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Decision support models for strategic production network configuration – A systematic literature analysis

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Abstract

The configuration of global production networks involves numerous strategic decisions, such as plants' spatial distribution and specialization. These decisions are highly complex. Many influencing factors such as local qualification and regulation have to be considered simultaneously. Furthermore, the factors are subject to high volatility and uncertainty. Additionally, decisions are characterized by many stakeholders, partly pursuing conflicting goals. There are numerous qualitative and quantitative decision support models trying to overcome these challenges. In this paper, 46 scientific publications were analyzed regarding considered decisions, objectives, influencing factors, and used models. In addition, the papers were evaluated in terms of configuration challenges, and future research needs were derived.

Keywords: Decision support models, network configuration, network design, global production networks, strategic decision making

1. Introduction

In recent decades, big and medium-sized corporations have internationalized their value creation. The results are global production networks (GPN). These are defined as a network consisting of geographically dispersed production units linked by flows of materials, information, and finance. [1] The motives for internationalization are diverse and range from access to specific markets and resources to cost-driven motives such as relocation to low-wage locations. Increasingly, location decisions are also dictated by the risk motive. [1,2] Failures in the supply chain, for example, are prompting calls for relocation to high-wage locations to reduce supply risks. [3] These motives show that the configuration of the production network is characterized by multiple, partly conflicting goals. In addition, such configuration decisions are influenced by a multitude of factors, which, in turn, are subject to high volatility and unpredictability. For example, fluctuating commodity prices, protectionist tariffs, and supply chain disruptions can change the advantageousness of locations and make network configuration a highly complex decision. [4]

For this reason, a variety of decision support models (DSM) exist. These are based on both quantitative and qualitative models and have different strengths and weaknesses to address the challenges in network design.

This paper analyzes the existing approaches in terms of their suitability for network configuration and determines research gaps in this area. For this purpose, a systematic literature review was conducted. Chapter 1.1 systematizes the decision by dividing network configuration into decision variables, objectives, and influencing factors. Chapter 1.2 addresses the configuration challenges, which will be used to derive the suitability and further research needs. Chapter 2 presents a systematization of DSM. Chapter 3 outlines the methodological approach of the systematic literature review, followed by the presentation of the results in Chapter 4. Finally, chapter 5 reflects on the results based on the configuration challenges and concludes with the derivation of further research needs.

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1.1. Network configuration as a decision problem

"The network configuration deals with the physical design of the network, and the capabilities of the sites on that network." [5] According to decision theory, a decision problem exists if at least two alternatives are possible. The network configuration can therefore be understood as a decision problem. Different configurations of the network are the alternatives, from which one most suitable to the decision-maker's goals is to be selected. A decision problem can be decomposed into *decision variables*, *objectives*, and *influencing factors*. [6] This decomposition will be used to analyze DSM and is further explained below.

The *decision variables* in the network configuration can be divided into the network structure, the specialization, the network resources, and the internal supply chain. The network structure covers the geographic dispersion and worldwide distribution of capacities. The network specialization defines the strategic purposes of the sites. The design of the network resources considers decisions regarding manufacturing layout, machines as well as the degree of automation. The internal supply chain represents the material flow between sites, customers, and suppliers. [5]

For the alternatives of the decision problem to be evaluated, the associated consequences must be represented in the model. The *objectives* express which consequences of the decisions the decision-maker attaches importance to. [6] A common concept here is the differentiation between competitive priorities and network capabilities. Competitive priorities are costs, quality, delivery, flexibility, innovation, and service. The competitive priorities are realized through network capabilities. These are access to market, access to resources, cost-effectiveness, mobility, and learning capability. [5]

In contrast to the decision variables, the *influencing factors* are parameters that the decision-maker cannot control but still impact the decision. (Quelle) The influencing factors can be divided into external and internal influencing factors. External influencing factors originate from the macroeconomic environment, such as market development, site-specific costs, logistical infrastructure, cultural, legal, political, and governmental factors. All these influencing factors are subject to dynamics and risk. [1] Internal influencing factors are inherent in the company, such as the structure, properties, and complexity of products and processes. [7]

1.2. Challenges in the network configuration

The presented decisions regarding network configuration are subject to numerous challenges, making the network configuration a highly complex decision area.

