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Volkswagen Group Logistics Applies Operations Research to Optimize Supplier Development

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Abstract. Volkswagen Group Logistics (VWGL) is responsible for the logistics and supply processes of the automotive brands of the Volkswagen Group. In this context, supplier development is vital for efficient and reliable material flows between the process partners. In recent years, VWGL implemented a collaborative approach for supplier development in logistics wherein it is crucial to identify disrupting suppliers and apply improvement measures to increase their logistics performance. Against this background, VWGL initiated a project to examine how supplier development measures can be implemented efficiently to improve the overall logistics performance of VWGL's supply base. This paper presents the developed operations research approach, which integrates Monte Carlo simulation and a knapsack model on the specific problem of supplier development. The approach consists of three stages: (1) data preparation, (2) measure evaluation, and (3) measure allocation. The approach is validated based on 18 existing less-than-truckload networks of VWGL. We find that, on average, considerable cost savings of 31% can be achieved throughout the networks compared with VWGL's previous procedure. A new workflow facilitates our approach to lift its potential in practical application sustainably.

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Keywords: supplier development • inbound logistics • automotive • Monte Carlo simulation

Introduction

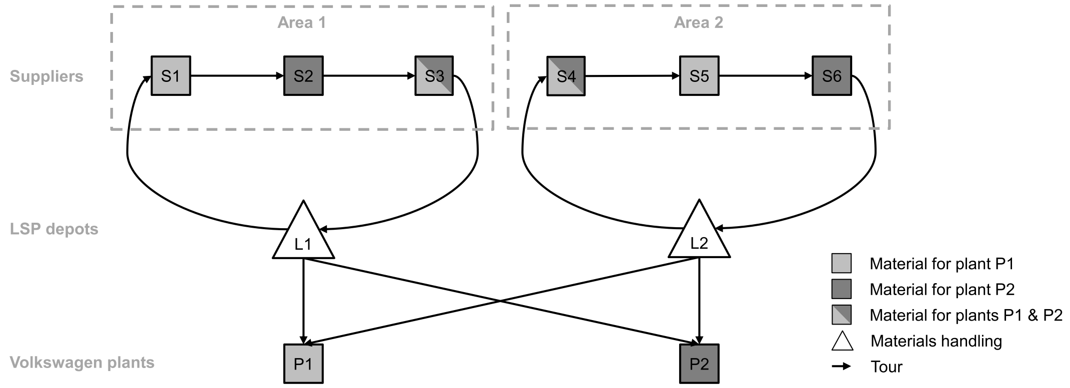
Volkswagen Group Logistics (VWGL) is responsible for the various logistics and supply processes of Volkswagen's 12 automotive brands. The inbound logistics process, managed by the material logistics department, involves three stakeholder groups: suppliers, logistics service providers (LSPs), and Volkswagen plants. The suppliers receive orders (call-offs) from the plants and prepare the demanded material for pickup by the LSPs, who ship it to the plants. Volkswagen holds contracts with the suppliers and the LSPs, but there are no direct contractual agreements between the suppliers and the LSPs. This ambiguity often leads to tensions between the process partners, especially when responsibilities for poor logistics performance must be identified.

VWGL applies supplier development to resolve those process-related concerns and thus establish an efficient and reliable material flow to their plants. Supplier development aims to improve the collaboration between the process partners by supporting the suppliers in adhering better to contractually agreed processes. The tasks of supplier development comprise the detection of disrupting suppliers, the evaluation of quality improvement measures at the suppliers, and the selection and rollout of the evaluated measures. Overall, the goal of supplier development is to improve the logistics performance of the supply network by reducing additional efforts for exception handling. Because of the extensive network size and limited monetary and personnel resources, this is a difficult task. Therefore, VWGL initiated a project with their academic partners to develop an approach for efficient supplier development. The network's high complexity and extensive data requirements indicated the need for developing a systematic approach based on operations research methods. The proposed approach enables the project partners to better understand the network structures, identify and evaluate improvement measures, and increase the acceptance of supplier management across all process partners.

Volkswagen's Inbound Transportation Network

VWGL act as a fourth-party logistics provider for their less-than-truckload (LTL) networks across Europe. They

Figure 1. LTL Process of VWGL



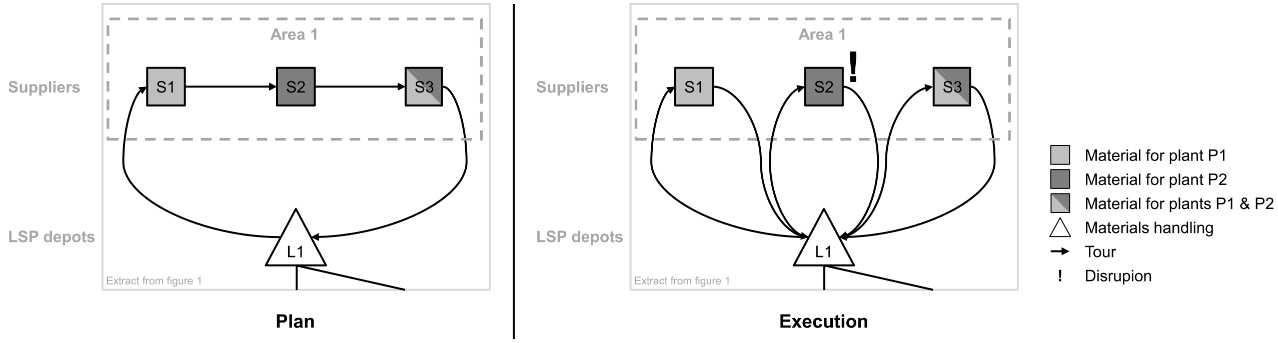
Notes. In the LTL process of VWGL, one LSP is responsible for the pickup of material from all suppliers of one geographical region. After consolidating and sorting the material at the depot, the LSP delivers the goods to the plants.

coordinate the LSPs transporting the material from the suppliers to the plants. The LTL process comprises four stages: call-off, transport notification, vehicle routing, and actual transport. The call-offs include the type and number of parts and the requested delivery date. The suppliers are responsible for producing the required material and initiating the pickup by sending a transport notification to the LSP. Each supplier is assigned to one LSP based on its location (area freight forwarding). The notifications are submitted within one workday and contain pickup times and shipping volumes information. The LSP uses the notifications to plan the tours for the upcoming day. After picking up the material from multiple suppliers, the LSP consolidates and sorts it at a depot and ships it to the Volkswagen plants.

The LTL process is subject to disruptions leading to delays. Apart from external disruptions such as bad weather conditions or dwell times at borders, performance is mainly impacted by the pickup process at the suppliers. Consider the illustrative example depicted in Figure 1. Given a disturbance of supplier S2 in Area 1, the LSP must interrupt the tour at this supplier, and the material may arrive late at the depot. Typical delays range from several minutes to several hours. Short delays are not critical because the LSP maintains buffer times. Longer, critical delays cause the LSP to return directly to the depot to deliver the already loaded material in time. In this case, additional tours are needed to pick up the material from the remaining suppliers (Figure 2), leading to extra costs at the LSP, which the disrupting supplier must cover. However, these costs are eventually passed to Volkswagen via increased material prices. Therefore, Volkswagen is ultimately affected by the inefficient cooperation of the process partners in that area.

Consequently, VWGL is highly interested in reducing delays induced by suppliers within their LTL networks. To achieve this, a dedicated team is responsible for identifying and improving poorly performing suppliers by applying targeted measures. In the following, we describe the related problem setting and VWGL's previous approach to "logistics process partner management"

Figure 2. Consequences of Disruptions at the Suppliers



Notes. If a disruption occurs at supplier S2, the planned tour (left) will be canceled to provide the material in time. The LSP directly returns to the depot without picking up the material from S2. The material from S2 and S3 is picked up on extra tours with additional trucks (right). VWGL experiences the inefficient cooperation of the parties by an increase in costs.

(LPM), which we use as a benchmark for evaluating the new approach presented in this article.

Problem Setting at VWGL

The limited personnel and monetary resources of VWGL restrict the number of improvement measures that can be executed in each period. Therefore, the measures must be allocated efficiently—that is, the expected cost reduction in the network must outweigh the costs of measure application. To this end, VWGL needs to identify the suppliers responsible for disruptions in the LTL process. The associated planning tasks are (1) detection of disrupting suppliers, (2) evaluation of improvement measures, and (3) measure selection.

