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ORIGINAL PAPER

# A proactive transshipment model for prototype parts logistics in the automotive industry

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## Abstract

In the logistics of prototype parts in the automotive industry, unique parts are stored in warehouses and provided to assembly service providers to ensure a timely assembly of the associated prototype vehicles. As the allocation of the assembly orders to the assembly service providers may change before the start of the assembly, the shipments are planned at short notice. This article considers the short-term task of planning shipments of individual prototype parts from multiple warehouses to multiple assembly service providers. The current literature on planning shipments focuses mainly on parts available in batch sizes larger than one. However, as prototype parts are individual, storing them in adequate warehouses is crucial. A mixed-integer linear programming model for planning transshipments of parts between the warehouses and shipments to the assembly service providers to minimize overall costs is presented. The model enables the utilization of spare capacities of planned transports for a proactive transshipment of parts between warehouses. To this end, the future shipment costs of parts to assembly service providers are approximated to determine suitable warehouses. A numerical study shows that the proactive approach leads to a considerable cost reduction.

**Keywords** Lateral transshipments · Multi-location inventory · Replenishment · Pooling · Reallocation · Redistribution

**Mathematics Subject Classification** M21 · C61 · R40

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## 1 Introduction

For many decades, the *automotive industry* has attracted significant research in business economics. This is particularly true for the production and logistics processes associated with the mass production of vehicles or their components. Tasks such as the design of the production network (Fleischmann et al. 2006), the associated assembly lines (Lopes et al. 2017), or the planning of assembly capacities and orders (Volling et al. 2013) have been frequently considered. Significant research also addresses the automotive industry's external and in-house parts logistics (Boysen et al. 2015).

However, before the mass production of vehicles, a careful product development process is required, during which the design of future vehicles is determined. To ensure the designed vehicles' feasibility and to test their technical functions, *prototype vehicles* are assembled. These are unique vehicles comprising components manufactured explicitly for the testing purposes of these vehicles. The assembly of prototype vehicles can be carried out by multiple internal or external assembly service providers whose locations may be spatially dispersed. However, the scheduling of assembly orders, their assignment to the assembly service providers, and the vehicles' configuration are done in the short term. To facilitate the timely shipment of the required prototype parts, typically, multiple warehouses are operated in proximity to the individual assembly service providers, where the parts can be stored as desired. In the literature, the scheduling of prototype vehicle assembly and their subsequent test runs have already received limited attention (Weckenborg et al. 2020a, b; Bartels and Zimmermann 2009; Reich et al. 2016; Shi et al. 2017). However, the associated logistics of prototype parts have been largely neglected in the scientific literature.

The short-term task of *prototype parts logistics* is to plan the shipments of parts from warehouses to assembly service providers (hereafter referred to as customers) and the transshipment of parts between warehouses. For the transports, logistics service providers are commissioned at short notice to provide a prespecified number of vehicles for transports between two locations (warehouse-warehouse or warehouse-customer), which the manufacturer can fully utilize. Given a customer order comprising parts from multiple warehouses, the manufacturer can initiate multiple transports from the warehouses to the customer or consolidate the parts in one warehouse for shipment in a single transport. Leveraging the spare capacity of the transports between warehouses allows for a proactive transshipment of additional parts. Thus, approximating future shipment costs of parts based on the assigned warehouse and proactively considering part transshipment between warehouses may be an important lever to improve the overall efficiency of prototype parts logistics. This is a challenging endeavor, as the parts are unique and can only be stored in one warehouse at a time.

In the *academic literature*, the transshipment of parts between warehouses without a customer order is known as a proactive lateral transshipment (Paterson et al. 2011). However, articles in this domain do not consider the unique character of prototype parts. To this end, this article describes the problem setting of prototype parts logistics and presents a mixed-integer linear programming model. The model aims to minimize transport costs while serving customer orders. An approximation of future shipment costs of parts depending on the assigned warehouse is incorporated to decide about proactive transshipment between warehouses. A numerical study demonstrates the advantages of the approach.

The *main contributions* of this article are twofold: First, a proactive approach for prototype part logistics in the automotive industry is developed for the first time. To this end, the parts' uniqueness and an approximation of future shipment costs are explicitly considered. Second, the impact of the approximation compared to a reactive approach neglecting this information is evaluated. In the numerical study, multiple parameters of the problem setting are varied to show that a proactive approach can provide significant benefits over a reactive approach for prototype parts logistics.

The *remainder* of this article is structured as follows: Sect. 2 provides an overview of the associated literature. The model is developed in Sect. 3 based on a detailed description of the problem setting. A numerical study is conducted in Sect. 4. The article concludes with a discussion and an outlook in Sect. 5.

## 2 Literature overview

This section provides an overview of the literature related to the article at hand. To this end, literature referring to inventory management for spare parts is introduced initially. Subsequently, an overview of the literature on reactive and proactive lateral transshipments is provided. Finally, applications for lateral transshipments in different industries are described.

*Inventory management* is a fundamental topic of operations management referring to the planning and control of matching supply and demand by distributing parts in the right quantities, to the right locations, and at the right time to minimize systemwide costs (Simchi-Levi et al. 2001; Srikanta Routroy 2005; Gümüs and Güneri 2007; Song et al. 2020). A specific application of inventory management approaches refers to managing spare parts. Since spare parts, as well as prototype parts, are usually available only in small quantities and their absence generates high costs, similarities exist between these types of parts. An overview of inventory management approaches for spare parts is given in Hu et al. (2018). The decisions about storing parts in several decentralized or one central distribution center is a crucial aspect of the spare parts supply chain (Cantini et al. 2024).

