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A Fuzzy Inference System-Based Approach For Assessing Strategic Capabilities In Global Production Networks

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Abstract

Intangible factors, e.g. the availability of infrastructure at a production site, and implicit knowledge, have an essential influence on the decision-making in global production networks. However, the consideration of intangible factors and implicit knowledge, especially in planning the production network configuration and determining the production network strategy, is usually done implicitly or only based on qualitative and subjective estimations. This can cause biased decisions and miscalculations that make additional and expensive adaptions in the global production network necessary. In order to address this challenge, this paper develops a methodology based on fuzzy inference systems (FIS) to enable a more quantitative and objective consideration of strategic network capabilities influenced by intangible factors and implicit knowledge. For this, the strategic network capabilities are described by several criteria aggregated through one or multiple cascading fuzzy inference systems. The resulting metrics for strategic network capabilities as well as intangible factors are normalized and comparable. Transparency about strategic network capabilities allows a focused discussion about the strategic configuration of the production network. Moreover, the metrics can also be used in other quantitative approaches such as mathematical optimization. The proposed methodology is demonstrated with 70 intangible factors, six strategic network capabilities, and 21 sub-capabilities from academic literature. It can be shown that the developed methodology can map intangible factors and implicit knowledge in a very flexible and detailed manner by selecting and weighting the describing criteria within the FIS in order to quantify strategic network capabilities.

Keywords

Global Production; Production Network Configuration; Production Strategy; Fuzzy Inference System; Intangible Factors; Decision-Making

1. Introduction

Today, large corporations as well as medium-sized companies organize their value creation in globally distributed production sites. The drivers of this internationalization are labor cost advantages, access to resources and the development of new sales markets. The results are global production networks (GPNs) [1]. However, current disruptive events such as COVID-19 and related entry regulations, supply shortages for different materials, Ukraine war, energy crisis and political tensions resulting in decoupling scenarios show the complexity and vulnerability of such GPNs. In particular, recent years have shown that the frequency of such disruptive events is steadily increasing, making risk reduction, adaptability and resilience increasingly the key success factor [2]. At the same time, sustainability is also increasingly on the strategic agenda of companies. Both legal regulations and market requirements must be taken into account in the configuration of production networks. In addition to these requirements for sustainability and adaptability, network decisions are also subject to a variety of other overlapping strategic motives. Due to these elusive,

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manifold aspects, a clear alignment of the production network configuration to the production strategy is very difficult. Therefore, the goal of this approach is to develop a method that quantifies network strategic capabilities based on fuzzy inference systems (FIS) in order to create comparability and transparency regarding fit of production strategy and configuration.

2. Global Production Network Configuration And Corresponding Challenges

Global production networks are formally defined as globally distributed production sites that are interconnected via material and information flows [1]. A distinction is made between GPNs, also called international manufacturing networks, which consist of intra-company networks, and inter-company networks, also called supply chains [3]. This paper focuses purely on intra-company networks. The design of production networks is also referred to as network configuration. Here, network configuration involves decisions about network structure including global dispersion of plants, allocation of resources and products as well as the assignment of plant roles including capability building [1].

The goal of the network configuration is to design the network in such a way that it optimally matches the strategic goals of the company as well as its specific environment. This congruence is referred to as strategic fit [4]. As mentioned at the beginning, the strategic motives can be manifold and partly contrary to each other. Strategic motives or capabilities and their interrelationships have already been discussed extensively in the literature. For example, [5] derived the four international manufacturing capabilities *resources accessibility*, *thriftiness ability*, *manufacturing mobility* and *learning ability*. [4], in contrast, differentiates between production strategy and production network strategy. A detailed discussion of strategic capabilities and their interdependencies can be found in [6]. The strategic capabilities differ in terms of their evaluability. For example, capabilities such as access to cheap labor or market proximity are easy to value in monetary terms. Other capabilities, such as access to qualified personnel and reliability of infrastructure, on the other hand, are difficult to quantify [7,8].