Task 1: Detection of Disrupting Suppliers

The detection of disrupting suppliers requires the definition of suitable criteria. Typical performance indicators in the context of inbound logistics, such as the frequency of delayed shipments or the amount of delayed material at a supplier, are problematic because they hardly consider the effect of disruptions on the downstream suppliers of a tour. However, the probability of disruption and the affected transport volume of each supplier may serve as criteria for the initial classification of the suppliers. One particular challenge is that VWGL cannot detect the disrupting supplier directly because they do not have insights into the tours of the LSP. Therefore, they ask the LSP for a list of the most disruptive suppliers and their delayed volume. This information is validated in cooperation with the suppliers.

Task 2: Evaluation of Improvement Measures

The second task concerns the evaluation of improvement measures by examining their effects on supplier and network performance. Before the rollout of our project, the evaluation of improvement measures was not standardized and was highly dependent on the individual assessment of the LPM employees based on their previous experience. Improvement measures aim at developing a course of action with the supplier to improve logistics performance. Two typical measures are on-site visits (M1) and online training (M2). Both seek to develop an individual plan with the supplier to eliminate the causes of disruptions. The effectiveness in reducing the supplier's disruption probability and the required effort by VWGL is higher for on-site visits than for online training.

Task 3: Measure Allocation

The third task concerns the selection and allocation of measures to suppliers to maximize the overall network performance. The entire VWGL network is divided into separate LTL networks differing in size and complexity. One employee is responsible for measure selection and execution in one or two of these subnetworks. The typical capacity of each employee is the execution of 10 on-site visits and 20 online trainings per year. The current LPM approach allocates the more effective on-site visits to the most disruptive suppliers: that is, measure M1 is applied to the top 10 suppliers with the highest delayed volume, and measure M2 is applied to the subsequent 20 suppliers. With this allocation strategy, the capacity of the LPM employees cannot be exceeded.

In summary, the LPM process can be characterized as a hands-on method to deal with the lack of data concerning the interdependencies between measure selection and network performance. It provides reasonable results but cannot guarantee an optimal allocation of measures to suppliers because network effects arising in the tours of the LSP that are due to interdependencies between adjacent suppliers are neglected. Especially if the suppliers are situated close to each other, there is a high likelihood that the LSP will collect their materials on the same tour, and delays may propagate from the first to the final pickup. That is why the individual assessment of one supplier's delayed volume is insufficient to identify the root cause of a delay. Moreover, the tours change daily and are challenging to predict because they depend on fluctuating demands of VWGL. Hence, the problem setting comprises three main challenges:

- VWGL cannot objectively detect disrupting suppliers without relying on LSP's data.
- The manual way of measure evaluation hinders the consideration of network effects.
- The current allocation strategy focuses on budget compliance instead of maximizing logistics performance.

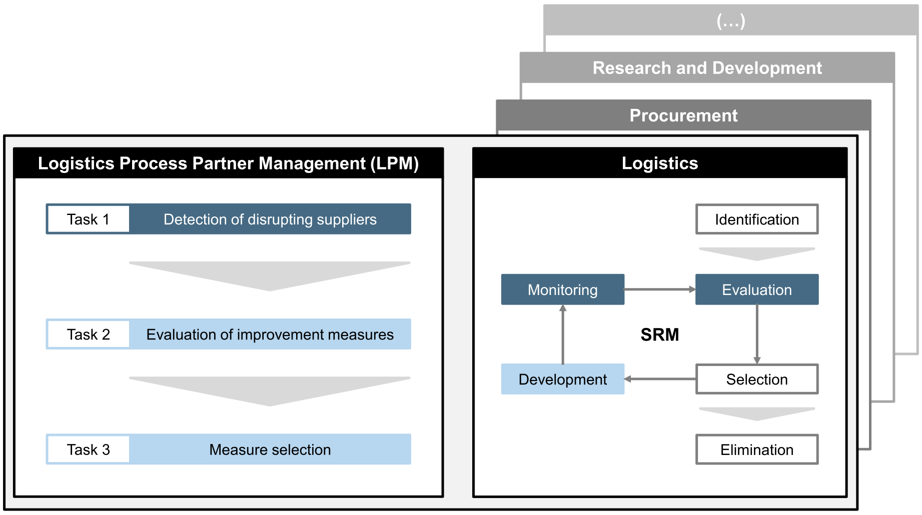
Therefore, this paper presents the development of a more advanced approach for VWGL based on quantitative decision support. The objective of this approach is the automated identification of a set of measures that maximize each LTL network's performance under a limited budget.

Related Work

The LPM approach of VWGL can be described as a highly specialized form of supplier relationship management (SRM) (Wieczorrek et al. 2017). The overall goal of SRM is to design a relationship with the supplier that reduces operational process costs and increases process quality (O'Brien 2022). Generally speaking, SRM covers all activities between buyer and supplier from a strategic standpoint: supplier identification, evaluation, selection, development, monitoring, and elimination (Glock et al. 2017). In the VWGL context, LPM mainly focuses on supplier evaluation and supplier development (Figure 3).

Supplier evaluation comprises the systematic data analysis to either select new suppliers or control existing suppliers according to a specific set of evaluation

Figure 3. (Color online) Joint Characteristics of LPM and SRM



Notes. There are joint characteristics of LPM and SRM: The detection of disrupting suppliers in LPM corresponds to the monitoring and evaluation phase in SRM. Evaluation of improvement measures and measure selection in LPM correspond to the development phase in SRM (SRM cycle from Glock et al. 2017).

criteria (Lasch and Janker 2005). Various approaches have been proposed in the related literature. Moreover, most decision-making techniques can be adopted for supplier evaluation problems. Chai et al. (2013) did a systematic literature review and categorized the pertinent approaches into multiattribute decision making, mathematical programming, and artificial intelligence. Their review also comprises fuzzy and hybrid approaches for supplier evaluation. Ho et al. (2010) distinguish between individual and integrated approaches and cover data envelopment analysis, mathematical programming, analytic hierarchy process (AHP), case-based reasoning, analytic network process, fuzzy set theory, and genetic algorithms. However, because evaluations are usually based on the individual characteristics of a supplier, they neglect network effects.

Supplier development is described as “any effort of a buying firm with its supplier to increase the performance and/or capabilities of the supplier and meet the buying firm’s supply needs” (Krause and Ellram 1997). Similar to the aforementioned supplier evaluation approaches, there are many different approaches to support decision making in the context of supplier development (Yawar and Seuring 2020). Because some authors integrate supplier evaluation as part of their supplier development model, there is a smooth transition between these two fields (Wieczorrek et al. 2019). Glock et al. (2017) distinguish between direct and indirect supplier development, depending on the involvement of the buying firm. For direct supplier development (which applies to the VWGL case), the approaches can be categorized into finding optimal investment volumes, gaining competitive advantages, deciding whether to keep or to switch a supplier, and evaluating different measures. For the latter category, mathematical models play an important role. On the contrary, indirect supplier development focuses on passive measures such as KPI targets and incentives. Krause et al. (1998) distinguish between reactive and strategic supplier development. Although reactive approaches primarily address specific operational problems, strategic approaches aim to find an optimal allocation of resources to improve the entire supply base.

Zhou et al. (2022) developed a stochastic programming model to maximize the manufacturer’s profit by selecting appropriate supplier development programs. Sherwin et al. (2016) adapt fault tree optimization to assign optimal supplier development programs. Both approaches have in common that they focus on orders of a manufacturer in a low-volume high-value industry, in which only small numbers of capable suppliers are considered. Focusing on the automotive industry, Yu et al. (2022) propose a supplier training model that supports the identification of suppliers’ training needs to reduce problems and obstructions in the supply chain from a car manufacturer’s perspective. Therefore, they focus on the design of supplier-specific training curriculums using a standardized questionnaire.

The approaches support decisions from a strategic perspective. They take general investment decisions and sustainability issues into account. Some focus on smaller networks, which are not comparable to the dimensions of the automotive industry. Also, considerations for LTL networks and the operational interaction between suppliers, LSPs, and manufacturers to reduce delay costs are missing. To the authors’ knowledge, there is no appropriate quantitative model covering VWGL’s problem setting.

The Approach

The development of the new approach focuses on information and data already available at VWGL, aiming to address the challenges of the current LPM process. Under consideration of network effects, the allocation of measures is objectified and partially automated to improve the daily work routine of the VWGL employees. The approach consists of three stages (Figure 4). It comprises data preparation (Stage 1), measure evaluation (Stage 2), and measure allocation (Stage 3). These are explained in the following sections.

