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Strategic global supply chain network design – how decision analysis combining MILP and AHP on a Pareto front can improve decision-making

Juri Reich\textsuperscript{a,b}, Aseem Kinra\textsuperscript{b,c}, Herbert Kotzab\textsuperscript{b,d} and Xavier Brusset\textsuperscript{e}

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\textbf{ABSTRACT}

Integrating a broad range of information types and finding trade-offs between conflicting goals is a challenge in global supply chain network design (GSCND). Effective decision support systems (DSS) should be user-friendly, provide transparency, and support human judgement. There is a wide range of optimisation models that aim to improve the outcome of network design decisions. However, their practical performance often remains unknown, as their implementation into the managerial decision process is largely neglected. Such theory-driven models usually focus on single aspects of the decision, without being able to accommodate the practical problem comprehensively. We employ the CIMO approach to resolve the issue and contribute by showing how an integration involving these methods can be useful for managers once the proper knowledge transfer has been effectuated. An innovative decision support framework, which combines mixed-integer linear programming, the Analytical Hierarchy Process, and the Pareto front is created and analysed during a case study in the med-tech industry. Results show that the framework accommodates managerial experience, integrates qualitative as well as quantitative criteria, and provides transparency over the entire range of efficient solutions. The framework and application results contribute towards the development of more flexible and easy-to-use decision support systems for GSCND.

\textbf{ARTICLE HISTORY}

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\textbf{KEYWORDS}

Supply chain design; global supply chain; multi-criteria decision making; decision support systems; analytical hierarchy process; design science research

1. Introduction and problem statement

Today’s economy is characterised by global supply chain networks that compete against each other (Christopher 2000). Exports accounted for 30% of global GDP in 2019 (World Bank 2020) and for almost 50% of GDP in advanced European economies (Lund et al. 2019). Global supply chain network design (GSCND) is derived from business strategy and environmental constraints (Melnyk, Narasimhan, and DeCampos 2014). It provides the framework for tactical and operational considerations (Meixell and Gargeya 2005; Meyr, Wagner, and Rohde 2015). It represents a complex managerial decision problem as decision-makers are required to deal with a high level of structural, as well as environmental complexity (Cohen and Lee 2020; MacCarthy and Athirawong 2003). Structural complexity is driven by decision parameters related to facilities and transportation nodes and does not directly depend on whether a network is global or local. Environmental complexity however is driven by macro-institutional and infrastructural diversity – factors such as political stability and legislation are much more relevant in global supply networks than in domestic ones (Ivanov et al. 2015; Kinra and Kotzab 2008a). GSCND decisions usually require estimations and assumptions and are characterised by a planning horizon of several years, as well as by high uncertainty, especially regarding external factors (Vidal and Goetschalckx 1997), such as political risk (Hansen, Mena, and Skipworth 2017) or public safety (Tukamuhabwa et al. 2015). A survey by McKinsey & Company found that supply chain managers expect environmental complexity to increase in the future. They consider themselves poorly prepared for this, mainly due to a lack of data, as well as a disconnect between information and decision-making (Gyorey, Jochim, and Norton 2010).

Operations Management (OM) and Decision Support Systems (DSS) literature provide optimisation models to support GSCND. However, implementation into the managerial decision process is neglected (Meixell and Gargeya 2005; Olhager, Pashaei, and Sternberg 2015). Thus, their performance in practice, and how they aid
to manage complexity in global supply chain decision-making, often remains unknown. The purpose of this study is to contribute towards developing a more effective and user-friendly decision analysis for GSCND. We employ the Context-Intervention-Mechanism-Outcome (CIMO) methodology (Denyer, Tranfield, and van Aken 2008) to understand the GSCND problem from a practitioner’s perspective, apply a solution to the relevant field problem, and therefore generate prescriptive, instrumental knowledge for better managerial decision-making.

Our research is motivated by the case of a multinational market leader in the med-tech industry. We helped redesign the company’s highly complex, poorly performing international distribution network. The decision involved selecting and locating distribution centres, as well as allocating inbound and outbound product flows. We devised the following research question together with the case company: *How can managers be supported to better understand and solve complex global supply chain network design problems characterised by a large range of qualitative and quantitative data and trade-offs between conflicting goals?*

We contribute to literature on hybrid AHP-MILP approaches (Irawan et al. 2018; Validi, Bhattacharya, and Byrne 2014) by showing that for optimisation methods from OM to be successfully implemented in practice, application-oriented specifications from the DSS domain (Power, Burstein, and Sharda 2011) should be considered in the solution design for the GSCND problem. Our findings show that managers benefited from utilising optimisation methods from OM in the way these were integrated by our novel decision support framework, which combines mixed-integer linear programming (MILP), the Analytical Hierarchy Process (AHP) and the Pareto front in an innovative way. Contrary to almost all existing literature, this study also describes how to deploy the managerial processes and routines as well as the corresponding know-how – from specification definition, over solution development, to implementation and testing.

The paper is structured as follows: the next section investigates literature on decision support for GSCND and identifies current issues and research needs. We lay out the methodology in section 3. Section 4 explains the development and application of the solution framework following the CIMO-logic. It begins by establishing an understanding of the problem and deriving specifications for an effective solution from both a theoretical and an empirical perspective. Based on these specifications a solution framework is designed, implemented, and tested. Section 5 discusses the theoretical and managerial implications of the research project, as well as its limitations, and points out avenues for future research. Section 6 concludes the paper.