This diversity and ambiguity of factors makes network configuration a highly complex management decision. [9] refers to these challenges as *detail complexity* and *hysteresis*. Detail complexity describes the number of influencing factors and strategic motives as well as the interactions between them. Hysteresis, on the other hand, describes the temporal discrepancy between the occurrence of a disruption and the adjustment of the network. Especially against the background of increasing volatility of the environment, short adaptation times are rapidly becoming a success factors [1]. This is counteracted by the rising complexity of details due to the increasing importance of intangible factors. Thus, the detail complexity makes the evaluation of network alternatives and fast decision making more difficult. For this purpose, decision support models are applied in network decision making. These help in structuring the decision problem and create transparency about decision alternatives. A large number of decision support models already exist in the literature. However, the detail complexity and hysteresis make it difficult to adequately model the decision situation [8]. Intangible factors, in particular, pose a major challenge and are therefore usually neglected, although they have a significant influence on the competitiveness in GPNs [7,10]. The following chapter is dedicated to a selection of decision support models and their handling of intangible factors.

3. State Of The Art

In the following chapter, the existing literature regarding the consideration of intangible factors in global production networks is reviewed and research gaps are identified. The found literature can be divided into two areas. The first area consists of more qualitative approaches like management frameworks that identify and describe intangible factors or evaluate intangible factors on a highly aggregated level. The second area contains more quantitative approaches that use intangible factors within multi-criteria decision-making methods as well as optimization or simulation models.

3.1 Qualitative Approaches For Identification Of Intangible Factors Within Production Strategy

The usage of intangible factors within the qualitative approaches varies from a solely identification of factors, e.g. [11], towards a detailed description of single factors by other criteria for performance evaluation, e.g. [12], or complex frameworks for strategy definition, e.g. [13].

[11] and [14] focus on the identification of different factors. [11] perform a literature review and identify 19 potential key factors for allocation and reallocation decisions in production networks. Similar to this, [14] identify 48 different tangible and intangible success factors as a starting point for further research. [15] and [16] identify and analyze different strategic factors for GPNs or reasons for a reallocation of production sites.

In contrast to the solely identification of various factors, [12] develop a framework to evaluate the supply chain performance based on quantitative and qualitative factors. Several approaches use a similar concept, by describing intangible factors through several other measures. They use fuzzy multi-attribute decision making (MADM) methods, such as fuzzy TOPSIS to evaluate a single plant location or a supplier and consider several intangible and tangible factors that are evaluated based on five to seven linguistic variables [17–19]. A more sophisticated use of intangible factors in strategic frameworks can be observed in [13] and [5]. Both focus on GPNs and the production strategy, respective the strategy fulfillment. They describe several network capabilities, competences or the network structure based intangible and tangible factors.

While reviewing the researched qualitative approaches it becomes apparent that one part of the approaches only identifies factors or develop a strategic framework based on the factors in a generic way. However, a systematic methodology to assess the single intangible factors is not developed, leaving the evaluation ultimately up to the subjective estimation of the expert. The other part of the reviewed qualitative approaches uses simple (fuzzy) MADM approaches to quantify the intangible factors, but they lack the complexity since only a few factors are selected. Moreover, they are not developed in a generic way but only for a specific use case, e.g. supplier evaluation. Furthermore, both sub-groups have in common that interdependencies between different factors are usually not considered in the evaluation of the factors or while developing the strategic frameworks.

3.2 Quantitative Approaches With Intangible Factors As Input

In the more quantitative approaches, quantified intangible factors often serve as input for an optimization or simulation model. Within the quantification are large differences and some approaches directly quantify intangible factors to integer-values [20–22]. Other approaches such as [23–25] define a methodology that is based on integer-values and does not consider any subjective estimation or implicit human knowledge. But since the focus of this work is to capture exactly them, these approaches are not considered any further.

[26] quantify intangible factors, such as staff qualification, directly in an optimization model as fuzzy numbers. In contrast, [27] evaluates the intangible factors, similar to the approaches in chapter 3.1, based on several factors and a survey with decision-makers. The evaluation serves as input for an optimization model for GPNs. A combination of [26] and [27] is presented by [28]. [28] use FIS to quantify intangible factors in a first stage. In a second stage, the resulting values are used in an optimization model. Other approaches use a self-developed system based on fuzzy logic to quantify risks and dependencies in GPNs [29] or use PROMETHEE to prioritize and evaluate different factors as input for a simulation model [30].

A detailed comparison of 46 qualitative and quantitative decision support models as well as their addressed objectives, influencing factors, and application areas in network configuration can be found in [8].

While reviewing the more quantitative approaches, it can be observed that they use mostly subjective estimations. Furthermore, the approaches are use-case specific and consider only selected intangible factors and thus usually lack the representation of interdependencies between factors. Therefore, the qualitative approaches do not represent the detail complexity that is inherent to the quantification of intangible factors and their consideration in decision making in GPN, see also [7,10].