Stage 1: Data Preparation

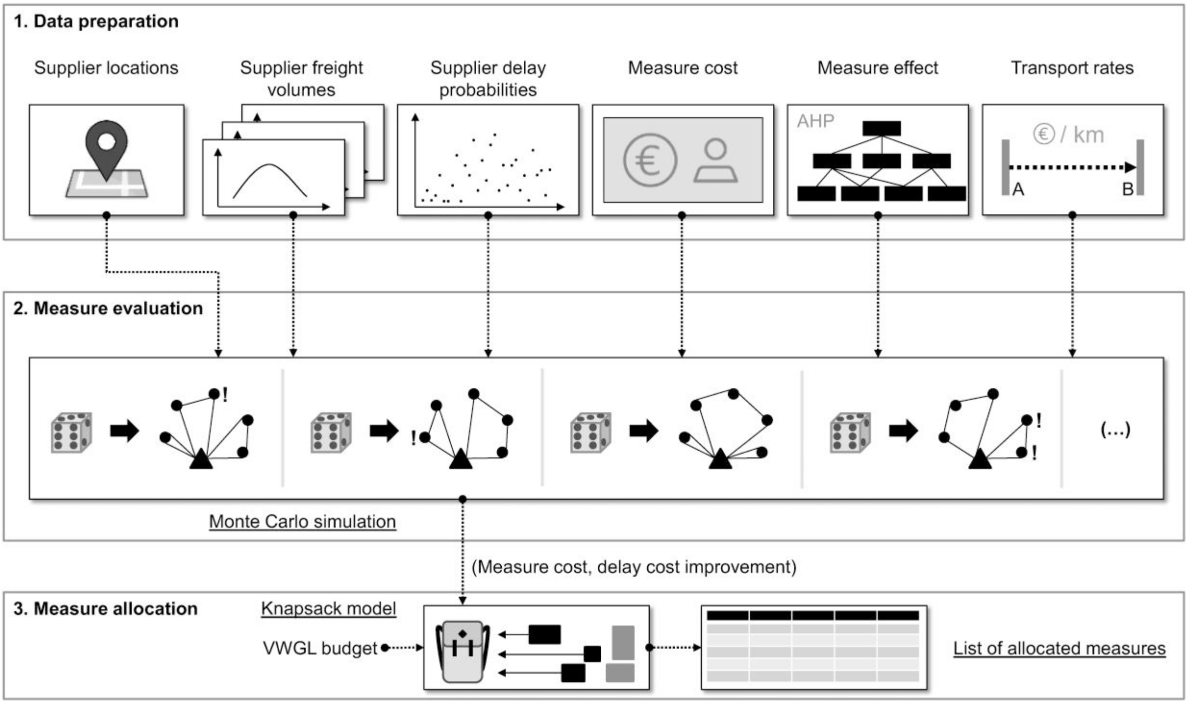
In the first stage, all necessary data related to the suppliers, their delivery performance, and the improvement measures are gathered and prepared for further computing. The model requires the locations (latitude and longitude) of all suppliers and the LSP depot in each LTL network. These data are queried from VWGL's internal supplier database and used to estimate transport distances. The model also requires the average freight volumes per weekday of each supplier. These data are obtained from VWGL's material flow management system for LTL transports and used with the transport distances to anticipate the LSP's vehicle routing. Moreover, the delay probabilities of all suppliers are derived with their cooperation based on historical data. They are needed to anticipate the performance of the individual LTL networks in Stage 2.

Furthermore, the costs and effects of the improvement measures are approximated. The main cost drivers are labor and travel. The measure effects indicate to what extent the delay probability of a supplier is reduced after allocating a specific measure. Because of missing operational data, we developed an AHP framework to quantify the measure effects based on an expert survey. The freight rates for extra tours constitute a final model input.

Stage 2: Measure Evaluation

In the second stage, a Monte Carlo simulation is conducted to examine the potential effect of a measure at a supplier on the network performance. It comprises six steps: (1) assign a measure to a supplier, (2) update the supplier's delay probability, (3) draw random transport volumes from a normal distribution, (4) solve the vehicle routing problem to anticipate the tours of the LSP, and (5) draw random delay occurrences and delay lengths. The delay occurrence is modeled using a Bernoulli distribution because there are only two possible results (delay or no delay). The delay length is modeled using a gamma distribution approximated from empirical data. Finally, (6) the network performance indicator is computed. It indicates the total delay costs induced

Figure 4. Three-Staged Approach for the Allocation of Measures to Suppliers



Notes. The three-staged approach for the allocation of measures to the suppliers of the LTL network: data preparation (Stage 1), measure evaluation (Stage 2), and measure allocation (Stage 3). The output is a list of measures to be allocated by the supplier development team.

by additional tours resulting from supplier disruptions. The execution of additional tours ensures that all materials arrive at the production site on time. Hence, the consideration of additional costs for production disruptions is not necessary.

The steps are repeated 10,000 times for every combination of measure and supplier to account for the daily changing tours the LSP may operate. With three potential measures and an LTL network with 100 suppliers, the Monte Carlo simulation has $3 \cdot 100 \cdot 10,000 = 3,000,000$ runs. As a result, the delay costs of the LTL network are obtained. The difference between the delay costs when a particular measure is applied and the status quo when no measures are applied reflects the delay cost improvement related to that measure. The pseudocode of the Monte Carlo simulation and the model of the vehicle routing problem are presented in the appendix.

Stage 3: Measure Allocation

The goal of the measure allocation stage is to determine the optimal portfolio of measures to maximize the benefits of measure allocation while complying with the available budget. This type of problem is well known as the "knapsack problem." The potential delay cost improvements for each measure at each supplier within the LTL network are known from the previous stage, and the measure costs and the (limited) budget for supplier development are derived from VWGL data. For example, two measures (M1 and M2) might be available, with costs of €4,000 and €1,500, respectively, and the budget for supplier development might be limited to €12,000. The solution of the model reflects the optimal allocation of measures to the suppliers. Verbal and mathematical model descriptions are provided in the appendix.

Analysis and Evaluation

The new approach is applied to analyze VWGL's 18 LTL networks in Europe. In 2019, materials from 3,514 suppliers were moved through these networks. After a characterization of the examined networks, the results of the new approach are presented and compared with those of the current LPM process to demonstrate the effectiveness of the new planning approach.

Examined Networks

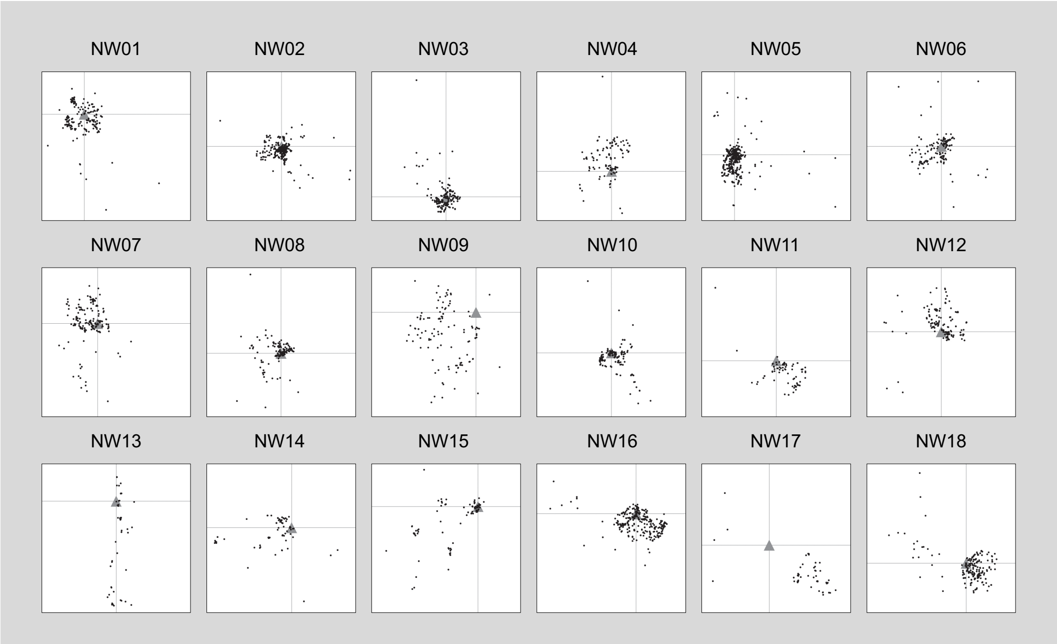
The examined networks differ regarding size and geographical dispersion of the suppliers (Table 1). The mean number of disruptions per supplier and year is reported as a performance indicator for the individual networks. Furthermore, the mean shipping volume per supplier and pickup, the mean distance from the suppliers to the LSP depot, and a qualitative description of the depot location are given.