## 2. State of the Field

### 2.1. Global supply chain network design and decision support requirements

Supply chain network design is a decision problem encompassing the location of facilities, selection of transportation arches and modes, as well as allocation of capacity, considering multiple products, components, suppliers, and markets (Chopra and Meindl 2016). GSCND extends the scope of this decision to locations across the world, requiring decision-makers to consider additional environmental complexity factors (Kinra and Kotzab 2008a, 2008b).

Several reviews about GSCND methods have been published. Vidal and Goetschalckx (1997) find that most tools are based on MILP. GSCND problems with their many quantitative and qualitative parameters are difficult to integrate into a standalone MILP. The authors suggest developing tools that consist of interrelated sub-models, each focusing on a specific set of factors – with MILP at their foundation. Schmidt and Wilhelm (2000) point out that integrating all relevant factors into one process improves the outcome. The authors suggest research to combine qualitative information with mathematical programming. Meixell and Gargeya (2005) find that while there exist sophisticated methods for most issues, there is no approach that covers the entire problem. More models are required that focus on multiple, conflicting goals and encompass a broader range of criteria. Mangiaracina, Song, and Perego (2015) confirm the dominance of quantitative cost minimisation. They criticise that few models allow weighting criteria and factors. Most neither evaluate qualitative information. The authors suggest developing tools that integrate quantitative with qualitative factors. According to Olhager, Pashaei, and Sternberg (2015) the challenge lies in tailoring models to specific problems. Mathematical models should be enhanced by qualitative parameters. More case studies are needed to merge structural issues with the ‘human factor’.

All reviews note that GSCND problems are characterised by heterogeneous data types describing environmental complexity. They stress the need to integrate qualitative information with quantitative optimisation models. In practice, however, managers tend to base their global design decisions on monetary considerations (Lampón, Lago-Peñas, and González-Benito 2015). In contrast, qualitative criteria are often ignored, even though they have been found to be usually more important to the outcome of GSCND decisions than quantitative ones (Kinkel and Maloca 2009), leading to costly mistakes, as described by the phenomenon of ‘reshoring’ (Srai and Ané 2016).
These issues imply that DSS for GSCND should evolve from single-target monetary optimisation towards calculating a range of efficient trade-offs with additional targets, such as quality (Flynn and Flynn 2005), resilience (Dolgui, Ivanov, and Sokolov 2018), reliability (Yildiz et al. 2016) and sustainability (Bhattacharya, Dey, and Ho 2015). To achieve this, quantitative optimisation such as MILP must be complemented with other methods that can handle diverse types of data. The AHP (Saaty 1980) is flexible to incorporate and process qualitative information, which makes it especially useful in assessing environmental complexity (Kinra and Kotzab 2008a). As AHP yields quantitative preference scores on a relative scale, it can be combined with quantitative optimisation models. MILP-AHP hybrids can potentially model complex distribution networks based on both quantitative and qualitative parameters. The next section gives an overview of such approaches in literature.

2.2. Existing hybrid MILP-AHP supply chain design methods

Ghodsypour and O’Brien (1998) and Korpela, Lehmusvaara, and Tuominen (2001) utilise MILP to design networks based on optimising AHP scores. AHP is used to assess supplier performance (Ghodsypour and O’Brien 1998) or preferences of clients and their utility to the focal company (Korpela, Lehmusvaara, and Tuominen 2001). A MILP target function designs the network under constraints to ensure the firm sources as much as possible from the best suppliers and sells to the most attractive customers. These two models are more flexible than standalone AHPs, as the MILP considers interdependencies and constraints. The downside is that all factors are represented by a dimensionless preference score in a zero to one interval.

Badri (1999) developed a multi-objective model that uses results of an AHP as partial input for a MILP. It aims to find the best trade-off between cost and environmental factors. Using AHP scores as input, the MILP minimises the sum of deviations of all objective values from pre-defined target values. Badri’s (1999) multi-objective model allows quantitative data to remain on its original scale while using the AHP scale for qualitative data. It calculates a trade-off between the two conflicting goals. However, the two different goals must be weighted against each other in the target function. The user needs to anticipate what weights will lead to the best trade-off before seeing a solution.

Ozgen and Gulsun (2014) solve a multi-objective location problem by minimising the sum of relative distances between the best and worst possible outcomes for each objective. The outcome is measured in the interval of zero to one. However, normalising targets to an interval from worst to best, implies that 0.1 from the optimum and 0.9 from the worst is equally desirable for both. Such an assumption is questionable. The worst outcome might be perceived only as marginally worse than the optimum, or it might be infinite times worse.

Validi, Bhattacharya, and Byrne (2014) combine MILP with AHP through a Pareto front to solve an operational distribution network design problem by selecting vehicles and routes. AHP is used to determine managerial preferences regarding vehicle types. A MILP then calculates alternative distribution network designs as trade-offs between emission and cost, displayed on a Pareto front. AHP is used to weigh the two conflicting goals, which themselves only consist of quantitative factors – cost and CO2 emission. The model is based on data from the Irish dairy industry, however, there is no implementation into the managerial decision process.

Irawan et al. (2018) propose a model to select ports for offshore windfarms and design the distribution system for components. Ports are pre-selected by AHP. Subsequently, component flows are determined by linear programming. The paper uses real-life data but does not describe how the model was adopted by managers.

A common missing feature in existing research is that the practical implementation of the GSCND models is not demonstrated. While existing contributions revolve around the decision outcome, behavioural aspects, such as the effect on the managerial decision-process, are not described. It is assumed that the decision-maker is rational and possessing certain knowledge and skills, which in turn should translate into smooth implementation. This is an issue across supply chain network design literature. While design principles are well-researched, the decision-making process within organisations has been neglected (Asmussen, Kristensen, and Wæhrens 2018).

