DESIGNING MULTI-SITE OPERATIONS NETWORKS

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Abstract
The design and planning of multi-site operations networks requires to find a strategic fit between fulfilling market requirements, considering individual site competencies and minimizing overall network costs. The purpose of this paper is to present and discuss an integrated approach for designing multi-site operations networks based on a qualitative analysis of the dimensions ‘market requirements’ and ‘site abilities’ followed by a quantitative optimization of the resulting production network based on the total landed costs of the manufacturing footprint. The proposed approach is validated by using a firm’s data set consisting of more than 50 product groups and over ten globally dispersed sites that serve a total of eight sales regions. The findings contribute to the understanding of how operations networks may be designed in order to meet market requirements, to consider individual site competencies as well as the overall costs.

Keywords:
Manufacturing networks, site competencies, production strategy.

1 INTRODUCTION
Over the past decades, the business focus of manufacturing companies has changed from supplying mainly domestic markets to competing in a global context, resulting in the establishment of international manufacturing networks with many dispersed sites. The reasons for companies to globally spread manufacturing are manifold, but include to better access markets, to access skills and knowledge, to mitigate risks like foreign exchange rates, to avoid trade-barriers and to exploit lower production and logistics costs. Global companies benefit in particular from multi-site manufacturing networks: Liberal markets with fewer trade barriers, lower transport and transactions costs allow to enter new markets with fewer restrictions and expand market shares further.

The manufacturing networks of today’s world are often very complex systems that are increasingly challenging to manage. Due to the dynamics of the market and numerous internal and external factors, like shorter product cycles, ever-changing and increased customer requirements, new competitors form emerging markets and new technologies, companies need to constantly rethink and adjust the structure of their manufacturing network. In order to successfully compete in an international manufacturing network, companies need to follow a long term strategy and use each site’s advantage to develop the manufacturing network, while at the same time, lowering the overall costs.

2 STATE OF THE ART
The review of current literature shows that a numerous of approaches exist for designing multi-site manufacturing networks. The target of this paper is to suggest a method that allows management to strategically develop the manufacturing network, while at the same time, lowering the overall costs.

In this paper, we present an approach for including qualitative, strategic input from key decision-makers into an quantitative optimization approach for designing multi-site manufacturing networks. The target of this paper is to support the decision making process. These approaches rely mainly on the participation and contribution of the key decision makers in a company and are ideal for encouraging conceptual thinking and forming an overall strategy. Quantitative approaches, on the other hand, form a data model of the selected network and use mathematical approaches like simulation or optimization in order to evaluate and select the preferred target scenario. Quantitative approaches are commonly used in academic research, but are often very focused on details that hinder a practical utilization in practice.

In this paper, we present an approach for including qualitative, strategic input from key decision-makers into an quantitative optimization approach for designing multi-site manufacturing networks. The target of this paper is to suggest a method that allows management to strategically develop the manufacturing network, while at the same time, lowering the overall costs.
generic approach to consider both strategic objectives and a quantitative analysis for designing manufacturing networks. However, the result of the strategic analysis cannot directly be utilized as input for designing the manufacturing network.

Wagner and Nyhuis develop the concept 'Global Variant Production System', which aims at dividing production into a variant-neutral pre-production and a variant-specific final production stage. For this, an as-is analyses of the value stream, total costs of ownership and logistics is carried out. After this, possible future scenarios are generated and evaluated based on a cost efficient procurement, competence-driven make-or-buy decisions and allocation of components. [12] The approach depicts a practical way of modelling manufacturing networks and evaluating possible future scenarios. The cost evaluation to compare the generated scenarios is focused on a mainly qualitative comparison of potential savings, but does not provide an integrated costs analysis.

Koberstein et al. present a concept for the strategic planning of global production networks that uses a two-stage stochastic mixed-integer programming model. This model focuses on depicting the impact of exchange rates and demand volatility on the expanses and investment of the future production network. The resulting net present value of a multi-stage scenario tree is used for evaluating the best target scenario. [13] The presented approach focuses mainly on the financial evaluation of network scenarios and only uses the projected customer demand as a strategic input criteria. Further important strategical criteria, like proximity to the customer or site qualification are not taken into consideration.

Lanza and Moser develop a multiple-criteria optimization model that identifies the best configuration for a future manufacturing network under uncertain and dynamic business environments. A mathematical optimization model integrates several objectives, like costs, delivery time, quality, flexibility, coordination, customer proximity and site qualification. Each objective can be weighted and further constraints can be considered in order to incorporate individual preferences by the decision makers. [14] The presented approach integrates many relevant dimensions into one integrated model and also considers strategic input. However, the mathematical complexity of the optimization model and the effort for gathering the required data suggests little practicability for larger network optimizations.