For a better understanding of the network structures and the depot locations, all 18 LTL networks are visualized in Figure 5. The LSPs usually locate their depots as close to the suppliers as possible. However, in some cases, LSPs maintain operations from already existing depots when commissioned for a new LTL network, resulting in off-centered or outside locations of the depots. Among the 18 LTL networks, 8 networks have a depot central to the suppliers' locations, 8 networks maintain off-centered depots, and 2 networks comprise depots outside most suppliers (NW09 and NW17). The latter networks may be more prone

Table 1. LTL Network Characteristics (2019)

Network	Number of suppliers	Mean disruptions per supplier and year	Mean shipping volume per supplier and pickup (kg)	Mean distance to depot (km)	Depot location
NW01	236	23	12,139	97	Centered
NW02	385	17	8,635	88	Centered
NW03	213	14	11,188	102	Centered
NW04	122	15	9,582	74	Off-centered
NW05	420	11	6,767	87	Centered
NW06	164	20	8,878	83	Centered
NW07	218	16	11,794	118	Off-centered
NW08	181	14	10,749	122	Centered
NW09	122	13	7,653	404	Outside
NW10	166	17	7,427	159	Centered
NW11	81	11	9,618	142	Off-centered
NW12	207	21	12,798	187	Off-centered
NW13	53	11	7,656	144	Off-centered
NW14	84	9	8,590	164	Off-centered
NW15	130	13	8,858	174	Off-centered
NW16	392	22	13,796	131	Centered
NW17	71	36	10,407	557	Outside
NW18	269	26	9,721	174	Off-centered

Figure 5. Locations of Suppliers (Black Dots) and LSP Depots (Gray Triangle) Within the Examined LTL Networks (2019)



to high delay costs in case of disruptions. The demand for transportation ranges from daily to once a week, but most suppliers do not have daily demands. Typically, one to five suppliers are served by one truck of the LSP.

Results

The results of the new approach are compared with those of the current LPM process as a benchmark. The current LPM process allocates measures to suppliers according to decreasing delayed volume, with 10 on-site visits (M1) and 20 online trainings (M2) available in each network. Because the LPM allocates all available measures, the measure allocation costs are identical across all networks. However, the potential delay cost improvements depend on the effectiveness of the measure allocation. For the new approach, the budget for measures is restricted to the cost equivalent of applying 10 times M1 and 20 times M2. The complete use of the budget is not enforced, however, and it can be split among M1 and M2 for each network individually.

The subsequent analyses focus on three key questions:

1. How does the new approach perform compared with the current LPM process regarding delay costs and measure allocation costs across the 18 LTL networks?

2. How does the allocation of measures differ between the two approaches?

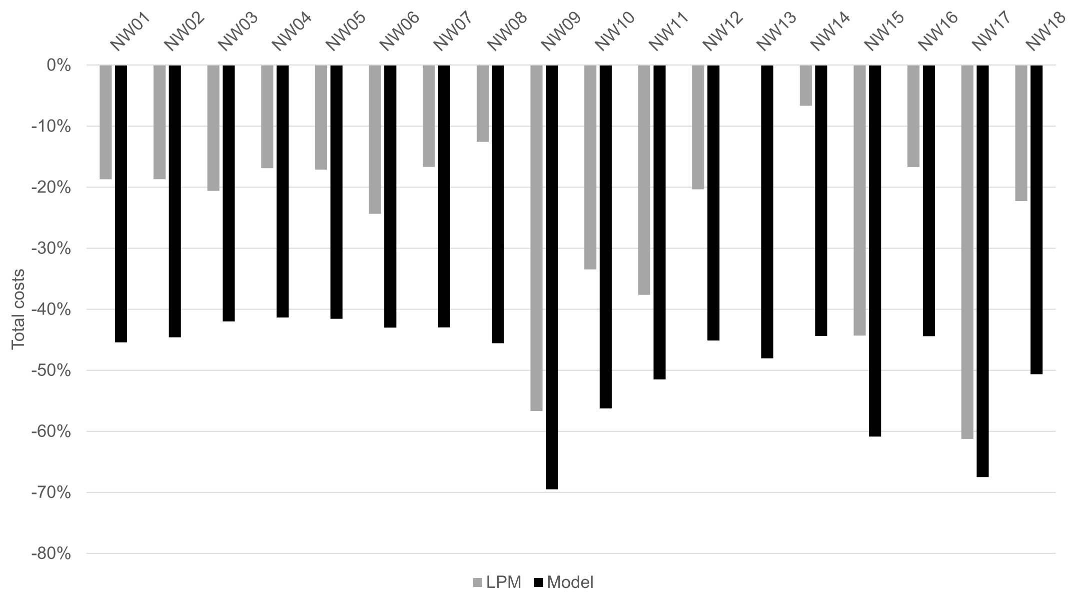
3. What is the potential of allocating all measures centrally instead of considering the 18 LTL networks separately?

Question 1: Performance of the New Approach Compared with the Current LPM Process

In nearly all of the 18 LTL networks, the total costs (sum of delay and measure allocation costs) can be reduced by both the current LPM process and our approach (Figure 6). However, the new approach outperforms the current LPM process for most networks. The cost savings that can be achieved with the new approach are, on average, 31% higher than those resulting from the current LPM process. Based on the total network sizes, the identified cost savings range in the six-digit area. For 14 of 18 networks, the results of the new approach imply significantly lower total costs than in the current LPM process. For the remaining four networks, the new approach only leads to minor additional improvements (NW09, NW11, NW15, and NW17). This is due to the correlation between distances and delay costs. In these four networks, the LSP depot is not centered, which induces long distances between the suppliers and the depot, making extra tours particularly costly. Although the new approach allocates the measures efficiently across the suppliers, the associated benefits of shorter additional tours and, thus, lower delay costs are outweighed by the generally longer tours in these networks.

In NW13, the current LPM approach is not effective at all. With only 53 suppliers, this is a particularly small network. Because all 30 measures are allocated in the current LPM process, the costs of measures outweigh the reduction in delay costs, leading to a total cost increase of 0.2%.

Figure 6. Comparison of the Total Costs (Sum of Delay and Measure Allocation Costs) Between the Current LPM Process and the New Model-Based Approach



Notes. The 0% line marks the initial situation in which no measures are applied. The new approach reduces total costs within each network. The LPM approach is characterized by minor improvements and fails to reduce costs in one of the networks (NW13).

One significant difference between LPM and the proposed model is budget utilization (Figure 7). Although the budget is always fully utilized in LPM, this only occurs in selected instances of the new approach. This illustrates how delay cost improvements are balanced with measure allocation costs to minimize total costs effectively. The seven LTL networks in which the new approach fully utilizes the budget are characterized by a high total number of disruptions per year across all suppliers (NW01, NW02, NW05, NW16, and NW18) or high distances between suppliers and the depot (NW09 and NW17). Both characteristics induce high delay costs if no measures are applied, leading to the utilization of the total available budget. On the contrary, for five LTL networks, the budget utilization is below 50% (NW04, NW11, NW13, NW14, and NW15). These networks are relatively small, comprising between 53 and 130 suppliers, and the number of disrupted suppliers within these networks is relatively low.