Paterson et al. (2011) provide an overview of the literature on *lateral transshipments*. They classify the literature into reactive and proactive transshipments. Reactive transshipments, on the one hand, refer to situations in which a shortage has already occurred and aim to react to these shortages. These types of problems are well-observed in literature (Axsäter 1990; Banerjee et al. 2003; Burton and Banerjee 2005; Zhang 2005; Wee and Dada 2005; Herer et al. 2006; Yang and Qin 2007; Zhao and Atkins 2009; Tang and Yan 2010; Tiacci and Saetta 2011; Liang et al. 2014; Park et al. 2016; Yao et al. 2016). Proactive transshipments, on the other hand, refer to situations before demand has occurred. Allen (1958) develops the first proactive model considering a single period and several storage locations. He determines an optimal redistribution of stocks. Agrawal et al. (2004) develop a dynamic approach for proactive transshipments. Their algorithm determines the optimal periods for the transshipment of stocks at the retailers. Burton and Banerjee (2005) compare the costs between a reactive and a proactive transshipment model with multiple echelons. Tagras and Vlachos (2002) analyze the operational characteristics of a pooling strategy with two locations and non-negligible transshipment times. They find proactive transshipments advantageous, especially when demand is highly variable. Jönsson and Silver (1987) focus on minimizing total backorders by applying constraints on the timing of transshipments. Lee and Whang (2002) exhibit a two-period model with one manufacturer and multiple retailers and obtain optimal stock levels and proactive transshipment policies. Rong et al. (2010) and Li et al. (2013) consider decentralized systems. Abouee-Mehrizi et al. (2015) use a proactive transshipment model to minimize the mismatch between supply and demand. Meissner and Senicheva (2018) also investigate a multi-site, multi-period inventory system with a single echelon. An optimal ordering and transshipment policy is determined through proactive transshipments and approximate dynamic programming.

Transshipments can be found in *different industries*. Some literature on transshipments refers to the fashion industry (Caro and Gallien 2010; Hu and Yu 2014; Naderi et al. 2020). Transshipments also occur in the retail industry. Specifically, lateral transshipment and emergency orders are investigated (Liao et al. 2014). Another application is the medical industry, where, e.g., uncertain demand for blood units meets their limited lifetime (Jin and Agirbas 2013; Najafi et al. 2017; Shokouhifar et al. 2021; Dehghani et al. 2021). Several articles refer to the spare parts industry (Paul and Yenipazarli 2013; Axsäter et al. 2013; Kranenburg and van Houtum 2009; Karsten et al. 2012; Olsson 2015; Boucherie et al. 2018; Topan and van der Heijden 2020). In the automotive industry, Glazebrook et al. (2015) develop a hybrid transshipment policy. Transshipment decisions are made when a bottleneck at a location needs to be covered by a reactive transshipment. However, they allow the transshipment to exceed the current bottleneck to avoid a future imbalance in the inventory system. The authors use dynamic programming to solve the model and propose a heuristic to estimate the future cost of a decision. In approximating these costs, it is assumed that no transshipments will be issued in the future.

To conclude this section, no existing approach considers the parts' uniqueness and the resulting decisions on allocating individual parts among multiple warehouses. Therefore, the following section describes the problem of prototype parts logistics in the automotive industry and the developed proactive transshipment model.

## 3 Model development

This section presents the proactive transshipment model developed for automotive prototype parts logistics. To this end, the problem setting is presented in Sect. 3.1. Further assumptions of the approach are justified in Sect. 3.2. The notation of the planning model is introduced in Sect. 3.3. The model formulation is given in Sect. 3.4.

### 3.1 Problem setting

The proposed planning model aims to support automotive manufacturers in the short-term planning of shipments of prototype parts from warehouses to customers, where parts may additionally be transshipped between warehouses before customer delivery. This section describes the problem setting. To this end, the characteristics of the logistics network are described. Subsequently, the sequential planning problem of prototype parts logistics is introduced. Finally, the considered objective is justified.

The considered *logistics network* centers an automotive manufacturer. The manufacturer operates multiple warehouses, which are spatially dispersed and characterized by a limited capacity to store prototype parts. One of the warehouses serves as a central hub. On the inbound side, the incoming shipments must be received at the central hub. Personnel with limited capacity are deployed to handle the parts. Possible actions for incoming parts include storage in the central hub or transshipment for storing in another warehouse. On the outbound side, ordered parts are commissioned by the warehouse personnel and shipped to the customers. A schematic overview of the assumed hub-and-spoke network is shown in Fig. 1.

The problem setting prototype parts logistics faces can be classified as a *sequential planning problem* recurring daily. Upon receipt of a customer order, the customer delivery must be ensured on the same day. Orders can contain multiple parts, which may be stored in different warehouses due to their uniqueness. The decisions of prototype parts logistics now refer to planning transports from warehouses to

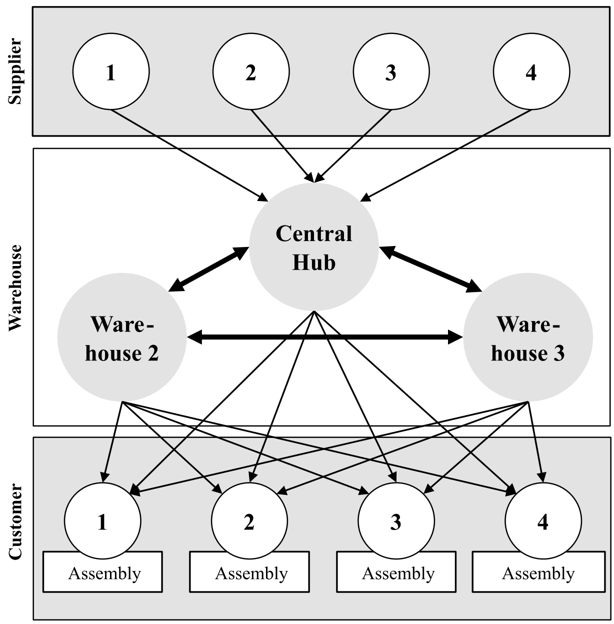



**Fig. 1** Schematic overview of the considered hub-and-spoke network for prototype parts logistics

customers and between warehouses. To fulfill a customer order with parts stored in multiple warehouses, the planner can initiate transports directly from different warehouses to the customer. Alternatively, the ordered parts can be consolidated by initially transshipping them between warehouses and delivering them to the customer in a joint transport. A transport between warehouses, which aims to consolidate parts of a customer order for a subsequently consolidated shipment, is referred to as reactive transshipment. All transports are carried out by external logistics service providers who, upon request at short notice, provide a vehicle with a predefined capacity at an agreed cost rate operating a commissioned transport warehouse-customer or warehouse-warehouse. The manufacturer can fully utilize the vehicle's capacity. Therefore, the manufacturer can additionally decide to transship non-ordered parts between warehouses. Such transshipment of parts between warehouses, which is not based on a customer order but aims to utilize the excess capacity of already commissioned transports, is called proactive transshipment.