The literature presented above indicates that a combination of AHP and MILP can be helpful for solving GSCND problems. However, there are limitations to the practical effectiveness of existing models. To answer our research question, we deployed a solution framework involving the methods presented above in the context of a practical example, following the CIMO paradigm described below. The solution framework takes the above-mentioned limitations into consideration when combining the AHP, MILP, and the Pareto front in an innovative way. Table 1 below summarises such limitations, as well as the features of this paper.
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Considers quantitative criteria</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Considers qualitative criteria</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Considers global criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deals with multiple objectives</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Integrates all objectives into a single decision</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Visualizes Trade-offs between objectives</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Implements solution into managerial decision process</td>
<td></td>
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<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

3. Methodology

3.1. CIMO-logic

We apply the CIMO-logic approach (Denyer, Tranfield, and van Aken 2008), which is also described in the related framework of design science research (DSR) [Van Aken 2007; Van Aken, Chandrasekaran, and Halman 2016; Holmström, Ketokivi, and Hameri 2009], to develop a new body of prescriptive knowledge for designing supply chain networks and demonstrate its usefulness in a practical case. In the next section, we start with the problem in-Context (the C in CIMO), which is the under-performance of the existing supply chain network and inadequacy of the managerial processes and routines to address it. We proceed to present the Intervention (I) by the scientific team counselling the managers, which is the design of the decision support framework combining three scientific methods. We subsequently develop a Mechanism (M) to support managers in their decision-making process concerning the transformation of the supply chain network, followed by describing the Outcome (O): the observable improvement of the decision process. Note that the emphasis here is on knowledge transfer and process transformation rather than the efficiencies achieved through the application of the scientific methods. Examples of similar papers in OM with practical applications and structure can be found in Brusset and Bertrand (2018) and Kinra et al. (2020).

3.2. Data

To understand the problem and solution requirements from the case company’s perspective, several interviews and workshops were conducted. Information describing product specifications, production quantities, sales, inventory capacities, handling processes, shipping fees, and transit times were collected and analysed to understand the network in detail. In close cooperation with analysts and experts from the case company, data from diverse sources was compiled and integrated, including internal IT systems for sales and accounting as well as from external providers. Transparency about product flows, costs, and capacity requirements was established, that was not available before. The company previously had no holistic visibility over the number, utilisation, and cost of distribution points. To understand the facilities,
Table 2. Overview of data.

<table>
<thead>
<tr>
<th>Step</th>
<th>Purpose</th>
<th>Data item</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding of problem and scope of researcher involvement</td>
<td>Understand company situation, historical context and overall strategy of the new management</td>
<td>Global supply chain strategy presentation</td>
<td>VP of operations</td>
</tr>
<tr>
<td></td>
<td>Understand the problem and how supply chain design decisions were made previously</td>
<td>Initial interview with problem owner</td>
<td>VP of operations</td>
</tr>
<tr>
<td></td>
<td>Understand how the supply chain is structured</td>
<td>Interview about general supply chain setup</td>
<td>VP of operations</td>
</tr>
<tr>
<td></td>
<td>Understand the expectations regarding researcher’s involvement, define cooperation approach</td>
<td>Scoping interview with problem owner</td>
<td>VP of operations</td>
</tr>
<tr>
<td>Construction of the solution framework</td>
<td>Understand which types of instruments there are and how many of each variation were sold</td>
<td>Sales data</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand on-time delivery figures for each transportation node</td>
<td>On time delivery data</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand product weights (gross and net) and measurements</td>
<td>Product specifications</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand demand volume for each instrument by destination country and city</td>
<td>Invoices</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand freight spend per facility</td>
<td>Freight spend</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand weight shipped (outbound and inbound) for each facility</td>
<td>Weight shipped</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand fixed and variable costs per distribution facility</td>
<td>Facility operating costs</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand price structure of 3 alternative logistics 3PLs for sea and air freight for all relevant routes</td>
<td>3PL price tables</td>
<td>Company IT systems</td>
</tr>
<tr>
<td></td>
<td>Understand criteria to assess facility preference, create AHP structure</td>
<td>Discussion/workshop on AHP criteria and structure</td>
<td>VP of operations</td>
</tr>
<tr>
<td></td>
<td>Gather expert opinions regarding the performance of each facility regarding each relevant AHP criterion (previously defined together with problem owner)</td>
<td>Expert interviews regarding facility performance</td>
<td>Internal consultants, directors of operations, site directors</td>
</tr>
<tr>
<td>Application of the solution framework</td>
<td>Rate the decision alternatives by pairwise comparison across all criteria</td>
<td>AHP pairwise assessment results and preference scores</td>
<td>VP of operations</td>
</tr>
<tr>
<td>Feedback and refinement</td>
<td>Obtain feedback from problem owner about our solution approach regarding both process and outcome</td>
<td>Final interview with problem owner</td>
<td>VP of operations</td>
</tr>
</tbody>
</table>

Table 3. Overview of interviews outside the case company.

<table>
<thead>
<tr>
<th>Company</th>
<th>Position</th>
<th>Industry</th>
<th>Size (employees)</th>
<th>Duration (min)</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company A</td>
<td>Senior VP operations</td>
<td>Healthcare</td>
<td>~ 15,000</td>
<td>90</td>
<td>Transcribed and coded</td>
</tr>
<tr>
<td>Company B</td>
<td>Director SCM</td>
<td>Telecom</td>
<td>~ 10,000</td>
<td>53</td>
<td>Recorded, transcribed and coded</td>
</tr>
<tr>
<td>Company C</td>
<td>Director SCM</td>
<td>Automotive</td>
<td>~ 20,000</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Company D</td>
<td>Head of Global SCM</td>
<td>Food</td>
<td>~ 1,000</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Company E</td>
<td>Head of Global Logistics</td>
<td>Chemicals</td>
<td>~ 50,000</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

External data on the environment was collected, and interviews with experts were conducted. Interviewees included senior managers, internal consultants, and facility directors. An overview of the data is presented in Table 2 below.