3.3 Derivation Of Research Gap

In summary, both literature groups (chapter 3.1 & 3.2) are missing a generic and systematic methodology to quantify or evaluate intangible factors in a way that reduces the influence of subjective estimations and that can represent interdependencies between different intangible factors.

Therefore, especially against the background of the detail complexity mentioned at the beginning, a gap in the systematic and analytical consideration of intangible factors in decision-making becomes apparent [8]. This gap is also reflected in practice. Intangible factors are perceived as relevant for decision-making, but are often only included by gut feeling and managerial judgement due to their difficult assessment [7,10]. However, in order to cope with the detail complexity, new research approaches are required that systematize intangible factors, quantify them and make them comparable with quantitative factors.

Therefore, the approach in this paper addresses the research gap and develops a fuzzy inference-based evaluation methodology for intangible factors. FIS seems appropriate for this problem since they can aggregate qualitative and quantitative metrics as well as additional subjective estimation to one metric. Additionally, they can be combined easily with other FIS to cover interdependencies between factors and represent the inherent detail complexity of the topic.

This method can be applied and adapted for various use-cases and quantifies intangible factors in a less subjective way while considering human-decision knowledge. The generated values for the intangible factors can be used to create transparency and evaluate the strategic fit in production networks as well as in quantitative approaches such as optimization or simulation.

4. Methodology For Assessing Strategic Capabilities In Global Production Networks

To develop the approach for quantification of intangible factors in global production networks, at first the foundations of fuzzy logic are briefly presented (chapter 4.1). Afterwards, the structure of the complete model is presented (chapter 4.2) and the derivation of the causality diagrams is explained (chapter 4.3). Finally, the structure and the definition of the FIS are formulated (chapter 4.4).

4.1 Foundations Of Fuzzy Logic

In contrast to classical crisp sets und numbers, where an object is part of a set or not or a number is a fix value, fuzzy sets and numbers have continuous grades of membership. So, an object can be partially part of several sets or values. The degree of membership is defined by membership function, that can represent linguistic evaluations as “high” or “low”. Transferred to intangible factors with no clear metrics, the evaluation of a strategic capability can be “high” or “low” or partially “high” and partially “low”, which allows to represent subjective suggestions and uncertainty about the “real” value [31,32]. The most common forms of membership functions are triangular and trapezoid functions (see Figure 1) [31].

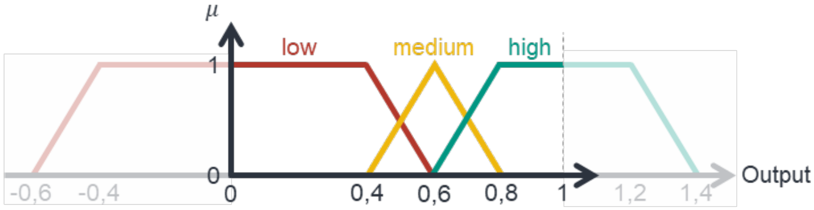

Figure 1: Standardized triangular and trapezoid membership functions for input and output variables

Analogously to classical crisp sets, the logic operations “and”, “or”, “not”, respective “intersection”, “union”, “complement” can be defined also for fuzzy sets. For further reading see [32].

Based on fuzzy sets, FIS can be defined. A fuzzy rule base allows to map human knowledge whereas the fuzzification imitates human subjective decision making. Basically, they follow a three-step structure of fuzzification, rule-based inference, and defuzzification. In the fuzzification, the input variables, such as the distance to highways, and the output variables, e.g. availability of infrastructure, are selected and formulated as fuzzy numbers. Furthermore, the evaluation in form of linguistic terms, the scales, and the according membership functions are defined by human decision-makers (see Figure 1). In the next step, the decision rules are defined with if-then rules related to the input and output variables in the rule base, such as "if the distance to the next highway is low, the availability of infrastructure is high". These rules are a formal description of implicit expert knowledge by the decision-makers. In addition, the inference method, so how the logical operators within the rules are defined mathematically, is determined [33–35]. There are different possibilities, but the most common one is the max-min inference. In the defuzzification, the resulting fuzzy output of rules is converted into a crisp-value. This can be done by several methods, while the centroid-method is the most common one [36].