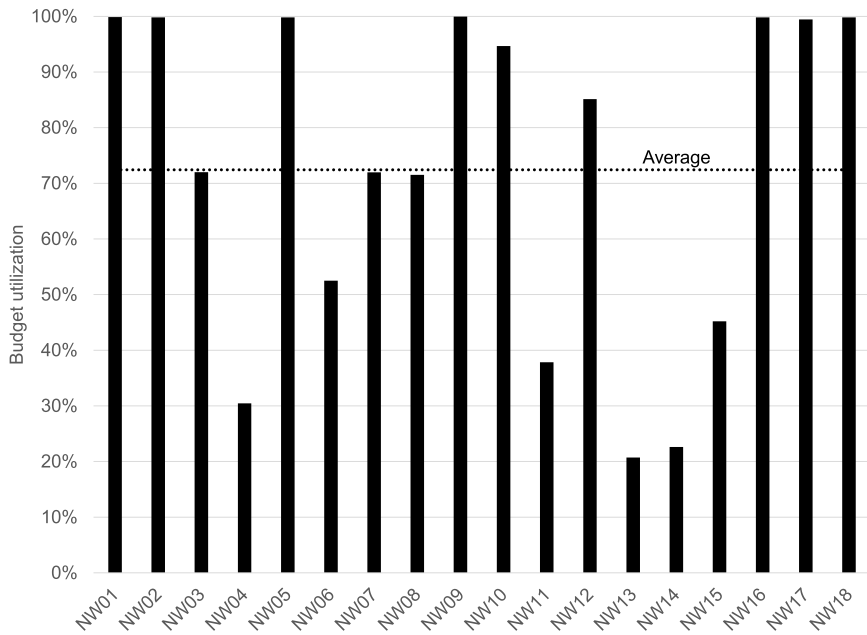
Question 2: Structural Differences in Measure Allocation Between the Two Approaches

All 3,514 suppliers are characterized by their probability of delay and normalized freight volume to analyze the structural differences in measure allocation between the two approaches (Figure 8). It becomes evident that the LPM process (Figure 8(a)) favors suppliers with a high freight volume, whereas our approach (Figure 8(b)) exhibits a stronger focus on delay probability. This is because our model considers the geographical dispersion of suppliers: if two suppliers, S1 and S2, are on the same tour, the delay of low-volume supplier S1 also affects high-volume supplier S2. On the contrary, the LPM approach emphasizes the individual properties of the supplier and neglects the underlying network structure.

Some suppliers with a disruption probability of 100% are only selected by the LPM process. Because these suppliers cause disruptions in every case, it seems surprising that the new approach does not identify these suppliers for measure application. This behavior is because our approach performs measure allocation based on the resulting total costs. Even though a delay occurs in every case, the disruptions at these suppliers incur fewer delay costs than the costs incurred by allocating a measure. This can be explained by the nature of the freight rates, depending on both weight and distance. If the supplier's freight volume is low or the supplier is close to the LSP depot, the delay costs are also low. This holds for settings in which only a few other suppliers are affected on the same tour. Otherwise, if the disruption occurs late on the tour, only a few short extra tours are required to complete the collection of goods from the entire tour.

The approaches can be further distinguished by the type and number of measures allocated (Figure 9). Because online trainings require less budget than on-site visits, measures can be allocated across more suppliers, which outweighs the lower impact of each online training. Our approach to measure allocation reduces total costs more than the LPM process (51% compared with 29%).

Figure 7. Budget Utilization of the New Approach Within the 18 LTL Networks



Notes. In 11 of 18 LTL networks (NW03, NW04, NW06, NW07, NW08, NW10, NW11, NW12, NW13, NW14, and NW15), it is beneficial to not completely use the budget for measures (72% on average). The LPM process always fully utilizes the budget (100%). Using our approach, additional cost savings can be achieved by allocating only effective measures.

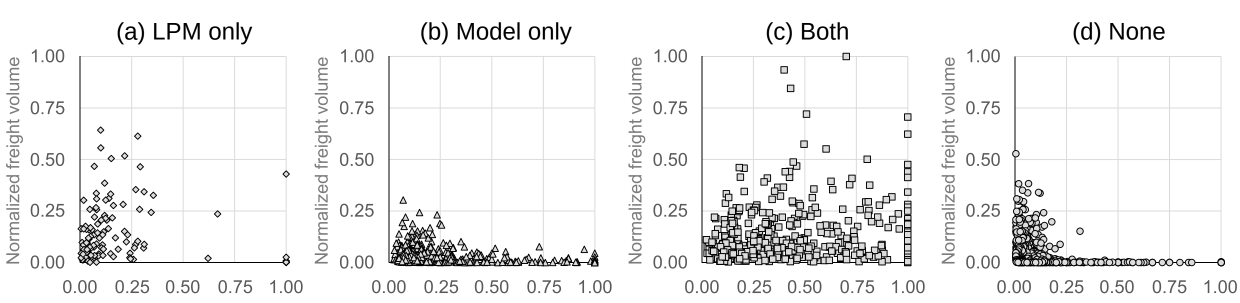
Question 3: Further Potential with Central Allocation of Measures

In the current LPM process, each employee is responsible for measure allocation and execution in individual LTL networks. For each network, 10 on-site visits and 20 online trainings are available. We investigate the impact of a centralized allocation of measures across networks. To this end, the 18 LTL networks are considered simultaneously, and the available budget is scaled accordingly.

The additional cost savings with the new approach are minor when allocating the measures centralized instead of decentralized (Figure 9). Although the total number of allocated on-site visits and online trainings increases, the marginal return of the additional measures in the centralized approach is low. This finding is supported by the average budget utilization for measures of 72% (Figure 7), which suggests a sufficient budget is available for most networks.

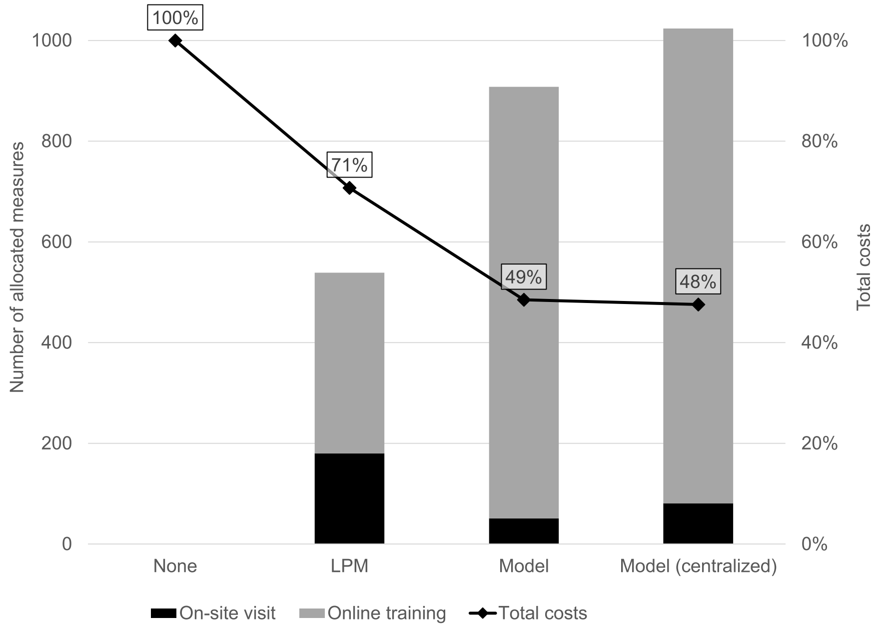
In summary, it becomes evident that the new approach outperforms the current LPM procedure. On average, the total costs are 31% lower. There are several reasons for this. Although LPM always fully uses the budget, the new approach minimizes total costs by balancing measure allocation costs and delay cost improvements. Moreover, the new approach favors the allocation of online trainings over the allocation of on-site visits. Even though one online training is not as effective as one on-site visit,

Figure 8. Comparison of the Measure Allocation Between the Current LPM Process and the New Model-Based Approach



Notes. Each dot within the graphs displays one supplier. Its position depends on its normalized freight volume and its probability of delay. (a) Suppliers selected for measure allocation by the LPM process only. (b) Suppliers selected only by our model. (c) Suppliers selected by both approaches. (d) Suppliers selected by neither of the approaches. However, the graphs do not indicate the criticality of the delays.

Figure 9. Comparison of the Measure Types Between the Approaches



Notes. LPM strictly allocates 10 on-site visits and 20 online trainings in each network, reducing total costs by 29%. Our model allocates significantly fewer on-site visits in favor of more online trainings. Total costs can be reduced by 51%. When measures are assigned centrally, a higher number of measures is allocated. However, the associated decrease in marginal return is significant.

it is more efficient to allocate the available budget to more online trainings than on-site visits. Another advantage is the consideration of more data, such as the delay probability of the suppliers and the anticipation of LSP's vehicle routing within the Monte Carlo simulation. Hence, the interdependencies of suppliers on the same transport can be considered, leading to improved results compared with the strict focus on individual properties of the suppliers as performed in the current LPM process.

