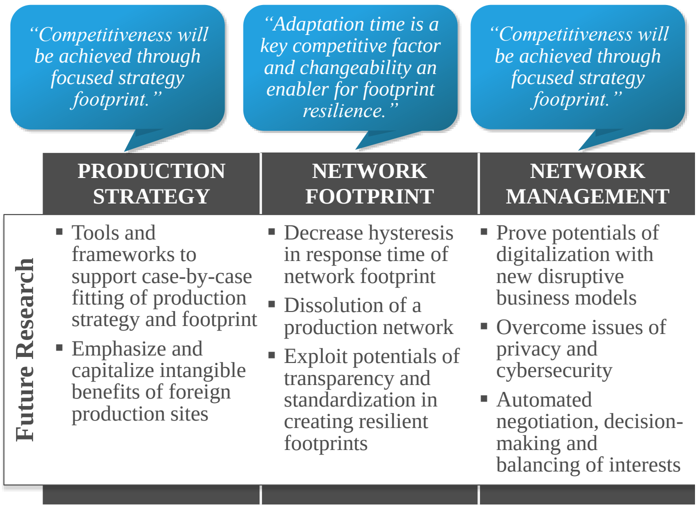


Figure 17. Prioritized need for future research.

7. Conclusion

Global production networks (GPNs) are one of the most critical form of organization. They account for a large part of today's global trade and are characterized by continuous evolutionary growth. Due to inefficient structures, the design and operation of GPNs poses challenges in practice. This keynote paper summarizes technical and scientific aspects in the area of global production within CIRP community and beyond. Building upon the motivation, industrial examples and a framework for designing and operating global production networks are presented. The framework structures the most important planning tasks and describes influencing factors, challenges, enablers and decision support systems. Based on an in-depth analysis of the current state of the art in forming the production strategy, designing the network footprint and operational network management, a need for future research is identified and elaborated in form of the three trends. Future research related to production network strategy shall focus on defining and maintaining the fit between production strategy and footprint design. Intangible benefits of a global production have to be taken into account. In the field of footprint design, the role of adaptability must be addressed and theoretical support for new emerging network and factory phenotypes has to be provided. Within network management, the potentials of digitalization and new forms of collaboration must be explored. The three trends meet the motivated challenges and help to transform historically grown rigid production networks into efficient networks with a focused and robust footprint.

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