Following the CIMO-logic, the solution was validated and generalised as described by O’Keefe (2014). Design specifications were derived from the relevant literature. The utility and validity of the presented approach were evaluated by constructing and testing the solution together with the problem owner and analysing the intervention. To validate and generalise the specifications and the usefulness of the solution framework in other contexts, interviews with five top managers in the supply chain areas of multinational companies from diverse industries were conducted. An overview of the interviews is presented in Table 3 below.

4. Deploying CIMO-logic and ensuing results

4.1. Context

After acquiring several competitors, the case company became the global market leader in its sector. It manufactures medical devices and consumables, including perishable and hazardous products, in factories across the world. Products are transported to distribution facilities and forwarded to customers. Some facilities are operated internally, others are outsourced. The company was recently acquired by an industrial conglomerate.
Benchmarks showed that it had the worst-performing logistics network of all subsidiaries. Shipping and inventory were expensive, on-time delivery rates were low. Inventory was widespread, causing low on-site availability rates and high stock-keeping costs. Both fixed and variable costs were too high, also because small facilities sent out large numbers of small shipments. Unit availability and delivery times had to be improved, while at the same time costs had to be decreased. The problem was therefore characterised by multiple, potentially conflicting goals. Communication and flexibility were poor and know-how and technical capabilities were widely dispersed. There was friction with external providers. Management had little visibility over the network and severe difficulties in implementing processes and quality measures. Labour performance, infrastructure, and the macro-environment differed across facilities. Such factors could not be solely measured by quantitative data. The company was facing a GSCND problem characterised by high complexity, conflicting goals, and a wide range of quantitative and qualitative factors.

Based on semi-structured interviews with managers, as well as on internal analyses, reasons for the poor performance were uncovered. Low priority was given to supply chain management (SCM). The function only served as an enabler for the sales department. Decisions were made by local units focused on short-term local business opportunities, rather than on an efficient overall network. Implications for the system were not considered, cross-border synergy potential was neglected. The organisation lacked the means to deal with these challenges, resulting in a complex and poorly performing distribution network. Management had no clear structure to design the distribution network but used various tools, analyses, and committees, generating inconsistent and heterogeneous results. Data was of poor quality and widely dispersed. Information systems lacked analysis and optimisation capabilities. To improve the company’s decision process as well as the outcome, more sophisticated tools were needed that provide analytical capabilities, but at the same time remain transparent and usable.

4.2. Intervention

4.2.1. Design requirements from the case study
As part of the new leadership’s supply chain vision, our role was to build and implement a decision support procedure based on scientific methods, to re-design the European distribution network. The goal was to create a system in close alignment with the company that could be handed over and used after our involvement.

The main requirement from the company was for the framework being able to model their complex distribution network. It must accommodate all relevant quantitative information, such as demand, capacity, freight cost, processing cost, and delivery times. However, it was crucial to the case company that it also includes qualitative data about operational quality within the facilities as well as the surrounding environmental complexity (Kinra and Kotzab 2008b). To emphasise, one manager specifically explained their negative experience of a prior centralisation project, where decisions were based on quantitative information alone, while regional environmental differences and complexities were ignored. It was equally important to managers that the solution framework allows collaboration and discussion. It should help stakeholders understand their problems by providing visualisation. Because knowledge was widely dispersed, input from different experts had to be accommodated in a transparent manner. Lastly, it was important for managers to make the decision themselves, leveraging their experience and expertise. They preferred an approach that generates a range of clearly specified options, rather than a single solution.

4.2.2. Design specification and empirical justification
Our design specifications are made in accordance with considerations in OM and DSS. Both domains look at the same problem from different angles. OM has a modelling focus and provides insight on how to represent a real-life problem as closely as possible and provide an optimum solution. Tools should integrate qualitative and quantitative data to ensure that all relevant factors can be considered. They also should be multi-objective to provide trade-offs between conflicting goals. All factors and goals should be structured and integrated into a single process to consider interdependencies.

Researchers in DSS on the other hand put greater emphasis on the application. They provide insight on interfaces between tools and managers, as well as on how researchers should execute the application. Managers should be closely involved in the process. Results should be visualised to make them understandable. Researchers must ensure that there is room for discussion and human reasoning, that all relevant experts can contribute, and that the final decision is made by the managers themselves (Power, Burstein, and Sharda 2011).

To establish a broader empirical picture, we interviewed several supply chain executives. Their responses confirmed the three main challenges of GSCND, namely the high complexity of networks, heterogeneous data types, and conflicting goals. Subsequently, we inquired how their ideal tool for GSCND would look like.

A summary of design specifications from OM and DSS literature, as well as sample quotes from managers that validate these can be found in Table 4. These will serve as
the theoretical underpinning for the development of the solution framework that is presented in the next section.

4.3. Mechanism

4.3.1. Choice of methods

Our solution framework is comprised of three well-established methods combined and applied in an innovative way to suffice the design requirements stated above. The framework is based on a cost-minimising MILP, supplemented by an AHP. Results are visualised on a Pareto front as trade-offs between conflicting goals.

MILP serves as the base of the framework because it allows managing structural complexity by precisely modelling large distribution networks based on all relevant quantitative parameters.