Practical Application and Enablers of Project Success

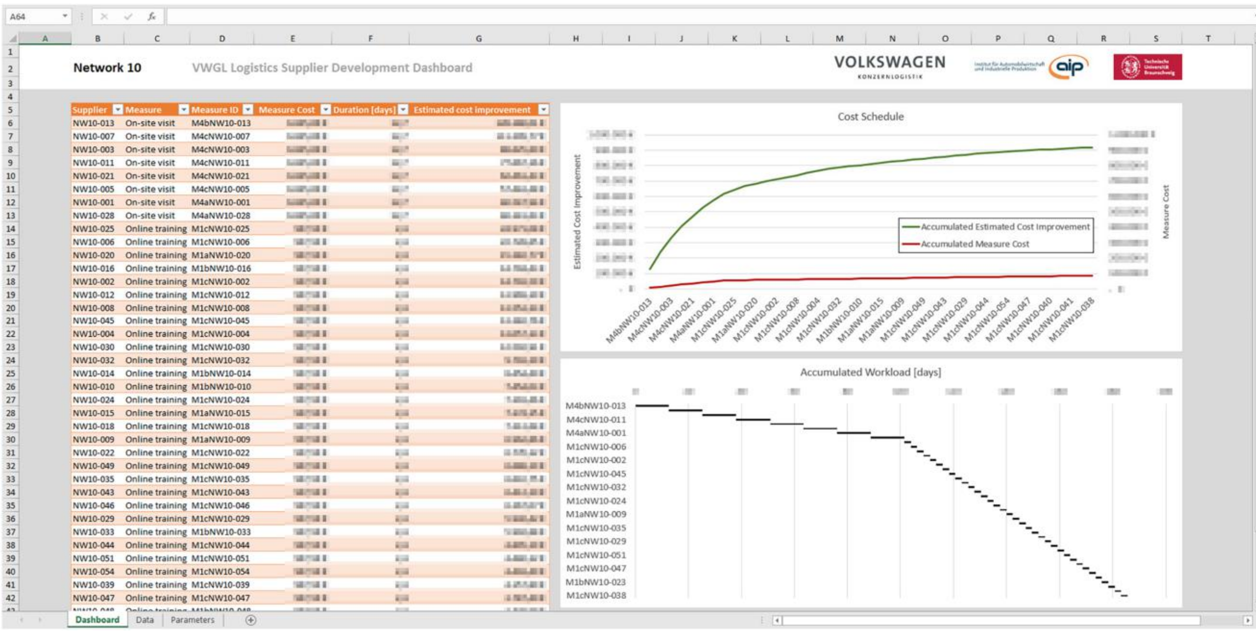
The promising results of our approach have motivated VWGL to exploit its potential in their daily work routine. To facilitate the practical application of our model, we developed a new workflow for measure allocation and execution in the logistics department of VWGL. The workflow is structured into five stages: (1) data extraction and preparation, (2) execution of the model, (3) visualization, (4) validation, and (5) measure execution. The required data are extracted from various VWGL databases using specific query templates. The data are then prepared for import into our model based on a well-documented standardized procedure. The model runs in Java and automatically generates a Microsoft Excel file in which the results of the simulation-based measure evaluation and optimization-based measure allocation are provided. A semiautomated dashboard enhances the report and supports the VWGL employees' working routines. It comprises a table of measures to be allocated and charts showing the cost schedule and team workload (Figure 10). The Excel-based dashboard implementation promotes broad acceptance, low employee training efforts, and a wide range of applications for further data processing.

The dashboard is an important tool for the VWGL employee to validate the model results. The cost improvements identified by the semiautomated workflow are in the six-digit area and therefore ensure a rapid amortization of the project.

Several factors accompanied the success of this project. Before developing the planning approach described in this article, we developed a risk map to better understand the interdependencies between suppliers, LSP, and VWGL in a previous project. In that project, we learned that an individual evaluation of suppliers, as practiced at VWGL, does not allow for methodologically informed decisions on measure allocation. In this context, we applied the AHP method, enabling us to use these insights for parametrizing the model, so that the experts of VWGL were already familiar with this technique.

On the VWGL side, the project was mentored by the management and broadly accepted by the employees. We had the opportunity to survey experts and management who provided comprehensive insights into the inbound logistics processes of one of the largest logistics companies in Europe. Furthermore, we were able to discuss and improve our approach continuously. We

Figure 10. (Color online) Microsoft Excel Dashboard Visualizing the Results of Our Model



Source. Used with permission from Microsoft and Volkswagen.

were also allowed to use VWGL's databases to feed our model from the beginning so that our approach yields relevant suggestions for the practitioners and is well established in the information technology infrastructure. Regarding the development of the new planning approach, it was advantageous that the academic partners already had experience implementing operations research approaches in automotive practice (Weckenborg et al. 2020).

Conclusions

We aimed to support VWGL's team concerning the measure allocation during supplier development activities in LTL networks. The problem setting covers three challenges: (1) the detection of disrupting suppliers in an objective manner, (2) the practical evaluation of the impact of improvement measures against the background of interdependencies between the suppliers within the LTL networks of VWGL, and (3) the examination of a measure allocation strategy to maximize the logistics performance of the supply base. We did not find adequate approaches in academic literature or commercial software, so we developed a semiautomated three-staged approach to allocate measures optimally. The stages comprise (1) data preparation, (2) measure evaluation, and (3) measure allocation. Our approach integrates a Monte Carlo simulation for measure evaluation with a knapsack model for measure allocation. We compare our results with those of the previously conducted procedure. The comparison shows that our new approach outperforms the current process by 31%. To operationalize this potential, we finally created a new workflow with VWGL and identified annual savings in the six-digit area. The presented approach is limited to LTL networks. In different settings, other interdependencies may need to be considered. Furthermore, it is dependent on data quality and data availability. As our work mainly focuses on the backend application, the execution of the core model might be cumbersome at first sight. Hence, implementing a proper user interface is a priority for future development.

Besides the aforementioned limitations, our collaborative approach in supplier development allows all partners of the inbound logistics process to work jointly on a common goal without wasting energy for recriminations, leading to higher satisfaction and more sustainable long-term partnerships. Through the generalistic design of the approach, every company with material flows between its supply base and its plants should be capable of adapting the methodology. Moreover, data-driven logistics is a fast-growing field, opening up a wide range for more operations research applications. In particular, the connection between supply chain performance, risk and resilience, and in-house data such as stock levels and demands may frame future developments.

Appendix

This appendix aims to provide further insights into the methods we developed for the interested reader. To this end, we initially report on the capacitated vehicle routing problem (CVRP) and the Monte Carlo simulation used to evaluate measures in Stage 2 of our approach. Subsequently, we provide the model formulation of the knapsack problem used for selecting measures in Stage 3 of our approach. Please refer to Figure 4 to recall the general procedure.

Capacitated Vehicle Routing Problem (Stage 2)

Sets and Indices.

$i, j \in S$: Suppliers (including depot), $S = \{0, 1, \ldots, n\}$
$k \in T$: Trucks/tours, $T = \{1, \ldots, K\}$

Parameters.

b_i: Transport demand at supplier i
C: Truck capacity
d_{ij}: Distance between suppliers i and j

Decision Variables.

x_{ijk}: Binary variable, one if truck k drives from supplier i to j, zero otherwise
y_{ik}: Binary variable, one if truck k serves supplier i, zero otherwise

$$\min \sum_{i \in S} \sum_{j \in S} \sum_{k \in T} d_{ij} \cdot x_{ijk} \tag{A.1}$$

subject to

$$\sum_{i \in S \setminus \{0\}} b_i \cdot y_{ik} \le C \qquad \forall k \in T, \tag{A.2}$$

$$\sum_{k \in T} y_{0k} = K, \tag{A.3a}$$

$$\sum_{k \in T} y_{ik} = 1 \qquad \forall i \in S \setminus \{0\}, \tag{A.3b}$$

$$\sum_{i \in S} x_{ijk} = y_{jk} \qquad \forall j \in S,\ k \in T, \tag{A.4}$$

$$\sum_{j \in S} x_{ijk} = y_{ik} \qquad \forall i \in S,\ k \in T, \tag{A.5}$$

$$\sum_{i \in R} \sum_{j \in R} x_{ijk} \le |R| - 1 \qquad \forall R \subseteq S \setminus \{0\},\ 2 \le |R| \le (n-1),\ k \in T, \tag{A.6}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall i \in S,\ j \in S,\ k \in T, \tag{A.7}$$

$$y_{ik} \in \{0, 1\} \qquad \forall i \in S,\ k \in T. \tag{A.8}$$

The symmetric Euclidian CVRP is a graph theoretic problem, where $G = (S, E)$ is a complete and undirected graph, $S = \{0, \ldots, n\}$ is the set of suppliers in which zero corresponds to the depot, and E is the set of edges (i, j) between suppliers i and j. The goal is to find exactly K simple tours ("circuits") where three conditions are met: (a) the depot is visited in each tour, (b) each supplier is part of exactly one tour, and (c) the sum of the supplier volumes of one tour is lower than the vehicle capacity (Toth and Vigo 2002). The mathematical model is taken from Fisher and Jaikumar (1981). The objective function (A.1) is to minimize the overall distance to serve all suppliers of the network. We assume that the transportation costs correlate with the distance, so a tour plan with minimum distance is also at minimum costs. The Euclidian distances between the suppliers are calculated based on their geo-coordinates. Constraints (A.2) ensure that the capacity of a vehicle will not be exceeded. Constraint (A.3a) prescribes that all tours contain the depot, and Constraints (A.3b) ensure that each supplier is served by exactly one truck. The decision variables are connected via Constraints (A.4) and (A.5). Short cycles are impeded by Constraints (A.6). The CVRP can be solved using different algorithms. In our case, the algorithm of Lin and Kernighan (1973) was adapted to obtain reasonably good results in a very timely manner. Against the background of 10,000 Monte Carlo runs, this property is of high importance.