First, network configuration is subject to a high level of *detail complexity*. It is the result of many interdependent sub-decisions such as the choice of location, the allocation of products, technologies, and resources, investment decisions, and capacity allocations in the network. [4] However, these sub-decisions must not be considered in isolation but must consider interdependencies with other sub-decisions, which are referred to as compound effects. [6] In addition, network configuration depends on many factors such as labor costs, transport costs, tariff barriers, local content requirements, and the availability of suppliers, which must be evaluated simultaneously. High uncertainty and volatility also characterize several influencing factors. Thus, unforeseen short-term and long-term changes in the environment can affect the competitiveness of a location. [1] Another difficulty lies in identifying and evaluating influencing factors. [8] In particular, less tangible influencing factors such as the availability of qualified personnel and political stability are rarely systematically considered but play an essential role in strategic decisions. [1]

The second challenge is due to the low adaption speed of GPN. The term network *hysteresis* describes the significant delay between a change in the environment and the implementation of a network adaption. [4] This delay occurs due to the time necessary to identify the change and a fitting solution and the time to adapt the network itself. [3]

These two inherent characteristics of network configuration make network decisions time-critical and challenging. Making such decisions requires an adequate representation of uncertainty and risk as well as tangible and intangible influencing factors. Furthermore, multidimensional objectives and conflicting goals must be considered. Due to the size of the decision problem, analytical models must also provide a decomposition into sub-decisions regarding potential compound effects. In addition, data acquisition and the traceability of the solution path represent further *analytical modeling challenges*. [4]

To cope with this complex decision space, decision support models are necessary.

2. Taxonomy of network decision support models

Decision support systems and frameworks help decision-makers in semi-structured, semi-routine settings, as they help to structure the decision context and provide information regarding the effects of different decision alternatives. Over the last decades, many context-specific decision support approaches have been developed. The most important distinction is between *qualitative* and *quantitative* decision support approaches. The former provides a categorical model of the examined system and helps decision-makers when the quantification of decision factors is challenging or undesirable. The latter enables decision-makers to quantify the effects of their decisions in complex situations.

Both types of decision support are based upon models, representations of the examined systems, simplified for a specific purpose. In the case of qualitative models, two types of models are distinguished here. *Generalistic frameworks* portray general aspects, properties, and behaviors of the type of modeled system and its environment. *Specific frameworks*, in contrast, are applied to a particular instance of the system and allow company- or situation-specific insights. Quantitative models can be distinguished by their force of expression. Commonly, four types of models with increasing force of expression are distinguished: descriptive, analytical, predictive, and prescriptive models. *Descriptive* models concentrate on representing the characteristics of a system. The relations and dependencies between different aspects of a system are captured by *analytical* models, aiding system understanding. *Predictive* models are capable of forecasting the entire system's behavior under a given set of circumstances. Finally, *prescriptive* models define specific solutions or configurations of a system under a given set of conditions and a set of objectives. [9] With an increasing force of expression, the requirements toward the specificity of the models also increase. Thus, higher levels of the force of expression are not always desirable. Several methods are used for quantitative models. Particularly noteworthy are linear and mixed-integer models and simulation for predictive models. For prescriptive models optimization and heuristics like genetic algorithms are widely applied.

This contribution, therefore, investigates which types of DSM are used most commonly for which applications, based on their appearance in academic contributions

3. Research design

This literature review is structured according to [10]. First, a search query (SQ) and relevant interdisciplinary research databases for a comprehensive first literature set were selected. Next, the literature was gathered from 13 different databases. The SQ consists of search terms divided into three sections, as shown in table 1. Considered contributions needed to reflect at least one term per section. Notations with a "*" refer to search options, including all variations of a word. After the initial search, 738 contributions in total were identified.

Table 1. Search terms for the systematic literature analysis.

Topic	Search Terms
GPN	global production networks, global manufacturing networks, international production networks, international manufacturing networks
Decision element	production strategy, network strategy, network design, network structure, network configuration
Decision support	congruen*, footprint, complexity, subnetworks, capability*, *layer*, decision, decompos*, simulat*, optimi*, harmoni*, align*, framework, model

Next, contributions were eliminated based on their title, abstract, and full-text, respectively. The resulting selection contained 46 contributions for the subsequent analysis. Reasons for eliminating papers were: (i) papers not accessible or available in English, (ii) publications with the focus on supply-chain management, (iii) papers about fiscal policy, (iv) papers dealing with the analysis of trade relations between countries, (v) focus on human resources management.