The *objective* is to satisfy customer orders at minimal costs. Short-term actions are taken as the demand is revealed only by the orders placed for the given day, and the orders must be served on the same day. Therefore, the planner arranges transport successively for each day so that the customer demand for the day is met with minimal costs. However, for parts not ordered on the current day, the planner may know which customers are more likely to demand these parts in the future. Additionally, the cost rates for commissioning warehouse-warehouse and warehouse-customer transports may be derived based on experience or are already agreed on. Therefore, the planner can approximate the future shipping costs to customers depending on the warehouse where the part is stored. It can thus be advantageous to proactively utilize spare capacity in transports planned for a day to transship non-ordered parts to potentially advantageous warehouses. This is reflected in a secondary objective criterion, which minimizes the approximated future costs of part delivery. However, the proactive transshipment intends not to cause additional transports, thus giving this objective criterion significantly less weight.

### 3.2 Assumptions

The modeling approach is based on further assumptions regarding the parts, the shipments and transshipments, the warehouses, and the approximation of future shipping costs.

- *Parts* are of same size. Customers can only order parts available in one of the warehouses, i.e., no order backlog is permitted.
- The transportation times of *shipments* and *transshipments* are negligible. The transports are commissioned between two locations, i.e., warehouse-warehouse or warehouse-customer paths are traveled. The costs incurred by transports depend on their origin and destination and are known deterministically beforehand. The vehicles available for transport are homogeneous in capacity and cost.
- The *warehouses* maintain limited staff capacity, i.e., handling operations for storing and picking parts are limited per period. Each storing and picking operation

consumes an identic proportion of capacity. Incoming parts must be stored in the period they arrive. The capacity of warehouses for storing parts is limited and known. If incoming parts exceed the capacity of a warehouse, a transshipment of parts to another warehouse is required.

- The planner can *approximate* the potential future costs for shipping parts to customers depending on the warehouse they are stored in.

### 3.3 Notation

This section introduces the sets, parameters, and decision variables of the planning model. The set $N$ contains locations, where each location $i, j \in N$ is either a warehouse ($N^{\text{Warehouses}} \subset N$) or a customer ($N^{\text{Customers}} \subset N$, with $N^{\text{Warehouses}} \cap N^{\text{Customers}} = \emptyset$). Each warehouse has a specific capacity $C_i^{\text{Storing}}$ for storing parts (in units) and a specific capacity $C_i^{\text{Handling}}$ for storing and picking (in units).

The set $P$ represents the prototype parts. As prototype parts $x \in P$ are unique, each part can only be stored in one warehouse $i$. The available inventory of warehouse $i$ is given by binary parameters $B_{xi}$. For the central hub, $B_{xi}$ also reflects the incoming shipments from suppliers. The demand is given by binary parameters $D_{xi}$. Each part can only be ordered once. Vehicles with a given capacity for parts $C^{\text{Vehicles}}$ (in units per vehicle) can be commissioned for transport to the customers or between warehouses. A fixed cost rate $r_{ij}^{\text{T}}$ (in monetary units) is incurred for each transport depending on the traveled path $(i, j)$. The approximated cost rate for the future shipment of part $x$ is reflected in parameters $r_{xi}^{\text{F}}$ depending on the warehouse where the part is stored (in monetary units).

The decision variables $z_{xij} \in \mathbb{B}$ indicate that prototype parts $x$ are shipped or transshipped between two locations $(i, j)$. The decision variables $\boldsymbol{w}_{ij} \in \mathbb{N}_0$ indicate the number of vehicles commissioned for transport between locations $i$ and $j$. Decision variables $\boldsymbol{R}^{\text{T}} \in \mathbb{R}_0^+$ and $\boldsymbol{R}^{\text{F}} \in \mathbb{R}_0^+$ reflect the realized and approximated costs of transports, respectively. The notation is summarized in Table 1.

### 3.4 Mathematical model

This section describes the planning model for prototype parts logistics. The Objective Function (1) minimizes two optimization criteria. The first term, $\boldsymbol{R}^{\text{T}}$, contains the realized costs for transports. The second term, $\boldsymbol{R}^{\text{F}}$, is a secondary objective and contains the approximated future shipping costs. The technical parameter $\varepsilon$ is intended to be chosen sufficiently small so as not to compromise the primary objective. Therefore, the secondary objective anticipates the advantageous transshipment of parts between warehouses utilizing the spare capacity of already commissioned transports.