4.2 Structure Of The Model For Quantification Of Strategic Network Capabilities

Such FIS are used to quantify strategic capabilities and intangible factors in GPNs based on human knowledge. Figure 2 shows the structure of the model. The strategic capabilities (blue) are quantified based on the network configuration (green) and influencing factors (gray). Influencing factors come from external and internal company environment. External influencing factors are, e.g. wage costs and demand. Internal influencing factors come from the company, but cannot be influenced by the configuration, such as product properties. Some influencing factors (e.g. political stability) are rather general from macro-economic aspects (yellow). Here, indices from databases can be used as metrics. The other influencing factors must be evaluated on a company-specific basis (dark blue). Relevant aspects of the configuration are the geographical distribution or the specialization of production sites. With the help of FIS, the strategic capabilities per plant are quantified based on the influencing factors. These are aggregated to a network score using weighting keys.

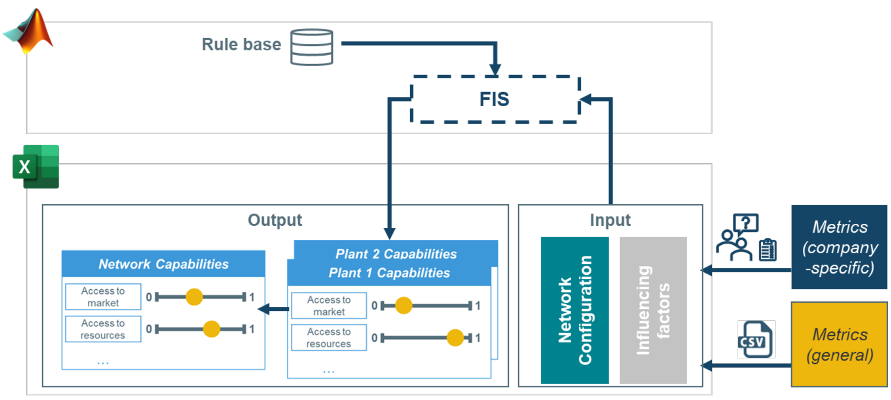

Figure 2: Structure of model for quantification of strategic capabilities in global production networks

4.3 Identification Of Causality Diagrams

Strategic capabilities are determined by a large number of influencing factors, some of which are interlinked in a highly complex manner [12]. But if more metrics are included in the quantification of strategic capabilities, the complexity increases, since in case of FIS, the number of rules increases significantly which makes it hard for human-decision makers to define a complete and consistent rule-base. Therefore, the different input factors that are relevant for the quantification are grouped additionally in different categories to gain causality diagrams for the intangible factors. In order to generate such structured causality diagrams, the method of networked thinking according to [37] was applied. A good size for these categories seems to be three to four factors per category. This aims to define clearly separated and relevant sub-measures for intangible factors. Each category as well as the evaluation of the strategic capability itself is represented by a FIS. So instead of defining one large rule-base, several smaller rule-bases for the categories are defined, which reduces the number of rules and simplifies the consistent and complete definition. An example for such a causality diagram is given by the sub-capabilities *access to cheap labor*, which is part of the strategic network capability *access to resources* in Figure 3. Here, GCR is the global competitiveness report by the world economic forum, which provides different indices for single nations [38].

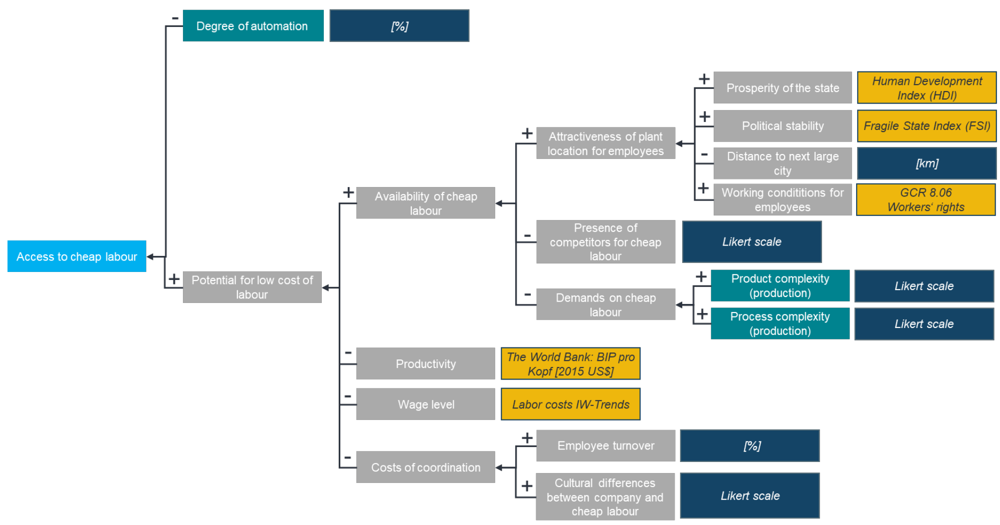

Figure 3: Exemplary causality diagram for the availability of infrastructure at a production site