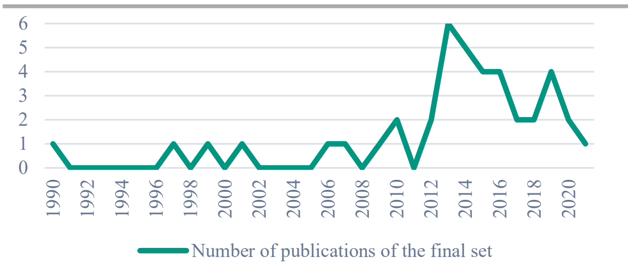

Fig. 1. Relevant literature over time

Figure 1 shows the publication number over time, confirming that network configuration has been in the interest of operations management research for decades. Moreover, an increase in approaches can be observed in the last 10 years. This could be explained by the fact that the need for decision support continues to grow due to increasing globalization and rising complexity in an uncertain business environment.

4. Results

The systematic literature review identified 46 relevant DSM. These are divided into the previously defined types, as shown in Figure 2.

20 qualitative frameworks were identified, 11 of which offer company-specific decision support. The remaining 9 are general frameworks that evaluate relationships independent of the company context. Of the 20 qualitative models, 8 approaches are supported by a procedure model. But procedure models are only combined with specific frameworks. 26 papers were classified as quantitative models, including 22 deterministic (D) and 4 stochastic (S) models. Almost all approaches forecast the system behavior so that at least a predictive character can be ascertained. 12 approaches even derive an optimal solution as a decision proposal and are thus marked as prescriptive models. Similar to the qualitative models, almost half of the approaches are embedded in a process model.

In the following, the DSM are analyzed concerning the decision variable (4.1), the objectives (4.2), and the influencing factors considered (4.3).

Type	Categorization	Stochastic/ Deterministic	includes Procedure Model	#
qualitative	Generalistic Framework (GF)	Not applicable (na)	no	9
qualitative	Specific Framework (SF)	Not applicable (na)	yes	8
qualitative	Specific Framework (SF)	Not applicable (na)	no	3
quantitative	Analytical (AN)	Deterministic (D)	no	2
quantitative	Predictive (PD)	Deterministic (D)	yes	7
quantitative	Predictive (PD)	Deterministic (D)	no	3
quantitative	Predictive (PD)	Stochastic (S)	yes	1
quantitative	Predictive (PD)	Stochastic (S)	no	1
quantitative	Prescriptive (PS)	Deterministic (D)	yes	3
quantitative	Prescriptive (PS)	Deterministic (D)	no	7
quantitative	Prescriptive (PS)	Stochastic (S)	no	2
Total				*46*

Fig. 2. Categorization of the identified decision support models

4.1. Considered decision variables in DSM

Next, the dependencies between examined decision variable and type of DSM are investigated, as shown in Figure 3. Decisions regarding network structure, including the geographic distributions of plants and their capabilities, are considered most frequently. Decisions regarding network resources are considered least frequently.

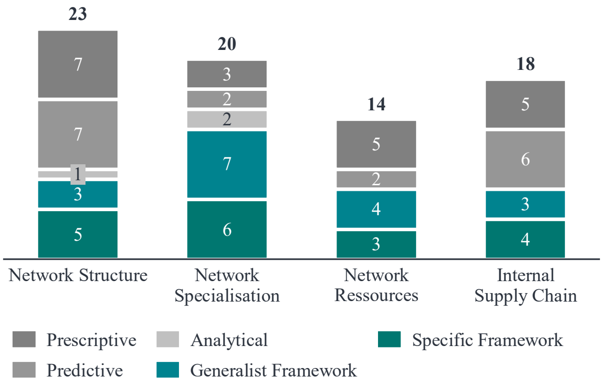

Fig. 3. Allocation of DSM for network configuration decision variables

For network structure, quantitative DSM are dominant with 65%. Most quantitative DSM use mixed-integer programming. [11–18] Other approaches solve the problem with heuristic methods such as genetic algorithms. [19,20] Almost all DSM are deterministic. Only two approaches model the network structure as a stochastic decision problem. [21] develops a markovian decision problem to develop risk-efficient migration paths from the status-quo to the target configuration. Another stochastic approach is provided by [22], who uses a discrete event simulation to distribute value-added modules in a dynamic network. Among the qualitative DSM, both specific and generalistic concepts are represented. Generalistic approaches make general statements concerning the network structure. [23] analyzes the relationship between structure types and external and internal influencing factors such as market, product, and process type. [24] abstracts the network structure to so-called configuration mechanisms and relates them to external influencing factors and performance outcomes. A specific framework is provided by [25], who developed a manufacturing configuration map to evaluate the associated strategic capabilities.