Constraints (2) ensure the inventory balance. Accordingly, part $x$ can only be transported from warehouse $i$ if it is stored there or transshipped to it from another warehouse $j$. Constraints (3) enforce the fulfillment of customer orders. Therefore, each part $x$ ordered by customer $i$ has to be delivered from either of the warehouses $j$. Constraints (4)–(6) ensure compliance with different types of capacity. To this end, Constraints (4)

**Table 1** Notation: sets and indices, parameters, variables

| | |
|---|---|
| **Sets and indices** | |
| $i, j \in N$ | Set of all locations |
| $N^{\text{Warehouses}}$ | Set of warehouse locations, with $N^{\text{Warehouses}} \subset N$ |
| $N^{\text{Customers}}$ | Set of customer locations, with $N^{\text{Customers}} \subset N$ |
| $x \in P$ | Set of parts |
| **Parameters** | |
| $B_{xi}$ | Stock of part $x$ in warehouse $i$, in units, parameterized in $\mathbb{B}$ |
| $D_{xi}$ | Demand of part $x$ by customer $i$, in units, parameterized in $\mathbb{B}$ |
| $C_i^{\text{Storing}}$ | Capacity of warehouse $i$ for storing parts, in units, parameterized in $\mathbb{N}_0$ |
| $C_i^{\text{Handling}}$ | Capacity of warehouse $i$ for handling parts, in units, parameterized in $\mathbb{N}_0$ |
| $C^{\text{Vehicles}}$ | Capacity of vehicles for transporting parts, in units per vehicle, parameterized in $\mathbb{N}_0$ |
| $r_{ij}^{\text{T}}$ | Cost rate for traveling locations $(i, j)$, in monetary units per vehicle, parameterized in $\mathbb{R}_0^+$ |
| $r_{xi}^{\text{F}}$ | Approximated cost rate for future customer delivery of part $x$ if stored in warehouse $i$, in monetary units, parameterized in $\mathbb{R}_0^+$ |
| $\varepsilon$ | A sufficiently small number, parameterized in (0, 1] |
| **Decision variables** | |
| $z_{xij} \in \mathbb{B}$ | $\begin{cases} 1 & \text{if part } x \text{ is (trans)shipped between locations } (i,j) \\ 0 & \text{otherwise.} \end{cases}$ |
| $\boldsymbol{w}_{ij} \in \mathbb{N}_0$ | Number of vehicles traveling $(i, j)$ |
| $\boldsymbol{R}^{\text{T}} \in \mathbb{R}_0^+$ | Sum of realized shipment and transshipment costs |
| $\boldsymbol{R}^{\text{F}} \in \mathbb{R}_0^+$ | Sum of approximated future shipment and transshipment costs |

address the capacity of warehouses for storing parts. These constraints consider the parts already stored in the warehouse (first term), transshipped to it (second term), and transshipped from it to another location (third term). Constraints (5) refer to the warehouses' capacity of handling operations, i.e., to transfer parts from the goods receipt area into the warehouse or pick parts from the warehouse for subsequent transport. Accordingly, these constraints consider the parts transshipped to warehouse $i$ from another warehouse (first term) and the parts shipped or transshipped from warehouse $i$ to another location. Constraints (6) determine the number of required vehicles $\boldsymbol{w}_{ij}$ traveling paths $(i, j)$ considering the vehicles' capacity and the number of transported parts.

$$\min \boldsymbol{R}^{\text{T}} + \varepsilon \cdot \boldsymbol{R}^{\text{F}} \tag{1}$$

subject to

$$\sum_{j \in N} z_{xij} \leq B_{xi} + \sum_{j \in N^{\text{Warehouses}}} z_{xji} \quad \forall x \in P, i \in N^{\text{Warehouses}} \tag{2}$$

$$D_{xi} = \sum_{j \in N^{\text{Warehouses}}} z_{xji} \quad \forall x \in P, i \in N^{\text{Customers}} \tag{3}$$

$$C_i^{\text{Storing}} \geq \sum_{x \in P} B_{xi} + \sum_{x \in P} \sum_{j \in N^{\text{Warehouses}}} z_{xji} - \sum_{x \in P} \sum_{j \in N} z_{xij} \quad \forall i \in N^{\text{Warehouses}} \tag{4}$$

$$C_i^{\text{Handling}} \geq \sum_{x \in P} \sum_{j \in N^{\text{Warehouses}}} z_{xji} + \sum_{x \in P} \sum_{j \in N} z_{xij} \quad \forall i \in N^{\text{Warehouses}} \tag{5}$$

$$C^{\text{Vehicles}} \geq \frac{1}{\boldsymbol{w}_{ij}} \cdot \sum_{x \in P} z_{xij} \quad \forall i \in N^{\text{Warehouses}}, j \in N \tag{6}$$

Constraints (7)–(8) compute the values of the optimization criteria. To this end, Constraint (7) calculates the realized costs for transports $\boldsymbol{R}^{\text{T}}$ considering the number of traveling vehicles and the associated cost rate per vehicle $r_{ij}^{\text{T}}$ for the paths $(i, j)$. Constraint (8) approximates the potential future shipping costs $\boldsymbol{R}^{\text{F}}$ considering the approximated cost rate for future customer delivery of part $x$ when stored in warehouse $i$ (i.e., $r_{xi}^{\text{F}}$) and the warehouse the part is stored in. Therefore, this term incentivizes the transshipment of parts to warehouses with lower approximated future shipping costs.

$$\boldsymbol{R}^{\text{T}} = \sum_{i \in N^{\text{Warehouses}}} \sum_{j \in N} r_{ij}^{\text{T}} \cdot \boldsymbol{w}_{ij} \tag{7}$$

$$\boldsymbol{R}^{\text{F}} = \sum_{x \in P} \sum_{i \in N^{\text{Warehouses}}} r_{xi}^{\text{F}} \cdot \left( B_{xi} + \sum_{j \in N^{\text{Warehouses}}} z_{xji} - \sum_{j \in N} z_{xij} \right) \tag{8}$$

$$\boldsymbol{w}_{ij} \in \mathbb{N}_0 \quad \forall i \in N^{\text{Warehouses}}, j \in N \tag{9}$$

$$z_{xij} \in \mathbb{B} \quad \forall x \in P, i \in N^{\text{Warehouses}}, j \in N \tag{10}$$

$$\boldsymbol{R}^{\text{T}} \in \mathbb{R}_0^+ \tag{11}$$

$$\boldsymbol{R}^{\text{F}} \in \mathbb{R}_0^+ \tag{12}$$

Constraints (9)–(12) define the range of the decision variables. The formulation can be classified as a mixed-integer linear programming model. The model is static and thus parameterized and applied periodically. This accommodates the short-term nature of the planning situation and the availability of demand information. The process of sequential planning is schematically illustrated in Fig. 2.