4.4 Definition Of The Fuzzy Inference Systems

After defining the causality diagrams (see chapter 4.3), they can be transformed into FIS. For this, every category as well as the aggregation to an evaluation for the according intangible factor is modelled as a specific FIS. This allows a detailed representation of the identified causalities and the included human knowledge. To create these FIS the three steps of fuzzification, rule-base inference and defuzzification are performed. Since the selection of the input and output variables is already done, only the scales of them needs to be defined. Since some of the input criteria can be measured directly, such as distances, the scales are fixed. For other criteria that stem from external indices or reports, such as the GCR, or that are estimated directly by decision makers, e.g. product complexity, a standardized scale from 0 to 1 is used. Due to the flexibility of FIS, intangible input factors that can only be approximated with difficult effort can also be integrated as fuzzy variables, thus allowing a feasible application. This is done for example for the cultural distance between the company and cheap labor (see Figure 3). As it can be seen from the causality diagram in Figure 3, the scales of the input variables vary strongly. This is covered by the FIS since they only use the linguistic evaluation of the variables and so the different scales can be considered together in a quantitative way. Therefore, the definition of the membership functions and the linguistic terms is done directly by the decision-makers. However, for most of the input and output variables, standardized triangular and trapezoid functions (see Figure 1), that can be transformed to individual scales, are used in terms of simplicity and comparability. Furthermore, since for the quantification many input variables and criteria can be used, only a few membership functions and linguistic terms are used per FIS, to reduce the complexity of the rule bases. The standardized membership function for the input and output variables is defined on the interval [0;1] and can be adapted for individual variables if necessary (see Figure 1).

Based on the previously defined causality diagrams, for each FIS the rule-base is defined by decision-makers. In these rule-bases the implicit knowledge and the decision base of human decision-makers is modeled. While formulating the rules, it is important that they are as consistent as possible and that they cover all cases of possible input variables' values. Due to the causality diagrams (see chapter 4.3) and the fact that each category respective FIS only have a maximum of four input variables the rules can be formulated very intuitive since every input is fuzzified with intuitive linguistic terms ("high", "medium" and "low"). For sake of simplicity the max-min method is chosen for the inference. For the defuzzification, the centroid method is used. For a better interpretability of the defuzzied values, it is important, that they can assume all values on the interval [0;1], since there is no other metric for evaluating intangible factors. Therefore, the centroid of the memberships for "high" and "low" needs to be 1, respective 0 as depictured in Figure 4. This must be done for all intangible factors and the corresponding categories. The cascading FIS contains the implicit expert knowledge for the evaluation of intangible factors and creates comparability between these factors and production sites and networks, since subjective influences from individual decisions are minimized.

5. Application In The Strategic Network Performance Assessment

Using the approach presented in Chapter 4, a tool for evaluating the strategic capabilities of the network was implemented. The tool allows to evaluate the strategic capabilities of the network based on local tangible and intangible influencing factors as well as configurational network decisions using the presented fuzzy inference systems. In sum, the 6 capabilities *access to market, access to resources, learning capability, efficiency, sustainability* and *changeability* are considered. These in turn are fed from sub-capabilities, as explained in 4.3. The capabilities per plant are then aggregated to a network score using weighting keys. Capability-specific weighting keys are possible. For example, *access to market* is weighted by sales volume and *efficiency* by production volume. Figure 5 shows the dashboard of the tool in the Excel interface using fictive data for illustrative purpose.