Monte Carlo Simulation (Stage 2)

Sets and Indices.

$i \in M$: Measures
$j \in S$: Suppliers
$k \in T$: Tours

Parameters.

δ_i: Effect of measure i
d^{lim}: Delay limit
p_j: Delay probability of supplier j
$L_j \sim \Gamma(\alpha, \beta)$: Delay length at supplier j (gamma-distributed with parameters α and β)
$O_j \sim \mathcal{B}(p_j)$: Delay occurrence at supplier j (Bernoulli-distributed with parameter p_j)
$V_j \sim \mathcal{N}(\mu_j, \sigma_j)$: Freight volume of supplier j (normally distributed with parameters μ_j and σ_j)

Variables.

c^{D}_{jk}: Delay costs of supplier j on tour k (within a Monte Carlo run)
C^{D}_0: Initial average delay costs of the entire network (if no measures are applied)
C^{D}_{ij}: Average delay costs of the entire network if measure i is applied at supplier j across all simulation runs
Δ_{ij}: Average delay cost improvement of the entire network if measure i is applied at supplier j across all simulation runs
d_k: Cumulative delay on tour k

The Monte Carlo simulation analyzes the benefits of a particular measure allocation. It calculates the average delay cost improvement Δ_{ij} if measure i is allocated to supplier j. Within each Monte Carlo run, a CVRP has to be solved to reflect the daily changing tours of the LSP, resulting from the randomly drawn freight volumes for each supplier j. For example, with 200 suppliers in the LTL network and two different measures, $2 \cdot 200 = 400$ possible measure allocations must be evaluated. In the course of the simulation, the random variables for freight volume V_j, delay occurrence O_j, and delay length L_j are each drawn $400 \cdot 10{,}000 = 400{,}000$ times. Under the assumption of approximately four suppliers on each tour, $400 \cdot 10{,}000 \cdot \frac{200}{4} = 100{,}000{,}000$ tours are created. To guarantee reproducibility and comparability, the seed value for the random generator is set to a constant value before evaluating a measure allocation so that every combination of a measure and a supplier is evaluated using the same set of random numbers. This also leads to the same results for solving the CVRP. That is why the tours from the evaluation of measure 1 at supplier 1 are saved and reused for the upcoming 399 combinations. This way, the CVRP has to be solved only 10,000 times—once per Monte Carlo run for the first combination of supplier and measure. By doing so, the run time of the simulation can be reduced significantly. However, there are 10,000 different tour plans to evaluate a combination of one supplier and one measure.

Pseudocode for Monte Carlo Simulation

//Function to compute the average delay costs of the network based on a Monte Carlo simulation
Function *simulate_network_delay_costs*
  Set seed of random generator to constant value
  For each Monte Carlo run
    For each supplier $j \in S$
      Draw random freight volume V_j
    Next
    Create a tour plan T by solving the capacitated vehicle routing problem
    For each supplier $j \in S$
      Draw random delay occurrence O_j
      If $O_j == 1$ (supplier is delayed) **Then**
        Draw random delay length L_j
      End if
    Next
    //Calculate delay costs at each supplier and aggregate them for all tours and the entire network
    For each tour $k \in T$
      For each supplier j on tour k
        If cumulative delay d_k within tour k exceeds delay limit d^{lim} **Then**
          Calculate delay costs c_{jk}^{D} for each downstream supplier j on tour k
        End if
      Next
    Next
    Calculate the total delay costs of the entire network (sum across all suppliers j)
  Next
  Calculate average delay costs of the entire network (across all Monte Carlo runs)
  Return average delay costs of the entire network
End function
//Generate initial situation for delay costs with no measures allocated
Calculate initial average delay costs C_0^{D} of the network by calling the function
simulate_network_delay_costs
//Evaluate the effects of measure application
For each supplier $j \in S$
  For each measure $i \in M$
    //Update delay probabilities if development measure is applied
    If measure i is applied to supplier j **Then**
      Update delay probability p_j by multiplying the initial value of p_j with the effect (improvement rate) δ_i of measure i
    End if
    Calculate average delay cost C_{ij}^{D} of the entire network by calling the function
    simulate_network_delay_costs
    Calculate average delay cost improvement Δ_{ij} as the difference between C_{ij}^{D} and C_0^{D}
  Next
Next

The calculation of the delay costs of supplier j on tour k (c_{jk}^{D}) is explained in the following example: The tour $k = 1$ is planned from depot to supplier S1 ($j = 1$) to S2 ($j = 2$) to S3 ($j = 3$) back to the depot. The delay limit d^{lim} is six hours. The delays are four hours at S1, four hours at S2, and two hours at S3. Thus, the cumulative delay d_1 exceeds the delay limit at S2. The LSP cancels the tour at S2 before loading to deliver the material from S1 at the depot in time. Because of that, extra tours have to be carried out to S2 (€200) and S3 (€150). The delay costs are $c_{11}^{\text{D}} = 0$, $c_{21}^{\text{D}} = 200$, and $c_{31}^{\text{D}} = 150$. Assuming that there are no further critical delays within the LTL network, the total delay costs are $\sum_{j\in S}\sum_{k\in T} c_{jk}^{\text{D}} = 350$. Moreover, the costs for the originally planned tour apply in any case because the LSP reserved its capacity accordingly. Therefore, the amount of €350 reflects the additional efforts to be covered. In practice, they will be invoiced. VWGL registers these costs as unplanned additional costs, making it easy to process the data without further subtraction from the regular LTL costs.

Knapsack Model (Stage 3)

Sets and Indices.

$i \in M$: Measures
$j \in S$: Suppliers

Parameters.

B: Total budget for measures
C_i^{M}: Application costs of measure i
Δ_{ij}: Average delay cost improvement of the entire network if measure i is applied at supplier j

Decision Variables.

x_{ij}: Binary measure allocation variable, one, if measure i is allocated to supplier j, zero, else

$$\max \sum_{i\in M}\sum_{j\in S}(\Delta_{ij} - C_i^{\text{M}}) \cdot x_{ij} \tag{A.9}$$

subject to

$$\sum_{i\in M}\sum_{j\in S}(C_i^{\text{M}} \cdot x_{ij}) \le B, \tag{A.10}$$

$$\sum_{i\in M} x_{ij} \le 1 \qquad \forall j \in S, \tag{A.11}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in M,\ j \in S. \tag{A.12}$$

The knapsack problem is modeled as a binary integer program. The objective function (A.9) is to maximize the difference between the delay cost improvement Δ_{ij} and the measure cost C_i^{M}. Constraint (A.10) ensures that the total budget for measures B is not exceeded. Constraint Set (A.11) guarantees that not more than one measure is allocated to one supplier. Constraint Set (A.12) ensures binarity of decision variables x_{ij}. It is one if measure i is allocated to supplier j or zero if measure i is not allocated to supplier j. Referring to the aforementioned example (200 suppliers, two measures), 400 binary decision variables and 201 constraints must be considered.

Knapsack models assume the benefits in the objective function to be additive. For example, after solving the knapsack model, three measures are allocated ($x_{ij} = 1$) within the LTL network.

- Measure 1 at supplier 1: $(\Delta_{11} - C_1^{\text{M}}) \cdot x_{11} = 1{,}000$
- Measure 1 at supplier 2: $(\Delta_{12} - C_1^{\text{M}}) \cdot x_{12} = 2{,}500$

- Measure 2 at supplier 3: $(\Delta_{23} - C_2^M) \cdot x_{23} = 1{,}400$

The total benefit is $\sum_{i \in M} \sum_{j \in S} (\Delta_{ij} - C_i^M) \cdot x_{ij} = 1{,}000 + 2{,}500 + 1{,}400 = 4{,}900$.