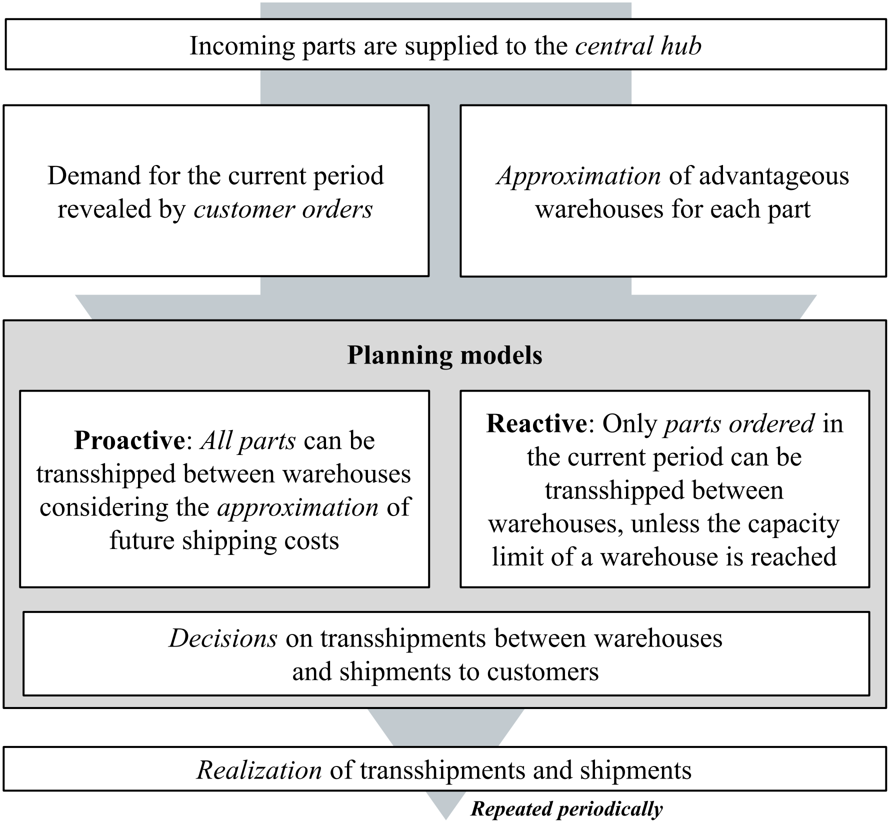



**Fig. 2** Process of sequential planning in the considered problem

## 4 Numerical study

This section introduces a numerical study and its results to evaluate the effectiveness of the proposed approach. Section 4.1 presents the study's design. Section 4.2 introduces the computational setup of the numerical study and the reactive model serving as a benchmark for comparison. The numerical results are presented in Sect. 4.3. Section 4.4 reports computational results.

### 4.1 Study design and data

This section introduces the design of the numerical study and the used data. To this end, the general assumptions on the considered logistics network and the scenarios are presented.

**Warehouses and customers** The study considers a hub-and-spoke network with three warehouses storing 1,000 parts. Warehouse 1 serves as a central hub for incoming shipments. Initially, 200, 500, and 300 parts are randomly allocated to Warehouse 1, 2, and 3, respectively (i.e., $\sum_{x \in P} B_{xi}$ for each warehouse $i$). The handling capacity of the warehouses for storing and picking operations is assumed to be similar to the initial inventory. The capacity of the warehouses for storing parts $C_i^{\text{Storing}}$ is computed based on the initial stock and an exogenously parameterized warehouse utilization. The warehouse utilization is varied among {60%, 80%, 95%} to create different scenarios that evaluate the impact of flexibility in the operation of the logistics network. An exemplary parameterization of the network for a warehouse utilization of 80% is given in Table 2.

10 different customers are considered. The warehouses and customers are spatially dispersed. A visualization of their locations, the distances between them, and the resulting cost rates $r_{ij}^{\text{T}}$ for one vehicle traveling $(i, j)$ are provided in Fig. 7, Tables 7, and 8 in Appendix A. The capacity of vehicles $C^{\text{Vehicles}}$ is limited to 50 parts per vehicle.

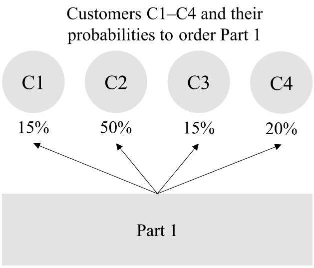
**Planning horizon and inventory turnover** Planning is conducted periodically using the developed planning model in a sequential planning approach. The experiments simulate the repeated application of the planning model to assess the advantages of a proactive approach to prototype parts logistics. Therefore, a planning horizon of 20 consecutive periods (i.e., days) is considered, representing a transient behavior of the network in earlier periods and allowing the observation of the system in a potential equilibrium.

Furthermore, in the numerical experiments, the inventory turnover varies among different scenarios. To this end, {1%, 5%, 10%} of the initial 1000 parts are ordered every period. The ordered parts are randomly chosen based on a uniform distribution considering all parts in inventory. To keep the average utilization of the warehouses constant during the planning horizon, the same number of parts are replenished into the network as are ordered by customers.

**Order generation and approximation of future shipping costs** For generating customer orders, it must be considered that the customer for each part is unknown before the order arrives. To achieve this, probabilities are generated for each part-customer combination, representing the likelihood of that customer ordering that specific part. A beta distribution is used to assign probabilities to customers. The probabilities resulting from the beta distribution are randomly assigned to the ten customers for each part. The used parameters and the resulting probabilities are described and summarized in Table 9 of Appendix A. The beta distribution is chosen based on observations from practice, indicating that planners can distinguish between more probable and less probable customers for a part.