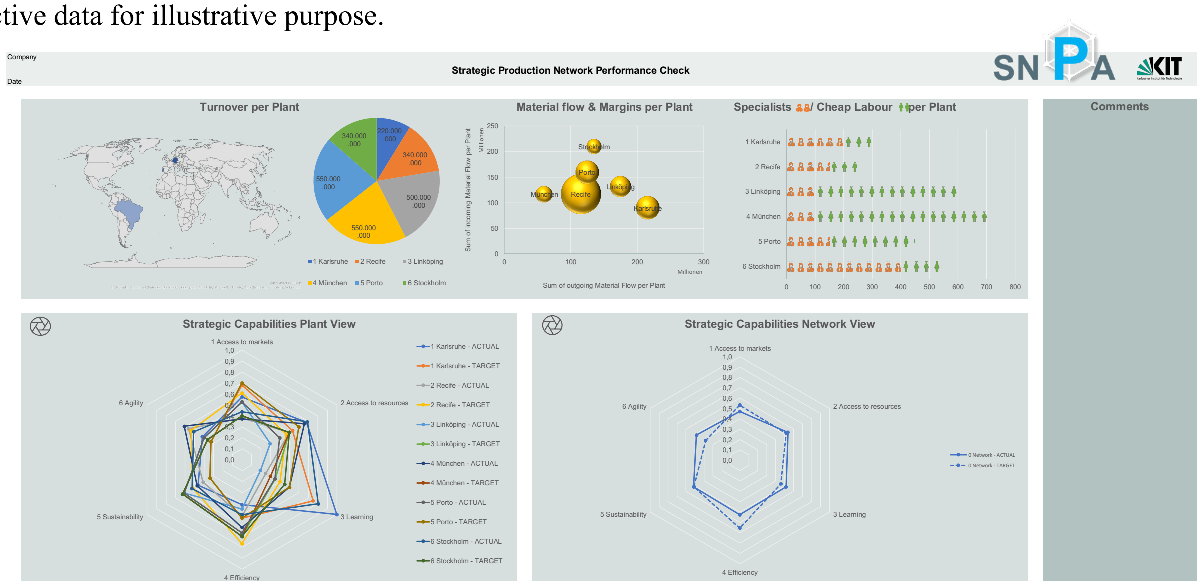

Figure 4: Dashboard of the Strategic Network Performance Assessment

The strategic capabilities per plant are shown on the bottom left, and the strategic capabilities of the network are shown on the right. In addition to the actual capabilities (solid lines), which are determined on the basis of the fuzzy inference system, a target capability (dashed lines) is also shown. The target is to be defined specifically for the company. The discussion of strategic differentiation factors according to [4] can promote the identification of strategic network targets. The direct comparison of target and actual strategic capabilities reveals strategic mis-fits. This enables a goal-oriented discussion of the strategic direction of the network and of potential action measures in the strategic network configuration. In addition to network targets, plant targets can also be defined, thus promoting a strategic focus through plant roles. Moreover, the tool displays further information such as sales and profit distribution. Number of employees and material flows are displayed, which support the manager in the strategic discourse.

6. Conclusion And Outlook

The strategic configuration of global production networks is a highly complex management decision. The multitude of influencing factors as well as their diversity, difficult comparability and mutual relationships influence the performance of the production network. Aligning the production network consistent with the production strategy, which is called strategic fit, requires transparency about these strategic capabilities. Previous approaches have so far insufficiently considered these mostly intangible strategic capabilities. Either models focus only on partial aspects and here especially costs or consider the strategic capabilities in a very aggregated way, so that the informative value and support for decision making remains low.

To this end, this paper presents an approach that quantifies strategic network capabilities based on influencing factors and network configuration. The 6 strategic capabilities are thereby composed of 21 sub-capabilities. The quantification is done via fuzzy inference systems, which in turn uses a rule base obtained by assessing causal relationships and leveraging implicit expert knowledge.

This approach has been implemented prototypically. The fuzzy inference systems have been implemented in MATLAB. MATLAB in turn interfaces with Excel to import the required input and export the quantified capabilities as output to be displayed in a dashboard. The visualization in a dashboard enables a focused discussion about strategic misfits in the network configuration. The input here includes company-specific variables collected in interviews, as well as macroeconomic indices from databases. In the next step, the tool will be applied in workshops with industry partners. The aim is on the one hand to validate the causal relationships found and on the other hand to evaluate the support potential in strategic network configuration.

The approach can be further developed with other methods from data science and artificial intelligence. For example, it would be conceivable to use preference learning to derive membership functions of the fuzzy variables [8]. A major challenge here is the data basis, as network decisions are often very complex and individual, making it difficult to generate a suitable data basis. Approaches with synthetic data could help here. Furthermore, individual strategic capabilities could be linked back to configuration variables and influencing factors in various analyses using e.g. structural equitation models.