The literature review shows that many approaches for designing manufacturing networks exist that are either strategical in character or that focus on a quantitative optimization. While the strategic approaches lack the direct integration of quantitative evaluation, most quantitative approaches do not consider strategically input. [10] The presented approach in this paper therefore tries to close the gap between both approaches and suggests a pragmatic way of using strategic input for a quantitative network optimization.

### 3 CONCEPT

The approach presented in this paper is based on the software-tool OptiWo, which uses a genetic algorithm for supporting the design of manufacturing networks. The development of OptiWo is subject of ongoing research and industrial consultancy of the Machine Tools and Production Engineering (WZL) of RWTH Aachen University and was previously presented in references [4, 15].

OptiWo uses a standardized data input for modelling production networks. The data model of the network consists of product groups with hierarchical process steps, similar to forecasting plans or a bill of material structure, as the smallest element for configuring network scenarios. In this way, many alternative configurations of a network may be modelled. E.g. by allocating all process steps of a product to one site, a 'world factory' with high utilization of economies of scale can be depicted. By allocating production volume of certain markets to separate sites, a 'local-for-local' network, with minimal transport costs and close proximity to the customers, can be modelled. In between, all conceivable network types can be configured, including site specialization for certain components or process steps, as described by Abele et. al. as a 'hub & spoke' network phenotype. [6] At the same time, the data model is fully flexible in terms of the scalability of the manufacturing volume. If the production volume allocated to a certain site is increased or decreased, the necessary resources are scaled accordingly (e.g. invest in new machines and adapting space requirements at each site).

In this way, the impact of future scenarios with higher manufacturing volumes can easily be depicted.

Considering additional boundary conditions, the genetic algorithm iteratively reconfigures the network through operations that are similar to natural selection. The fitness function of the genetic algorithm evaluate the total land costs (TLC) for each of the iterations and thereby searches for a cost-minimized target network. After many generation, a target network is selected. More detailed information of the data model and optimization approach can be found in [15]. In more than ten industrial cases, the software OptiWo showed that it is capable of handling various production networks in terms of network size, product portfolio, etc. and find suitable target network scenarios. However, the practical experience indicates that a sole focus on the total landed costs of manufacturing networks often does not adequately match the strategical considerations of decisions makers. The conventional approach was therefore extended to also consider strategic input.

In this paper, we present an optimization approach for designing manufacturing networks that uses a pragmatic way of considering strategic input. The strategic input parameters are used in order to limit the solution space of the input data for the optimization and develop alternative scenarios of the target networks that are aligned with the overall production strategy. The approach consists of four steps, as presented in Figure 1. In the first step, the

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**Legend:**

**Focus of this paper**

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**Figure 1. Approach for designing multi-site networks.**
fundamental specifications for the optimization approach is defined and the data model for the as-is network is established and calibrated. The second step considers the future development of the network, e.g. changes in manufacturing volumes, changes in input parameters like labor costs or consideration of new sites or products. The third step focuses on integrating the strategic view on the network and is the main focus of this paper. The last step aims at evaluating the resulting networks and identifying the recommended target network.

3.1 Setting the data model

Crucial for a successful design of manufacturing networks is to define the objective (e.g. market growth or cost reduction) and scope (e.g. one product group or selected sites) for designing the network as concrete as possible. If objective and scope of the network design are clearly defined, it is easier to specify the needed level of abstraction. E.g. if the scope of the network design is narrow, fewer sites and product groups need to be considered, making a more detailed network model feasible. If the scope is wider, the level of abstraction needs to be adjusted accordingly.

When the level of abstraction is defined, the model of the as-is manufacturing network is derived by gathering and aggregating the as-is data of the network. According to the selected level of detail, all relevant data for depicting the total landed costs in a manufacturing network, is considered, including:

- Manufacturing program for each product group, for each site and target sales region
- Working plan data for the product groups, including process times and used resources (machines, machine-operator ratio)
- Fixed and variable manufacturing costs (machine hourly rates, depreciation, material consumption, purchased part costs, energy, direct and indirect labor costs)
- Costs of transport and duty for material flow between production sites and sales regions
- Location dependent costs (area costs for rent, depreciation, management, etc.)