Qualitative DSM predominate with regard to the strategic specialization of locations and networks. Quantitative approaches in this area often focus on make-or-buy decisions for certain components or products, represented in the model as binary variables. [12,14,21] Competencies and responsibilities of the locations are often not taken into account. The analytical DSM presented by [26,27] approach the interaction between sites by evaluating the flow of information. Qualitative DSM make it possible to formalize strategic site competencies in terms of product, process, market, and suppliers at an appropriate level of abstraction. The Ferdows' plants roles model is often used for this purpose. [28]

In terms of network resources, the approaches are equally distributed. However, it can be observed that the level of detail varies greatly here. Thus, qualitative DSM are often deriving recommendations for rather general decisions such as the degree of automation [5] or the complexity of processes. In contrast, quantitative DSM make a more specific statement about, e.g., the implementation of a particular machine based on the target costs. [11,15]

The internal supply chain structure is more often modeled by quantitative DSM. The network structure's capacity distribution strongly influences the definition of the material flow, so approaches often consider these partial decisions simultaneously in a decision problem. [15,29,20,18]

4.2. Considered objectives in DSM

The identified DSM consider a range of different objectives. The relative share of objectives used is shown in Figure 4. Visibly, qualitative DSM cover a wider range of objectives. Quantitative DSM focus on efficiency/cost, risk, profit, dependability, flexibility, and quality. Dependability describes the reliability of delivery and adherence to delivery dates. However, qualitative DSM also cover more intangible objectives such as access to markets, resources, learning, and mobility, which were introduced as network capabilities.

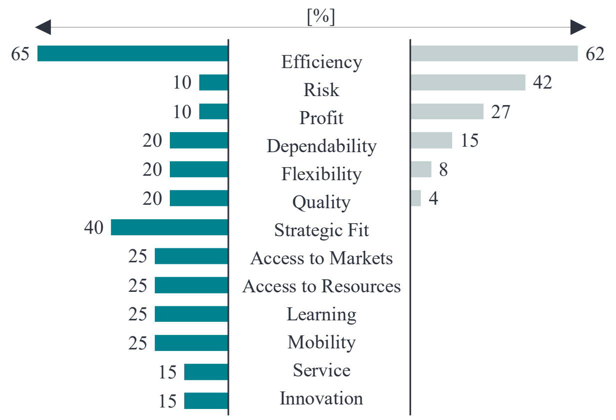

Fig. 4. Objectives in qualitative (left) and quantitative (right) DSM

In both DSM, the primary objective is efficiency or cost. Qualitative DSM seek to address uncertainty in the network by including risk as an objective in almost half of the approaches. For example, variance and standard deviation of expected cash flows are used as risk measures. [21] The second most common target in qualitative DSM is the *strategic fit*. This term describes the congruence of organization and environment. [30] In terms of network configuration, it represents the strategy's alignment with the network footprint taking the environment into account. There are different ways to measure the concept of strategic fit. [31] Approaches such as [5,25] characterize fit as portfolio deviation, where a deviation of the idealized portfolio of specific criteria is associated with performance losses. Approaches by [23,32,7]describe the strategic fit as the match of network properties and factors, e.g., location competence, process, and product complexity.

The DSM can also be differentiated into mono- and multi-objective. As figure 5 depicts, almost half of the approaches pursue only one objective. 12 approaches even pursue three or more objectives simultaneously. The proportion of qualitative DSM increases as the number of objectives increases. Thus, qualitative DSM often consider network capabilities and/or competitive priorities simultaneously. [33,34,28,5,1,25] With regard to quantitative DSM, cost- or profit-oriented approaches are often evaluated as a trade-off with risk minimization or increased flexibility. [13,35,29,36,37,2]

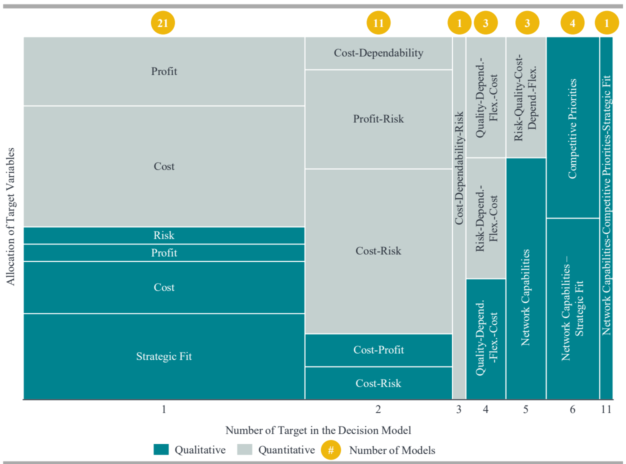

Fig. 5. Allocation and number of objectives in DSM

4.3. Considered influencing factors in DSM

As described in chapter 1, the network configuration is determined by many external and internal factors. Consequently, the identified DSM differ in the scope of the considered influencing factors. Figure 6 shows the percentage of the DSM in which the corresponding influencing factor is considered. Most DSM consider market, costs, product, and process factors. Furthermore, quantitative DSM hardly reflect intangible influencing factors such as cultural, legal, and political factors. Qualitative frameworks address these factors more frequently, but still only in less than 30% of cases. [38,1,39,25]