AHP on the other hand was chosen for its suitability to manage environmental complexity (Kinra and Kotzab 2008a, 2008b). The AHP can accommodate qualitative as well as quantitative data, by translating verbal preference judgments into a numerical scale. Because of pairwise comparison as its underlying technique, AHP produces a quantitative preference score on a relative scale – contrary to simpler techniques, such as the Weighted Score method. This means that an AHP score of 0.4 is exactly twice as preferable as a score of 0.2. This makes AHP scores excellent input for mathematical programming methods, such as MILP.

While factors and criteria are infinite, AHP limits the number of decision alternatives to nine. Saaty (1980) follows the theory of Miller (1956), who defined a limit of seven pieces of information, ‘plus or minus two’, that humans can process simultaneously. This limit also applies to the range of comparison between the alternatives, rated on a nine-point scale which means that an item can be preferable by a factor of up to nine than another, but not greater. This is an artificial limitation based on the notion that the human brain cannot compare stimuli which differ too much (Saaty 2013). Promethee-I, another popular pairwise

<table>
<thead>
<tr>
<th>Domain</th>
<th>Derived Design Specifications</th>
<th>Supporting literature</th>
<th>Empirical validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Operations Management literature / model-focused</td>
<td>Integrate and process qualitative as well as quantitative input data</td>
<td>Vidal and Goetschalckx (1997), Schmidt and Wilhelm (2000), Meixell and Gargeya (2005), Mangiaracina, Song, and Perego (2015), Olhager, Pashaei, and Sternberg (2015)</td>
<td>'Choice of ports depends mostly on soft factors, not price ( . . . ) we deal with a great multitude of data types that are difficult to model’ – Head of Global SCM, Food</td>
</tr>
<tr>
<td>From Decision Support Systems literature / application-focused</td>
<td>Consider multiple objectives and calculate all trade-offs between the conflicting goals</td>
<td>Meixell and Gargeya (2005), Mangiaracina, Song, and Perego (2015)</td>
<td>'I always must find tradeoffs between conflicting factors' – Director of SCM, Automotive</td>
</tr>
<tr>
<td></td>
<td>Execute a single optimisation process so that all interdependencies are considered</td>
<td>Vidal and Goetschalckx (1997), Schmidt and Wilhelm (2000)</td>
<td>'We need a holistic view over the entire system and consider interdependencies.' – Head of Global Logistics, Chemicals &amp; FMCG</td>
</tr>
<tr>
<td></td>
<td>Closely involve managers in the tool construction and application</td>
<td>Courtney (2007), Land (2008)</td>
<td>'Such systems should be assisted by people who help implement it, guide through the process, determine which data to use and help interpret the results’ – Head of Global Logistics, Chemicals &amp; FMCG</td>
</tr>
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<td></td>
<td>Clearly visualise results to make them understandable to all stakeholders</td>
<td>Wagner (2007), Watson (2007)</td>
<td>'The big challenge is showing the results of complex problems in a simple manner for executive decision makers’ – Head of Global Logistics, Chemicals &amp; FMCG</td>
</tr>
<tr>
<td></td>
<td>Ensure that managers can see and discuss all efficient options and make the final decision themselves</td>
<td>Land (2008), McCosh (2007)</td>
<td>'I do not believe a system can make a strategic decision. People have still to oversee it. A system can help discuss and make an informed decision.' – Head of Global SCM, Food</td>
</tr>
</tbody>
</table>

1563
comparison-based method, avoids this limitation by using preference functions for all criteria. However, Promethee-I does not provide structure to the problem and is difficult to explain and replicate by non-specialists (Macharis et al. 2004). Contrary to Promethee-I and importantly for our case study, AHP is simple and easy to use for managers (Chan et al. 2008). AHP, therefore, satisfies the design specifications from both OM and DSS literature, as it provides flexibility as well as usability to the solution framework.

The AHP and MILP are integrated following the suggestion of Klose and Drexl (2005) by using cost minimisation as the primary goal and other objectives as soft constraints, which are relaxed to generate alternative solutions. Trade-offs between goals are shown on a Pareto front, where all points are non-dominated compromises between targets (Pareto 1906). This allows us to integrate two methods to execute a multi-objective optimisation for a complex problem, one of our model-focused design considerations. Simultaneously it satisfies our application-focused considerations by providing clear visualisation to stakeholders. The Pareto front serves as a basis for discussing the range of efficient network configurations and eventually selecting the preferred solution.

Figure 1 summarises our solution approach, including the way the methods were applied.

4.3.2. Model formulation

We begin with formulating the MILP. Terms 1–10 below describe a three-tier distribution network where multiple product types are transported via different routes and modes from factories to distribution centres (DCs), and from DCs to customers. The target function minimises the cost of the network.

\[
\text{Summand 1: Total variable shipping cost from factories to DCs} \quad \min \sum_{p,f,d,m} (S_{p,f,d,m} \ast WT_{p} \ast VCSF_{f,d} \ast ZP_{m})
\]

\[
\text{Summand 2: Total variable shipping cost from DCs to customers} \quad + \sum_{p,d,c,m} (S_{p,d,c,m} \ast WT_{p} \ast VCSF_{d,c} \ast ZP_{m})
\]

\[
\text{Summand 3: Sum of fixed cost for all DCs} \quad + \sum_{d} (FIX_{d} \ast Y_{d})
\]

\[
\text{Summand 4: Sum of variable product handling cost for all DCs} \quad + \sum_{p,f,d,m} (S_{p,f,d,m} \ast VCH_{p})
\]

(1)