Crucial for a valid model is to not only depict the as-is model, but also compare the model to the real manufacturing network in order to identify inconsistencies and calibrate the input data. Thereby a two-step approach has proven to be most efficiency, as shown in Figure 2.

In OptiWo, the initial point for calculating the total landed costs is a capacity model of the manufacturing network. In essence, the capacity is determined by the working plan data and the manufacturing volumes, which define the production hours for each machine. The chosen shift model then defines the number of machines, its utilization and the number of required direct and indirect personnel. If the capacity model does not depict the as-is network adequately, the input parameters must be calibrated. After the capacity model of the manufacturing network is acceptable, the validation of the costs can be carried out. In order to validate the cost model, the costs for personnel and machine depreciation as well as costs per product proved to be valuable measurements in order to calibrate the cost model. If costs do not depict the as-is network sufficiently, the cost input parameters need to be calibrated. For validating and calibrating the data model, OptiWo provides a number of visualization tools that allow to better understand the depicted network. E.g. a world map pictures the value streams in the network, waterfall charts depict the costs and a tree map illustrates the numbers and utilization of the machines within the network.

3.2 Depicting future scenarios for the network

After the as-is model is validated, the objective of the second step is to define the future scenarios that will be considered for designing the manufacturing network. Since transforming multi-site international networks takes considerable time, it makes sense to consider scenarios that lie well ahead of the current situation. The forecasting horizon of these future scenarios depends considerably on the scope and objective of the network design, as discussed in 3.1. Typically, the planning horizon lies between three to ten years into the future. Thereby intermediate scenarios (e.g. every two years) help to plan the migration of the as-is network to the desired target network. In order to do so, the most probable conditions for the company’s network need to be estimated. In particular the future sales volume, split by the defined sales regions and the development of input parameters like wage levels and site productivities, are from interest. In addition, the future scenarios can also consider possible new sites and new product groups.

The basis for all future scenarios is the as-is model of the network. If a new scenario is defined, e.g. with higher sales volume and more expensive wages, the as-is data input is altered or extended according to the assumed future conditions. In the same way, sensitivities of the data input
can be considered to estimate the effect of certain input parameters on the network design.

<table>
<thead>
<tr>
<th>Site A</th>
<th>Site B</th>
<th>Site C</th>
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Legend: ✔ Allocation permitted

Figure 3. Solution space for the network.

### 3.3 Strategy fit

The third step of our approach considers additional strategic input. Without any additional strategic input, the genetic algorithm optimizes the network free of any restrictions. However, if additional boundary conditions are implemented, the algorithm only allocates products to the non-restricted manufacturing sites. In this way, the solution space of the network that the genetic algorithm uses is reduced. This principle is exemplarily demonstrated in Figure 3.

In this example, site A could supply product A to all sales regions. However, site B and site C are permitted to supply to certain sales regions, but not all. In this case the genetic algorithm will attempt to find the cost-optimal solution within the given solution space. If only one site is permitted for a certain product, the solution space for this product is ‘one’ and no optimization will occur for this product. In order to determine, if the genetic algorithm is allowed to allocate a product (P) that is supplied to certain sales region (i) to a manufacturing site (j), the following notation is established:

\[
N_{i,j} = \begin{cases} 
\text{True (allocation permitted)} & \text{if } \text{allocation permitted} \\
\text{False (allocation not permitted)} & \text{otherwise}
\end{cases}
\]  \hspace{1cm} (1)

In our approach we use these boundary conditions in order to consider additional strategic input by systematically narrowing down the solution space of the target network. The key question is, how well does a product fit to a certain manufacturing site from a strategic point of view. To answer this question, the portfolio-analysis from Schmidt is extended [16]. The general approach of Schmidt uses the two dimensions ‘market complexity’ and ‘product maturity’ to allocate products to sites in a manufacturing network. We extend this approach, for also considering the sites in the network in the same way. Essentially, the sites need to fulfill the product and market requirements in order to manufacture a certain product, as is illustrated in Figure 4.

**Product and market requirements**

- Market complexity
  - Customer-specific configurations
  - Importance of local regulations
  - Just-in-time delivery

- Market service
  - Closeness to customers
  - Service level
  - Adherence to delivery dates
  - Flexibility

- Product maturity
  - Stable manufacturing processes
  - Seldom changes to the processes and product
  - Low dependency on local supplier

- Product competency
  - High manufacturing competency
  - Product ramp-up competencies

The first dimension in our approach analyses the market or the customers’ point of view. Products that compete in a market with high complexity should be manufactured at local sites, close to customer. If market complexity is low, a product can more likely be produced at a single site that serves the whole market. Evidence for a high market complexity are, for example, a high share of customer-specific configurations, a high importance of local regulations or a requirement to deliver the products just-in-time. The market complexity from a product point of view is matched with the ability of the sites to serve a specific market. For example, a high market service of a site for a specific market is given, if its customers are close, it can provide a high level of delivery service with adherence to delivery dates and is flexible in terms of manufacturing volumes.