**Table 2** Exemplary parameterization of the warehouses for a warehouse utilization of 80%

| Warehouse | Initial inventory [units] | Handling capacity [units] | Storing capacity [units] |
|---|---|---|---|
| 1 | 200 | 200 | 250 |
| 2 | 500 | 500 | 625 |
| 3 | 300 | 300 | 375 |




| Customers | W1 | W2 | W3 |
|---|---|---|---|
| Customer C1 | 50 · 0.15 | 150 · 0.15 | 300 · 0.15 |
| Customer C2 | 100 · 0.50 | 100 · 0.50 | 200 · 0.50 |
| Customer C3 | 200 · 0.15 | 100 · 0.15 | 100 · 0.15 |
| Customer C4 | 300 · 0.20 | 150 · 0.20 | 50 · 0.20 |
| Approximation of future shipment costs | 147.5 | 117.5 | 170.0 |

**Fig. 3** Example for approximating future shipment costs $r^{F}_{xi}$. The probabilities of customers $i$ (here: C1–C4) to order part $x$ (here: Part 1) are multiplied by the transport costs between customers and warehouses (here: W1–W3)

**Table 3** Scenario parameters and identifiers

| Inventory turnover | Warehouse utilization | Scenario |
|---|---|---|
| 1% | 60% | $C_{1\%,60\%}$ |
| | 80% | $C_{1\%,80\%}$ |
| | 95% | $C_{1\%,95\%}$ |
| 5% | 60% | $C_{5\%,60\%}$ |
| | 80% | $C_{5\%,80\%}$ |
| | 95% | $C_{5\%,95\%}$ |
| 10% | 60% | $C_{10\%,60\%}$ |
| | 80% | $C_{10\%,80\%}$ |
| | 95% | $C_{10\%,95\%}$ |

In the proactive planning model, an approximation of future shipping costs of parts is considered depending on the warehouse a part is stored in, i.e., parameter $r^{F}_{xi}$. The same probabilities previously used for generating customer orders are utilized for this approximation. Thus, it is assumed that the planner can perfectly predict the probabilities of customer orders of parts. Furthermore, the approximation is based on the known cost rates of transports between two locations $r^{T}_{ij}$. An exemplary visualization of the approximation of future shipping costs is given in Fig. 3. The approximation serves to identify potentially beneficial warehouses for each part as a basis for decisions on a proactive transshipment of parts between warehouses.

**Summary of scenarios and instance generation** The study considers nine scenarios varying the inventory turnover and warehouse utilization. For each of these scenarios, 20 instances are generated. Each instance randomly assigns the probabilities of customers to order parts. In the sequential application of the model, the ordered parts are revealed successively for each period and serve as deterministic input data. The considered scenarios and their identifiers are summarized in Table 3.

### 4.2 Approach for comparison and computational setup

The proactive model is compared to a reactive model. To this end, the model formulation introduced previously is adapted. The reactive model consists of the Objective Function (13) and Constraints (2)–(7) and (9)–(11). In contrast to the proactive model, only two situations allow the reactive model to transship parts between warehouses. First, this holds for parts ordered by a customer in the current period to facilitate consolidated shipments to customers. Second, parts may be transshipped to an alternative warehouse when the capacity of a warehouse is otherwise exceeded. Accordingly, the reactive model does not use the approximation of future shipping costs.

$$\min \boldsymbol{R}^{\mathrm{T}} \tag{13}$$

Both models are implemented in Python 3.10.9 and solved using Gurobi 10.0.1 on machines with 64 GB RAM and eight Intel Xenon Platinum 8180 CPU threads at 2.5 GHz.

### 4.3 Numerical results

This section presents the results of the numerical experiments comparing the proactive and reactive planning models. To this end, the results refer to the costs and transports. All instances of all scenarios were solved optimally.

The results on the costs of proactive and reactive planning models are summarized in Table 4 reporting the cumulative costs over the considered planning horizon of 20 periods. Generally, costs for both models increase with higher warehouse

**Table 4** Cumulative costs of proactive and reactive planning models over 20 periods

| **Scenario** | **Reactive** | **Proactive** | | |
|---|---|---|---|---|
| | Avg. (SD) [EUR] | Avg. (SD) [EUR] | Avg. (SD) rel. improvement [%] | best/worst rel. improvement [%] |
| $C_{1\%,60\%}$ | 24,007 (728) | 20,635 (835) | 14.0 (2.6) | 19.0/8.6 |
| $C_{1\%,80\%}$ | 24,245 (660) | 20,956 (849) | 13.6 (2.8) | 17.3/6.6 |
| $C_{1\%,95\%}$ | 24,675 (671) | 21,798 (786) | 11.6 (2.8) | 15.9/5.1 |
| $C_{5\%,60\%}$ | 35,348 (252) | 32,007 (238) | 9.4 (0.6) | 10.3/8.1 |
| $C_{5\%,80\%}$ | 35,919 (212) | 32,125 (333) | 10.6 (0.8) | 11.9/8.7 |
| $C_{5\%,95\%}$ | 36,176 (193) | 33,005 (301) | 8.8 (0.5) | 10.0/7.9 |
| $C_{10\%,60\%}$ | 35,879 (397) | 32,560 (196) | 9.2 (1.1) | 11.0/7.0 |
| $C_{10\%,80\%}$ | 37,123 (120) | 33,923 (458) | 8.6 (1.3) | 10.8/5.9 |
| $C_{10\%,95\%}$ | 37,567 (28) | 34,312 (289) | 8.7 (0.8) | 10.0/7.4 |

*Legend*: Each scenario contains 20 instances. Average (Avg.) and standard deviation (SD) of costs in Euro (EUR), relative (rel.) improvement of the proactive model compared to the reactive model in %, and best and worst relative improvement in %

utilization (ceteris paribus). This can be explained by the increasing need to transfer parts to another warehouse due to insufficient capacity at the central hub. Furthermore, costs increase with an increase in inventory turnover (ceteris paribus) for both models. The explanation for this is intuitive, as the increased number of ordered parts very likely results in an increased number of required transports and, consequently, costs. When comparing the results of the planning models for the individual scenarios, the proactive model yields lower costs for each instance. The achievable cost reduction ranges from 5.1−19.0%. Therefore, the proactive planning model is advantageous in terms of costs.