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References

[1] Lanza, G., Ferdows, K., Kara, S., Mourtzis, D., Schuh, G., Váncza, J., Wang, L., Wiendahl, H.-P., 2019. Global production networks: Design and operation. CIRP Annals 68 (2), 823–841.

[2] Lanza, G., Schuh, G., Friedli, T., Verhaelen, B., Rodemann, N., Remling, D., 2020. Transformation globaler Produktionsnetzwerke. Zeitschrift für wirtschaftlichen Fabrikbetrieb 115 (4), 196–199.

[3] Rudberg, M., Olhager, J., 2003. Manufacturing networks and supply chains: an operations strategy perspective. Omega 31 (1), 29–39.

[4] Friedli, T., Mundt, A., Thomas, S., 2014. Strategic Management of Global Manufacturing Networks. Springer Berlin Heidelberg, Berlin, Heidelberg.

[5] Shi, Y., Gregory, M., 1998. International manufacturing networks-to develop global competitive capabilities. Journal of Operations Management 16 (2-3), 195–214.

[6] Netland, T.H., Frick, J., 2017. Trends in Manufacturing Strategies: A Longitudinal Investigation of the International Manufacturing Strategy Survey, in: , International Manufacturing Strategy in a Time of Great Flux. Springer, Cham, pp. 1–16.

[7] Kaiser, J., Steier, G.L., Seeger, T., Friedli, T., 1117. Entscheidungsfindung in der Gestaltung und Koordination von globalen Produktionsnetzwerken. Zeitschrift für wirtschaftlichen Fabrikbetrieb (9), 522–527.

[8] Steier, G.L., Benfer, M., Werz, P., Ziora, M., Lanza, G., 2022. Decision support models for strategic production network configuration – A systematic literature analysis.

[9] Ferdows, K., 2014. Relating the Firm's Global Production Network to Its Strategy, in: , International Operations Networks. Springer, London, pp. 1–11.

[10] Steier, G.L., Silbernagel, R., Maier, T., Peukert, S.K., Lanza, G., 2022. The Role of Intangible Influencing Factors in Strategic Network Decision-Making [in press], in: 29th EurOMA Conference, July 1 - 6, 2022. Book of Proceedings, Berlin, Deutschland, 01.07.2022 – 06.07.2022.

[11] Balbontin, C., Hensher, D.A., 2019. Firm-specific and location-specific drivers of business location and relocation decisions. Transport Reviews 39 (5), 569–588.

[12] Bhatnagar, R., Sohal, A.S., 2005. Supply chain competitiveness: measuring the impact of location factors, uncertainty and manufacturing practices. Technovation 25 (5), 443–456.

[13] Scherrer, M., Deflorin, P., 2017. Linking QFD and the manufacturing network strategy. International Journal of Operations & Production Management 37 (2), 226–255.

[14] Ng, H.S., Kee, D.M.H., 2012. Development of Intangible Factors for SME Success in a Developing Country. International Journal of Academic Research in Business and Social Sciences 2 (12), 198–213.

[15] Mishra, S., Singh, S.P., Johansen, J., Cheng, Y., Farooq, S., 2019. Evaluating indicators for international manufacturing network under circular economy. MD 57 (4), 811–839.

[16] Vanchan, V., Mulhall, R., Bryson, J., 2018. Repatriation or Reshoring of Manufacturing to the U.S. and UK: Dynamics and Global Production Networks or from Here to There and Back Again. Growth and Change 49 (1), 97–121.

[17] Awasthi, A., Chauhan, S.S., Goyal, S.K., 2010. A fuzzy multicriteria approach for evaluating environmental performance of suppliers. International Journal of Production Economics 126 (2), 370–378.

[18] Chu, T.-C., 2002. Selecting Plant Location via a Fuzzy TOPSIS Approach. The International Journal of Advanced Manufacturing Technology 20 (11), 859–864.

[19] Govindan, K., Khodaverdi, R., Jafarian, A., 2013. A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. Journal of Cleaner Production 47, 345–354.

[20] Becker, A., Stolletz, R., Stäblein, T., 2017. Strategic ramp-up planning in automotive production networks. International Journal of Production Research 55 (1), 59–78.

[21] Bihlmaier, R., Koberstein, A., Obst, R., 2009. Modeling and optimizing of strategic and tactical production planning in the automotive industry under uncertainty. OR Spectrum 31 (2), 311–336.

[22] Hochdörffer, J., Klenk, F., Fusen, T., Häfner, B., Lanza, G., 2021. Approach for integrated product variant allocation and configuration adaption of global production networks featuring post-optimality analysis. International Journal of Production Research, 1–25.