The first summand describes the total variable cost for shipping products from factories to DCs. Quantity $S$ shipped of products $p$ from factories $f$ to DCs $d$ via mode $m$ is multiplied by the weights $WT$ of products $p$, multiplied by variable cost $VCSF$ of shipping one weight unit from factories $f$ to DCs $d$, multiplied by the price factor $ZP$ for shipping mode $m$. $ZP$ describes how much more expensive alternative shipping modes are to the
cheapest mode – in this case, air shipment versus ocean freight. Variable shipping cost includes rates of logistics providers, tariffs as well as possible additional costs. The term is summed up for all factories, DCs, products, and shipping modes. Summand two describes the total variable cost of shipping products from DCs to customers, similar to the previous term describing shipping from factories to DCs. Summand three describes the sum of fixed cost FIX for each DC d, including wages, maintenance, depreciation, and taxes, incurred by opening the facility. Summand four describes the handling cost of products in DCs. Quantity S of products p arriving in DCs d from factories f via modes m is multiplied by the variable handling cost VCH per unit of product p. This is summed up for all factories, DCs, and products.

There are three decision variables: S(p, f, d, m) determines quantity S of product p shipped from factory f to DC d via mode m. S(p, d, c, m) determines quantity S of product p shipped from DC d to customer c via mode m. Y(d) is a binary variable determining whether to use DC d.

\[ \begin{align*}
Y_d \cdot M - \sum_{p,f,m} S_{p,f,d,m} \geq 0 & \quad (2) \\
X_{p,f} = \sum_{d,m} S_{p,f,d,m} & \quad (3) \\
\sum_{p,f,m} S_{p,f,d,m} \cdot \text{WT}_p \leq K_d & \quad (4) \\
\sum_{p,f,m} S_{p,f,d,m} = \sum_{p,c,m} S_{p,d,c,m} & \quad (5) \\
\sum_{d,m} S_{p,d,c,m} = R_{c,p} & \quad (6) \\
T_{\text{MaxTarget}}_p \geq \frac{\sum_{d,m} (S_{p,f,d,m} \cdot T_{F_{f,d}} \cdot Z_{T_m})}{\sum_{f,d,m} S_{p,f,d,m}} + \frac{\sum_{d,c,m} (S_{p,d,c,m} \cdot T_{D_{d,c}} \cdot Z_{T_m})}{\sum_{d,c,m} S_{p,d,c,m}} & \quad (7) \\
\forall S_{p,f,d,m} \in \mathbb{N} & \quad (8) \\
\forall S_{p,d,c,m} \in \mathbb{N} & \quad (9) \\
\forall Y_d \in \{0, 1\} & \quad (10)
\end{align*} \]

Constraint (2) regulates that DC d can only be used when its binary constraint Y is set to one. ‘M’ represents a very large number that ensures the left part of the equation is below zero if Y is set to one. Constraint (3) ensures all production X of product p in factory f is shipped out to any of the DCs d using any of the modes m. Constraint (4) ensures the total weight of products p coming from any factory f does not exceed maximum capacity K of DC d. Constraint (5) requires that all products p shipped from factories f via mode m to a DC d must be shipped out of DC d to customer regions c. Constraint (6) requires quantity S of product p to customer region c coming from DCs d to equal demand R for product p in customer region c. Optional constraint (7) requires the sum of weighted average transit times for a product p between factory f and DC d and between DC d and customer c not to be higher than the desired transit time. Constraints (8) and (9) require variables S to be positive integers. Constraint (10) requires variable Y to be binary.

Quantitative factors regarding cost and delivery time are covered by the MILP presented above. However, other crucial aspects are qualitative and must be assessed differently. We use the AHP where location decision criteria are hierarchically structured. All alternatives, in this case, the potential distribution centres, are compared against each other in terms of performance regarding each criterion.

AHP criteria can be defined in cooperation with experts from the case company, following the considerations laid down by Saaty (1980). The pairwise comparison in the AHP yields preference factors for each decision alternative. The AHP is integrated by adding a soft constraint (11) to the MILP which requires the network to yield a minimum overall AHP score weighted by throughput. Quantities shipped to open DCs are multiplied by the AHP score of respective DCs and divided by the sum of all items. The more product flows through the preferred facilities, the higher the overall score.

\[ \text{MinAvgAHP} \leq \frac{\sum_{p,f,d,m} (S_{p,f,d,m} \cdot \text{AHP}_d)}{\sum_{p,f,d,m} S_{p,f,d,m}} \quad (11) \]

To create the Pareto front, the user starts with the initial result without the AHP constraint. The AHP constraint is then introduced and its lower bound gradually increased. All combinations together form the Pareto front. An alternative approach to potentially decrease computation effort would be to integrate the AHP as a second objective function into the optimisation. The multi-objective linear programme would then calculate the entire Pareto front at once.

### 4.3.3. Application

After collecting the data described earlier, we proceeded to build the cost-minimising MILP using MS Excel. As the model was too complex for the built-in solver, we used two more powerful solvers: Gurobi and COIN-CBC.
The second step was to lay out and execute the AHP. Beforehand, management pre-selected seven DCs as possible candidates for the future setup. Pre-selection was done purely on size, as the company’s overall strategy was to concentrate distribution in fewer, larger facilities. Because the number of decision alternatives was not larger than nine, AHP could be used for both structuring the decision problem, as well as for assessing the alternatives. Had there been more than nine candidates, it would have been still possible for AHP to structure the decision, but another method not based on pairwise comparison, such as Weighted Scoring, would subsequently have been used to rate the alternatives.