Figure 4 compares the average costs per period for reactive and proactive approaches considering the 20 instances of Scenario $C_{5\%,80\%}$. The costs per period vary only slightly in the reactive approach. In the proactive approach, the costs are identical to those in the reactive approach in the first two periods. Subsequently, they decrease until they stabilize at a lower level. Therefore, the benefits of the proactive approach emerge over time. In the early periods, the proactive and reactive approaches consider the same initial allocation of parts to warehouses and are obliged to deliver the ordered parts to the customers. Consequently, the proactive approach must initially carry out the same transports as the reactive approach and cannot reduce costs in the early periods. However, the transports in the proactive approach include not only the parts explicitly ordered by customers or those necessarily transferred due to insufficient capacity at the central hub but also additional parts anticipating advantageous warehouse locations. In the subsequent periods, the benefits of proactively transshipping parts between warehouses can be realized, resulting in continued cost reductions when using the proactive approach.

These findings are supported when evaluating the number of transshipped parts. The transshipment of parts can, generally, occur for three reasons. Firstly, a non-ordered part can be proactively transshipped if storing it in a different warehouse is considered advantageous (proactive approach only). Secondly, currently ordered parts may be transshipped between warehouses to consolidate orders and allow for an advantageous shipment to the customer (proactive and reactive approaches).

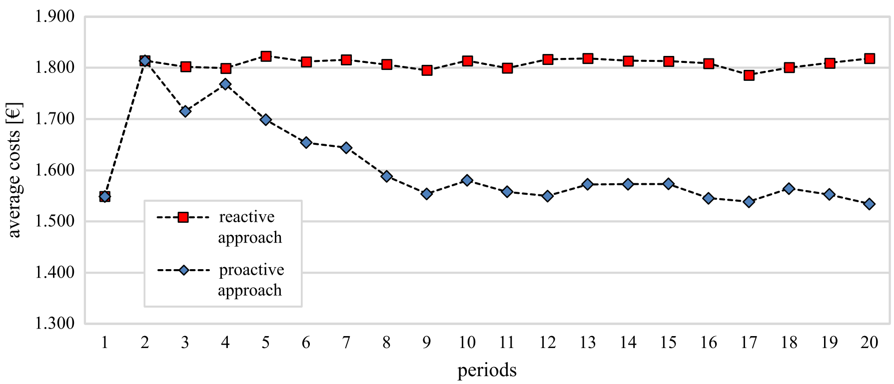



**Fig. 4** Visualization of the average costs per period for reactive and proactive approaches considering the 20 instances of Scenario $C_{5\%,80\%}$

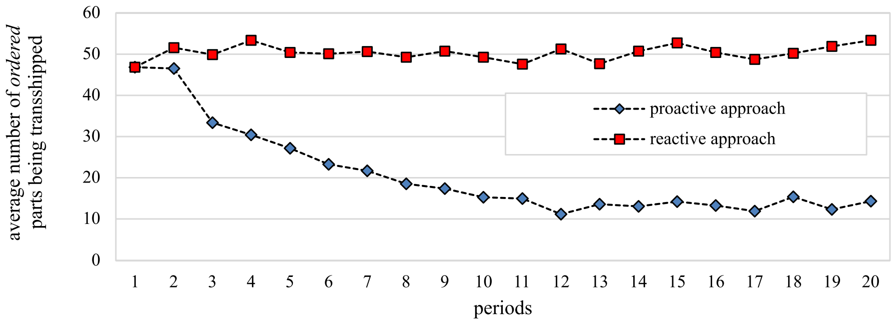



**Fig. 5** Visualization of the average number of *ordered* parts being transshipped per period for reactive and proactive approaches considering the 20 instances of Scenario $C_{5\%,80\%}$

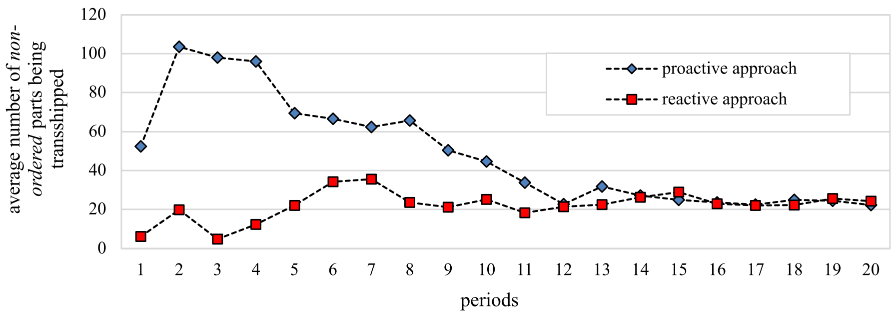



**Fig. 6** Visualization of the average number of *non-ordered* parts being transshipped per period for reactive and proactive approaches considering the 20 instances of Scenario $C_{5\%,80\%}$

Thirdly, transshipping parts may become necessary if the capacity of a warehouse is otherwise exceeded (proactive and reactive approaches). Figure 5 visualizes the average number of *ordered* parts being transshipped per period for reactive and proactive approaches considering the 20 instances of Scenario $C_{5\%,80\%}$. The number of ordered parts being transshipped using the reactive approach remains relatively stable. The transshipment is caused by a consolidation of parts before their customer shipment. In the proactive approach, the number of ordered parts being transshipped decreases over time. This is due to the option of proactively transshipping non-ordered parts using the proactive approach. Figure 6 visualizes the number of non-ordered transshipped parts. Accordingly, the proactive approach transships a significantly increased number of non-ordered parts in the earlier periods. This is done by utilizing the remaining capacities of necessary transports, thus incurring no additional costs. After this initial phase, both approaches transship approximately the same number of non-ordered parts per period. However, the proactive approach enables the shipment of customer orders at lower costs. Therefore, the proactive approach remains advantageous beyond the initial phase, as it continuously selects advantageous parts for transshipment to the associated beneficial warehouses, considering the approximation of future shipping costs.