		External Factors						Internal Factors		
		Market	Cost	Logistics	Culture	Politics and Government	Legal	Risk	Product	Process
Quantitative	Prescriptive	33%	42%	33%	0%	25%	0%	17%	67%	50%
	Predictive	42%	33%	33%	8%	8%	0%	17%	42%	42%
	Analytical	50%	0%	0%	0%	0%	0%	50%	50%	50%
Qualitative	Generalist Framework	56%	56%	44%	11%	11%	11%	22%	44%	33%
	Specific Framework	55%	55%	45%	18%	27%	9%	36%	45%	45%

0 % 100 %

Fig. 6. Considered influencing factors in DSM

5. Discussion and Outlook

Network configuration is subject to many sub-decisions, influencing factors, and objectives. Furthermore, it is characterized by the tension between rapidly changing and unpredictable influencing factors and rigid adaptation mechanisms in the network. These compounding challenges result in high analytical complexity and require appropriate DSM.

In the systematic literature review, 46 qualitative and quantitative DSM were analyzed. The analysis shows that qualitative DSM are used primarily for more strategic tasks like network specialization and location roles. Quantitative DSM tend to be used for more tactical decisions such as allocating resources and determining material flow relationships. In addition, qualitative DSM are characterized by a broader range of objectives, whereas quantitative DSM are usually cost-driven. Concerning the influencing factors considered, a similar picture emerges. Thus, qualitative DSM also consider more and, in particular, intangible influencing factors. However, concerning the level of detail, a significant discrepancy can be observed between quantitative and qualitative DSM. For example, qualitative DSM are usually considered at a high level of abstraction so that a subjective, company-specific evaluation is required to derive a decision recommendation. In addition, qualitative DSM lack strong statements about cause-effect relationships, so the support potential is often low.

Based on these results and the network challenges, the following future research needs can be derived. Future DSM should include more intangible influencing factors and target variables at the highest possible level of detail to account for detail complexity. Thereby, an objective evaluation of the intangible factors must be given. Quantitative DSM already offer a more objective assessment and should be extended to intangible factors and targets. Potential approaches here would be, e.g., fuzzy logic and artificial intelligence. Another research direction is the evaluation of decision alternatives. Multidimensional objective functions are usually easy to implement, but the weighting of objectives as a representation of the preferences of several decision-makers is a major challenge. Preference learning known from other disciplines could be a possible solution. [40] Further development of existing qualitative DSM is also purposeful. Hence, DSM should consider the configuration in more detail to investigate concrete cause-effect relationships between objectives, influencing factors, and network properties. In particular, Ferdows' concept of subnetworks should be operationalized in DSM to derive more precise statements regarding a specific network. In addition, hybrid models could combine the advantages of both approaches and thus lead to a more stringent continuity of planning from the strategic to the tactical level. For strategic, long-term decisions, such as site selection or role, the analysis suggests that qualitative approaches like [17,22,31] are initially useful. To concretize the network planning with the required resources and capacities, mathematical optimization methods such as [19,24,32, 37] are suitable. For the migration from the actual to the target configuration, changeover costs must also be taken into account. Due to fluctuating planning premises, a continuous revision of this planning is required as shown by [8] and [13]. By combining approaches, the entire life cycle of the network configuration planning can be supported.

Because of increasing uncertainty in the macroeconomic environment, the challenge of hysteresis becomes increasingly critical. Thus, qualitative and quantitative DSM need to take uncertainty into account. Future approaches should efficiently identify the need for change, e.g., by using monitoring approaches. Furthermore, multiple future scenarios have to be considered when evaluating network alternatives. Again, intangible factors play an important role here since the impact of economic policy measures, for example, is difficult to assess a priori, but can significantly impact competitiveness. In addition to identifying the need for action, data acquisition and preparation for the planning phase constitute a major problem. Here, approaches like a digital twin of the production network as conceptualized by [41] are desirable to accelerate decision preparation. The third research direction concentrates on the flexibility and changeability of network configurations themselves to be more resilient to disruptions.

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