Because of the simplifying assumption of the knapsack model that the benefits of the allocated measures are additive, the model's objective function value might deviate from the total benefit computed by the Monte Carlo simulation (which considers network effects). The relative differences in total benefit of these two approaches for the optimal set of allocated measures in each network as determined by the knapsack model are displayed in Table A.1. In 17 of 18 networks, the additive objective function of the knapsack model overestimates the total benefit (except NW09). However, the differences in the range of −1.6% to +0.5% are rather small.

Generally, knapsack problems are NP-complete, and the computation of optimal results for large instances is not trivial. With 400 binary decision variables and 201 constraints in our example, however, optimal results are computed in less than a second using the CPLEX solver running on a Windows 10–based virtual machine using 8 threads of an Intel Xeon Platinum 8180 CPU and 32 GB RAM. Evaluating all possible combinations of measures using the more accurate Monte Carlo simulation would require considerable computational effort, which could hardly be justified in this practical application. In our example with 200 suppliers and two improvement measures plus a do-nothing option, $(2 + 1)^{200} \approx 2.7 \cdot 10^{95}$ different combinations would have to be considered. Even if the average computing time of eight seconds to evaluate one measure allocation (10,000 Monte Carlo runs) could be reduced to one millisecond, the total duration of the Monte Carlo simulation would still be far beyond business requirements.

Table A.1. Inaccuracies in Total Benefit Because of the Simplifying Additivity Assumption of the Knapsack Model

Network	Inaccuracy
NW01	−1.2%
NW02	−0.8%
NW03	−0.9%
NW04	−0.9%
NW05	−0.9%
NW06	−0.6%
NW07	−1.6%
NW08	−0.5%
NW09	0.5%
NW10	−1.4%
NW11	−0.6%
NW12	−1.1%
NW13	−1.5%
NW14	−0.7%
NW15	−0.9%
NW16	−0.8%
NW17	−1.1%
NW18	−0.6%

Notes. The table shows the relative difference when comparing the objective function value of the additive knapsack model with the total benefit computed by the Monte Carlo simulation (considering network effects) for the optimal set of measures as determined by the knapsack model. Negative values indicate that the knapsack model overestimates the total benefit.

References

Chai J, Liu J, Ngai E (2013) Application of decision-making techniques in supplier selection: A systematic review of literature. *Expert Systems Appl.* 40(10):3872–3885.

Fisher ML, Jaikumar R (1981) A generalized assignment heuristic for vehicle routing. *Networks* 11(2):109–124.

Glock CH, Grosse EH, Ries JM (2017) Decision support models for supplier development. Systematic literature review and research agenda. *Internat. J. Production Econom.* 193(Part 3):798–812.

Ho W, Xu X, Dey PK (2010) Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *Eur. J. Oper. Res.* 202(1):16–24.

Krause DR, Ellram LM (1997) Critical elements of supplier development. The buying-firm perspective. *Eur. J. Purchasing Supply Management* 3(1):21–31.

Krause DR, Handfield RB, Scannell TV (1998) An empirical investigation of supplier development: reactive and strategic processes. *J. Oper. Management* 17(1):39–58.

Lasch R, Janker CG (2005) Supplier selection and controlling using multivariate analysis. *Internat. J. Physical Distribution Logist.* 35(6): 409–425.

Lin S, Kernighan BW (1973) An effective heuristic algorithm for the traveling-salesman problem. *Oper. Res.* 21(2):498–516.

O'Brien J (2022) *Supplier Relationship Management. Unlocking the Value in Your Supply Base*, 3rd ed. (Kogan Page Limited, London).

Sherwin MD, Medal H, Lapp SA (2016) Proactive cost-effective identification and mitigation of supply delay risks in a low volume high value supply chain using fault-tree analysis. *Internat. J. Production Econom.* 175:153–163.

Toth P, Vigo D (2002) An overview of vehicle routing problems. Toth P, Vigo D, eds. *The Vehicle Routing Problem* (SIAM Monographs on Discrete Mathematics and Applications, Philadelphia), 1–26.

Weckenborg C, Kieckhäfer K, Spengler TS, Bernstein P (2020) The Volkswagen Pre-production center applies operations research to optimize capacity scheduling. *INFORMS J. Appl. Analytics* 50(2):119–136.

Wieczorrek S, Grunewald M, Spengler TS (2019) Supplier development considering interdependencies in the inbound logistics of the automotive industry. Bode C, Bogaschewsky R, Eßig M, Lasch R, Stölzle W, eds. *Supply Management Research* (Springer Fachmedien Wiesbaden, Wiesbaden, Germany), 99–119.

Wieczorrek S, Hermes A, Grunewald M, Spengler TS, Braun M (2017) Logistisches prozesspartnermanagement in der beschaffungslogistik bei der Volkswagen AG. Göpfert I, Braun D, Schulz M, eds. *Automobillogistik. Stand und Zukunftstrends* (Springer, Wiesbaden, Germany), 53–75.

Yawar SA, Seuring S (2020) Reviewing and conceptualizing supplier development. *Benchmarking Internat. J.* 27(9):2565–2598.

Yu VF, Qiu M, Gupta JND (2022) Improving supplier capability through training. Evidence from the Chinese Automobile Industry. *Comput. Industrial Engrg.* 163:107825.

Zhou R, Bhuiyan TH, Medal HR, Sherwin MD, Yang D (2022) A stochastic programming model with endogenous uncertainty for selecting supplier development programs to proactively mitigate supplier risk. *Omega* 107:102542.

Verification Letter

Simon Motter, Chairman of the Management Board, Volkswagen Group Logistics; Enno Fehse, Director Material Logistics, Volkswagen Group Logistics, 38436 Wolfsburg, Germany, writes:

"We are writing to you on behalf of Volkswagen Group Logistics in Wolfsburg to confirm the application of Operations Research (OR) within our Inbound Logistics Department as well as the results reported by Sönke Wieczorrek, Christian Thies, Christian Weckenborg, Martin Grunewald, and Thomas S. Spengler.

"The introduced simulation and optimization approach for supplier development precisely meets our needs in logistics process partner management. It helps us to identify the optimal allocation of supplier development measures that has the largest impact on the overall performance of the supply network. Moreover, it significantly reduces the high manual planning effort. Due to the innovative model, we are able to identify cost improvements in the six-digit area for our area freight forwarding networks.

"We highly appreciate the expertise of Mr. Spengler and his team who guided our successful development and implementation of OR methods in the field of supplier development. That is why we are strongly encouraged to explore the application of OR to generate significant cost savings in related fields of the Volkswagen Group. If you need any further information, please feel welcome to contact us."

Sönke Wieczorrek is project manager at Volkswagen Group Logistics. He is also a PhD candidate at the Institute of Automotive Management and Industrial Production at Technische Universität Braunschweig, Germany. He holds an MSc degree in industrial engineering with majors in production and logistics. His research interest is in supplier relationship management against the background of handling uncertainties and improving supply chain resilience.

Christian Thies is assistant professor of resilient and sustainable operations and supply chain management at Hamburg University of Technology, Germany. He completed his PhD in business administration at Technische Universität Braunschweig and also holds an MS degree in supply chain engineering from the Georgia Institute of Technology. His research focuses on sustainable production systems and supply chains with a particular interest in the automotive industry.

Christian Weckenborg is an assistant professor at the Institute of Automotive Management and Industrial Production at Technische Universität Braunschweig, Germany. He holds an MSc degree in industrial engineering and a PhD in business administration. His research focuses on contributions of technology-oriented management in production and logistics. To this end, operations research methods are applied to provide informed business decision support.

Martin Grunewald is project manager at the Group IT at Volkswagen AG. He holds a diploma in business mathematics and completed his PhD in business administration at the Institute of Automotive Management and Industrial Production at Technische Universität Braunschweig, Germany. He worked on several projects in the field of production, logistics, and after sales in the automotive industry.

Thomas S. Spengler is professor and director of the Institute of Automotive Management and Industrial Production at Technische Universität Braunschweig, Germany. He holds a PhD from Karlsruhe Institute of Technology, Germany. His research covers the development and implementation of techno-economic models and quantitative methods for decision support. His work has been published in a variety of academic journals. Since 2020, he has been a member of the German Science and Humanities Council.