A workshop with management was conducted to define and structure AHP criteria describing non-financial performance and environmental complexity. Three first-level categories were defined: ‘Past Performance’, ‘Current Capabilities’ and ‘Environment’. Each had between three and five subcategories. Pairwise comparisons between all categories and subcategories were conducted to derive importance weights. Interestingly, managers considered the ‘environment’ criterion significantly more important than the other two main criteria, ‘capabilities’ and ‘past performance’. This confirms the importance of environmental complexity for the company’s decision problem and the use of AHP as part of the solution, as it can provide structure to an ill-structured problem and process qualitative data, both which are important for design problems characterised by high environmental complexity (Kinra and Kotzab 2008b).

After the AHP structure was ready, the decision alternatives had to be rated according to the defined criteria. The necessary knowledge was dispersed to such a high degree that a group AHP (Dyer and Forman 1992) was infeasible. Instead, data regarding the facilities collected earlier from IT systems and expert interviews was coded and compiled in a two-dimensional matrix, which summarised all information describing each facility along each sub-criterion of the AHP. The information matrix was presented to managers for review and discussion. Based on this, pairwise comparisons between all decision alternatives within all sub-criteria were conducted, producing scores that were aggregated into an overall preference score for each potential location. For executing the AHP we used the software ’PriEsT’ (Siraj, Mikhailov, and Keane 2015). The AHP is visualised in Figure 2.

Subsequently, the AHP results were integrated into constraint (11) of the MILP, as described in the previous section. Now all variables could be solved, including seven variables \( Y (d) \) for selecting locations and 1,365 variables \( S (p,f,d,m) \) and \( S (p,d,c,m) \) for determining flows of all product types and shipping modes from factories to DCs and from DCs to customer regions. By gradually relaxing constraint (11), all efficient network configurations were calculated, creating the Pareto front as depicted in Figure 3.

### 4.3.4. Results from the solution approach application

The cheapest network under the given constraints costs 3.1 m EUR per year and yields a weighted AHP score of .148. It spreads the capacity over three distribution centres. The following two configurations on the Pareto front with AHP scores of .149 and .150 include a fourth facility. The network with the maximum weighted facility preference score of .168 costs 5.7 m EUR per year. In this configuration, all capacity is routed through the highest-scoring facility. We calculated a total of 21 network configurations, each representing a 0.01 interval in the efficient range of weighted AHP scores. Using a normal desktop computer, each solution took an average of 34 s to calculate with the COIN-CBC solver and 115 s with the Gurobi solver, using a branch-and-bound tolerance of 0.5%. Both solvers delivered identical results.

### 4.4. Outcome

The Pareto front provided transparency over the interplay between cost and performance. Managers could visualise trade-offs, change assumptions and calculations, discuss alternatives, and eventually select the design best suited to their strategy. The curve becomes steeper at the cost versus score combination of 3.5 m and 156, implying rising marginal cost for additional performance. The solution preferred by management was at this point. It represented a configuration where capacity was spread almost evenly between two large facilities – both located close to production sites in Western Europe. Once they were presented with the Pareto front and data depicting product flow for each of the 21 efficient configurations, managers required no further decision support to select a final solution. If requested, we could have conducted one or multiple AHPs to help select the preferred configuration on the Pareto front.

The problem owners received the framework positively as a method to structure information and create a set of options and expected outcomes. Table 5 below summarises their feedback, as well as how the solution fulfils the design requirements and specifications. Managerial experience was accommodated by constructing and applying the solution in close cooperation. From the beginning, it was crucial to generate a common understanding of how processual and technical deficiencies led to poor decision-making in GSCND. The application demonstrated the benefits of good data and analytical capabilities and helped define action items to become a ‘data-strong’ organisation. The initial step taken by the
company to ensure long-term implementation was to hire a data analytics specialist whom the researchers trained to take over the tool.

Following the CIMO-logic, the training and handover of the solution was the final phase of the researchers’ involvement with the company. It was conducted in several sessions. The analyst was introduced to the logic of the MILP and AHP and extensively trained in the use of the Excel-based calculation sheets and solvers, as well as the AHP tool. The analyst was also instructed to calculate the Pareto front and to interpret its results. Furthermore, the analyst was trained to conduct sensitivity analyses and consistency checks. After the solution was tested and implemented in the field, the final phase following the CIMO-logic is to generalise and discuss the intervention, which is done in the following section.
5. Discussion

Researchers note the lacking managerial acceptance of scientific decision support methods (Power, Burstein, and Sharda 2011). Our intervention-oriented research showed that managers can benefit from utilising design methods from theory as these can provide structure and objectivity. The data collected during the intervention (Tables 2 and 5) as well as from interviews with managers outside the case company (Table 3), confirms that application-oriented specifications are as important to the successful implementation of GSCND decision analysis as model-focused specifications (Table 5). First, decision support experts must work closely with managers to explain the underlying techniques and cooperate with them in tailoring the tools to the specific problems of their companies (Courtney 2007; Land 2008). Second, the results should be visualised to facilitate discussions (Wagner 2007; Watson 2007). Lastly, the final solution must be selected by experienced managers to ensure acceptance by stakeholders and commitment to its implementation (Land 2008; McCosh 2007). This study did so by employing the CIMO-logic (Denyer, Tranfield, and van Aken 2008) to develop and test within a practical context how prescriptive knowledge derived from theory can be successfully transferred to managers as practical knowledge.

Several managerial implications can be derived from our in-depth analysis of the case company. Firms facing a high degree of both environmental and structural complexity need a holistic view of their networks that includes all interdependencies. A strong SCM function should manage the network, continuously monitor its performance, and lead the decision-making and design process. Data provides transparency, but it is only useful in conjunction with information and decision support systems that combine analytical capability and usability (Gyorey, Jochim, and Norton 2010). These aspects were lacking and have been improved by our intervention.