The second dimension that is considered in the approach, is the maturity of the product from a manufacturing point of view. Products that are rather new or that have a low level of product maturity in regards to manufacturing should be manufactured at a site with high competencies. More mature products can more likely be produced at sites with lower competency levels. A high level of product maturity is indicated, if the manufacturing processes are stable, changes to the processes and product are seldom and the importance of local supplier is little.

In order to put the theoretical approach into practice a 4-point ordinal scale is used for determining the strategic parameters. A rating of (1) determines a very low level in the strategic categories market complexity, market service, product maturity and product competency and a rating of (4) a very high level respectively. In between, a rating of (2) low and (3) high is also possible. The rating of the strategic input of these four strategic categories is done on the basis of expert knowledge. In order to ensure a thorough assessment and avoid a one-sided rating, a broad range of experts from various departments, e.g. including manufacturing, sales and product management, should be involved.

\[
N_{i,j} = \begin{cases} 
\text{Market service}, i,j \geq \text{Market complexity}, i,j \text{ AND } \\
\text{Product competency}, i,j \geq \text{Product maturity}, i,j
\end{cases}
\]  \hspace{1cm} (2)

i : sales region
j : manufacturing site
N : product

After the strategy input in all four categories is determined, equation (2) defines the condition that needs to be fulfilled in order to permit a product allocation. An allocation is allowed if the market service of a site for a specific sales
After optimization, the resulting network can be analyzed, for example by investigating the resulting logistic links between the manufacturing sites and the sales region, as shown in Figure 6. In this case the resulting network has much less complex transport links due to a local manufacturing approach.

4 PRACTICAL APPLICATION

The presented approach was validated in collaboration with an industrial partner in the metal working industry. For this project, the firm’s data was used and a network model with more than 50 product groups, more than ten globally dispersed sites and a total of eight sales regions was established. The as-is network of the company considered was generally affected by many mergers and acquisition of former competitors and a historically grown network. The objective of the bilateral project was to develop the future global manufacturing network strategy and to identify savings potential in the configuration of the network. Saving potential was particularly assumed to be generated by consolidating product groups from different sites, but needed to be matched with the available competencies and market access of the sites within the network.

Figure 7 depicts the as-is network and the optimized network of one product group. The world map overview and the table with the solution space give a representative insight of the results of the network design. As seen by the logistics links between manufacturing sites (blue pins) and sales regions (green pins), the European sites play a pivotal role for the as-is network. Thereby many redundancies can be observed: For example, site 8 supplies the Asian-Pacific and the European sales region. Asia pacific is at the same time supplied by the local site number 3 and the European market is also supplied by site 11.

The strategic input derived by key decision-makers of the company, limits the solution space for the optimization considerably, as shown in the table in Figure 7. While all as-is manufacturing sites (highlighted in blue) remain part of the solution space, most sites that do not have any prior knowledge to manufacture the particular product group were excluded by the strategic input. The sole exception are site 4 within Eastern Europe and site 10 in Latin America, which were considered capable of manufacturing the product groups in question for particular markets. From a market point of view, the strategic input indicates a...
preference to local manufacturing sites, as can be observed by the Indian market which is only allowed to be supplied by site 1 which is located within India. On the other hand, site 8 is permitted to potentially supply all remaining sales regions, widening the solution space for the genetic algorithm.

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5 CONCLUSION

The approach presented in this paper, offers a pragmatic approach to consider qualitative, strategic input for a quantitative manufacturing network optimization. In this way, quantitative network optimization can be further enriched by considering strategic input by decision makers in order to generate more realistic network scenarios from optimization. Considering strategic input also improves the acceptance from decision makers by involving them more closely in the quantitative network design approach. In our approach, the strategic input considers market and product dimensions and matches the requirements to the abilities of the sites in the network. In this way, unrealistic and nonsensical allocations of products to sites are prohibited. As a second outcome, the solution space is considerably limited by the strategic input, allowing optimization approaches to find a suitable target configuration much quicker. By testing and validating the presented approach in an industrial case, the applicability of the approach was ensured.

6 ACKNOWLEDGMENTS

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7 REFERENCES