[23] Brintrup, A., Puchkova, A., 2018. Multi-objective optimisation of reliable product-plant network configuration. Applied network science 3 (1), 1.

[24] Moser, R., 2014. Strategische Planung globaler Produktionsnetzwerke: Bestimmung von Wandlungsbedarf und Wandlungszeitpunkt mittels multikriterieller Optimierung. Zugl.: Karlsruhe, Karlsruhe Inst. für Technologie, Diss., 2014. Shaker, Aachen, XII, 139, XX S.

[25] Paquet, M., Martel, A., Montreuil, B., 2008. A manufacturing network design model based on processor and worker capabilities. International Journal of Production Research 46 (7), 2009–2030.

[26] Ozgen, D., Gulsun, B., 2014. Combining possibilistic linear programming and fuzzy AHP for solving the multi-objective capacitated multi-facility location problem. Information Sciences 268, 185–201.

[27] Prinz, A., 2016. Mathematische Modellierung zur Optimierung der Wertschöpfungsverteilung nach quantitativen und qualitativen Kriterien in Produktionsnetzwerken der diskreten Fertigung. Dissertation. Universität Stuttgart.

[28] Sadic, S., Sousa, J.P. de, Crispim, J.A., 2018. A two-phase MILP approach to integrate order, customer and manufacturer characteristics into Dynamic Manufacturing Network formation and operational planning. Expert Systems with Applications 96, 462–478.

[29] Niknejad, A., Petrovic, D., 2016. A fuzzy dynamic Inoperability Input–output Model for strategic risk management in Global Production Networks. International Journal of Production Economics 179, 44–58.

[30] Ude, J., 2010. Entscheidungsunterstützung für die Konfiguration globaler Wertschöpfungsnetzwerke: Ein Bewertungsansatz unter Berücksichtigung multikriterieller Zielsysteme, Dynamik und Unsicherheit. Zugl.: Karlsruhe, Karlsruher Institut für Technologie, Diss., 2010. Shaker; Wbk Inst. für Produktionstechnik, Aachen, Karlsruhe, III, 154, XXXIII S.

[31] Klir, G.J., Yuan, B., 1995. Fuzzy sets and fuzzy logic: Theory and applications. Prentice Hall PTR, Upper Saddle River, New Jersey, 574 pp.

[32] Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8 (3), 338–353.

[33] Deb, S.K., Bhattacharyya, B., 2005. Fuzzy decision support system for manufacturing facilities layout planning. Decision Support Systems 40 (2), 305–314.

[34] Frank, H., 2002. Fuzzy Methoden in der Wirtschaftsmathematik: Eine Einführung, 1. Aufl. ed. Vieweg, Braunschweig, Wiesbaden, 241 pp.

[35] Mamdani, E.H., 1976. Advances in the linguistic synthesis of fuzzy controllers. International Journal of Man-Machine Studies 8 (6), 669–678.

[36] Tanaka, Y., 1993. An overview of fuzzy logic, in: Proceedings of WESCON '93. WESCON '93, San Francisco, CA, USA. 28-30 Sept. 1993. IEEE, pp. 446–450.

[37] Gomez, P., Probst, G.J.B., 1995. Die Praxis des ganzheitlichen Problemlösens: Vernetzt denken, unternehmerisch handeln, persönlich überzeugen. Haupt, Bern, Stuttgart, 301 pp.

[38] Schwab, K., 2019. The Global Competitiveness Report 2019. World Economic Forum. https://www.weforum.org/reports/global-competitiveness-report-2019. Accessed 24 March 2022.

Biography

Gwen Louis Steier, M.Sc. studied industrial engineering at the TU Darmstadt and the Karlsruhe Institute of Technology (KIT). He is a research associate at the wbk Institute of Production Science of KIT in the department of Production Systems with a focus on Global Production Strategies.

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Dr.-Ing. **Sina Peukert** did her PhD at the Institute of Production Science in the field of robustness enhancement in production networks. Since 2020, she leads the research group Global Production Strategies.

Prof. Dr.-Ing. **Gisela Lanza** studied industrial engineering at the Karlsruhe Institute of Technology (KIT) and held the first shared professorship "Global Production Engineering and Quality" at KIT in cooperation with Daimler AG. Ms. Since 2003, she has been head of the Production Systems Department at the wbk Institute of Production Science of KIT.