The paper also adds to theory by contributing to the research issues and design requirements from OM, described in Section 2.1 and Table 4. Our solution considers conflicting objectives (Meixell and Gargeya 2005), processes unstructured and qualitative data (Mangiaracina, Song, and Perego 2015), and integrates all interdependencies into a single decision process (Schmidt and Wilhelm 2000) while being relatively simple to understand and apply. While most SCM research focuses on individual operational problems, the framework presented in this paper supports strategic decisions at the group level (Schorsch, Wallenburg, and Wieland 2017), by providing visibility for senior management to support long-term navigation of structural and environmental complexity in GSCND.

Table 1 visualises how the solution is different from existing hybrid approaches that combine AHP with MILP. While there exist AHP-MILP hybrids that assess

<table>
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<tr>
<th>Requirements</th>
<th>Solution</th>
<th>Sample statements by problem owner</th>
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<tbody>
<tr>
<td>Integrate and process qualitative as well as quantitative input data</td>
<td>The AHP accommodates any qualitative factors while the MILP includes quantitative factors. In the final solution, quantitative factors are preserved in their original units.</td>
<td>Before, we would not really consider any qualitative information in the decision process. Now we can do that. (...) Such data quality and depth has not been seen before in this company.</td>
</tr>
<tr>
<td>Consider multiple objectives and calculate all trade-offs between the conflicting goals</td>
<td>Our model finds the range of efficient trade-offs between minimum cost calculated by the MILP and maximum network-wide site performance, included as AHP scores weighted by product throughput.</td>
<td>The framework gives us a clear and easy to understand picture of all the trade-offs we must make in designing our global distribution. Between cost, process quality and duration. I knew they existed, but now I can clearly put them in perspective.</td>
</tr>
<tr>
<td>Execute a single optimisation process so that all interdependencies are considered</td>
<td>Our model considers all relevant factors at once and finds all efficient trade-offs between conflicting goals.</td>
<td>Our visibility was limited to single locations, now we see the big picture. (...) We can now see how the network changes if certain aspects are different. (...) We can play around with data, conduct scenario analysis, test business cases.</td>
</tr>
<tr>
<td>Closely involve managers in the tool construction and application</td>
<td>Both AHP and MILP were constructed together with managers, including selection, collection, and weighting of all information.</td>
<td>We learned a lot about the complexity of our supply chain by modelling it. (...) The tool challenges us to replace assumptions, anecdotal evidence, and opinions with hard facts. (...) It helps us build analytical capabilities by showing what data is useful for what kind of analysis.</td>
</tr>
<tr>
<td>Clearly visualise results to make them understandable to all stakeholders</td>
<td>The Pareto front shows all efficient network configurations, as well as the interplay between conflicting goals.</td>
<td>When somebody approaches me with an idea, I can enter the data into the model and see the impacts.</td>
</tr>
<tr>
<td>Facilitate discussions and ensure that managers realise that they themselves make the decision</td>
<td>All input information, the AHP results and the Pareto frontier were presented to managers, so they could discuss and select a configuration based on their business strategy.</td>
<td>Of course, it will not dictate our decisions, but the framework will be great in committees and project groups as it gives concrete talking points and objective numbers (...) It helps us elaborate a good mutual decision.</td>
</tr>
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</table>
global environmental complexity (Badri 1999) and visualise trade-offs (Validi, Bhattacharya, and Byrne 2014), none of the papers combine both capabilities. Furthermore, contrary to existing AHP-MILP hybrid approaches (Badri 1999; Ghodsypour and O’Brien 1998; Irawan et al. 2018; Korpela, Lehmusvaara, and Tuominen 2001; Ozgen and Gulsun 2014; Validi, Bhattacharya, and Byrne 2014), we describe a real-life application to demonstrate how a solution framework for GSCND combining three optimisation methods can be successfully deployed, and its approach and results become accepted and utilised by managers.

However, there have also been some limitations. The methods used rely heavily on data. Missing information must be replaced by assumptions and estimations, which can be imprecise. The MILP is linear and static, representing ‘a sensible trade-off between realism, scope, complexity, and solvability’ (Melo, Nickel, and Saldanha-da-Gama 2009). The AHP limits the decision alternatives to 9 items to ensure consistency (Saaty 1980). As a strategic tool, it is unsuitable for operational decision-making with a short time horizon, because it simplifies or excludes several operational parameters. The model’s effectiveness cannot be proven by large datasets and multiple applications, as the employed methodology focussed on a specific field problem and the subsequent generalisation of findings. Nevertheless, the main contribution of the study is not the model itself, but to describe how a solution can be effectively constructed and implemented to support the managerial decision process for GSCND.

More research is needed to find out what application and problem areas the solution framework is best suited to. For example, if it could help manage long-term uncertainty and volatility to mitigate the ripple effect (Ivanov, Dolgui, and Sokolov 2019). Furthermore, a longitudinal study could describe the model’s usage after the researcher’s involvement ended, as well as its impact on supply chain performance. The framework can be developed further by integrating it with tactical and operational methods. Such integration can contribute to developing an integrated operations design framework. Research indicates that a fully integrated decision process can lead to better results than hierarchical planning, where different levels are addressed sequentially (Asmussen et al. 2018).

6. Conclusion
The purpose of the study was to develop more effective and user-friendly tools to manage the decision difficulties of complex GSCND problems. For this we developed and implemented a decision support framework, which combines MILP, AHP, and the Pareto front in an innovative way, using CIMO-logic. The designed approach could calculate the entire range of efficient network configurations and provide transparency over the interplay between cost and performance. It accommodated existing managerial experience and stimulated knowledge-transfer by providing visualisation. Managers could see trade-offs, discuss solutions, and select the network design best suited to their strategy.

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