**Table 5** Operational indicators of proactive and reactive planning models

| Scenario | Reactive | | | Proactive | | |
|---|---|---|---|---|---|---|
| | Avg. (SD) transports [x] | Avg. (SD) utilization transports [%] | Avg. (SD) transshipped parts [x] | Avg. (SD) transports [x] | Avg. (SD) utilization transports [%] | Avg. (SD) transshipped parts [x] |
| $C_{1\%,60\%}$ | 34.6 (2.7) | 34.6 (4.9) | 330.7 (81.6) | 17.4 (1.7) | 82.8 (5.7) | 714.9 (51.5) |
| $C_{1\%,80\%}$ | 35.8 (2.9) | 35.8 (4.5) | 374.9 (77.1) | 19.6 (2.2) | 71.6 (7.4) | 694.4 (43.2) |
| $C_{1\%,95\%}$ | 39.7 (3.0) | 39.7 (4.3) | 426.4 (93.1) | 25.6 (2.2) | 52.4 (6.0) | 664.5 (56.7) |
| $C_{5\%,60\%}$ | 57.0 (1.1) | 57.0 (2.9) | 1113.2 (80.3) | 39.5 (1.4) | 70.0 (2.5) | 1382.2 (41.0) |
| $C_{5\%,80\%}$ | 58.3 (0.7) | 58.3 (2.5) | 1446.0 (74.7) | 40.2 (1.5) | 68.9 (2.8) | 1382.3 (34.3) |
| $C_{5\%,95\%}$ | 59.9 (0.3) | 59.9 (2.2) | 1690.9 (64.5) | 44.8 (1.8) | 60.7 (2.6) | 1358.9 (43.0) |
| $C_{10\%,60\%}$ | 60.0 (0.9) | 60.0 (2.1) | 1847.4 (56.5) | 43.9 (0.7) | 94.9 (2.3) | 2079.7 (47.8) |
| $C_{10\%,80\%}$ | 75.4 (1.7) | 75.4 (1.2) | 2331.9 (39.8) | 50.4 (2.0) | 79.5 (3.6) | 1998.4 (56.7) |
| $C_{10\%,95\%}$ | 79.8 (0.5) | 79.8 (0.7) | 2579.2 (27.4) | 55.3 (1.5) | 76.3 (2.1) | 2107.3 (55.6) |

*Legend*: Each scenario contains 20 instances. Average (Avg.) and standard deviation (SD) of commissioned transports in count x, Avg. and SD of the utilization of transports in %, and Avg. and SD of transshipped parts in count x

The results on the number of transshipped parts, the number of transports, and their utilization are summarized in Table 5 for all considered scenarios. The proactive approach consistently requires significantly fewer transports than the reactive approach, effectively avoiding their associated costs.

## 4.4 Computational results

In the previous experiments, networks with 1,000 parts were evaluated. To assess the suitability of the proposed approach for larger settings, additional experiments are conducted for instances with 10,000 and 50,000 parts. Therefore, ten instances of each size are compared regarding required computational times for Scenario $C_{5\%,80\%}$.

**Table 6** Computational times of proactive and reactive planning models for instances of scenario $C_{5\%,80\%}$

| Number of parts | Reactive | Proactive |
|---|---|---|
| | Avg. (SD) CPU [s] | Avg. (SD) CPU [s] |
| 1,000 | 0.65 (0.1) | 1.0 (0.3) |
| 10,000 | 14.0 (3.2) | 28.9 (18.3) |
| 50,000 | 176.4 (54.4) | 663.9 (400.0) |

*Legend*: Each line contains 10 instances. Average (Avg.) and standard deviation (SD) of computational times (CPU) seconds (s)

Table 6 summarizes the computational results. Generally, the computational time increases significantly with the considered number of parts. However, for instances of a practical size, the computational time remains reasonable.

## 5 Discussion and outlook

This article develops a new approach to parts logistics considering proactive transshipments between multiple warehouses. The approach is motivated by prototype parts logistics in the automotive industry and thus incorporates the uniqueness of the considered parts. A planning model is developed based on mixed-integer linear programming. The proactive planning model is compared to an alternative (reactive) one. Extensive numerical experiments demonstrate that by anticipating future customers for the unique parts, a reduction in transportation costs of 5–19% can be achieved compared to the alternative approach. The proactive approach utilizes the remaining capacities in necessary transports between warehouses to transship parts toward a potentially advantageous location.

This is the first approach explicitly considering the parts' uniqueness and an approximation of future shipment costs in transshipment models as motivated by the application in prototype parts logistics. The approach and results were discussed with a German car manufacturer. In the current practice of prototype parts logistics in the automotive industry, the reactive approach is used and serves as the benchmark in this article. Consequently, in practice, if there is a need to transship parts between warehouses, no parts other than the required ones are considered. However, anticipating future customers for individual parts is possible based on the planners' experience. Therefore, managers in practice should consider leveraging this knowledge to contribute to more efficient parts logistics. The achievable savings are largest in applications with low inventory turnover. Therefore, applications in prototype parts logistics are generally well-suited.

Although the present article highlights the potential of a proactive approach to planning transshipments between warehouses, some assumptions limit the general applicability of the findings. These include assuming that parts have the same volume, so no conclusions can be drawn regarding the advantage of transshipping based on the size or mass of parts. Additionally, future work needs to expand the assumption of the underlying probability distribution of future customers made in the numerical experiments. This implies that planners can predict this distribution perfectly, which might not be accurate in practice. However, additional preliminary experiments suggest that the quality of the forecast does not have a decisive influence on the advantage of proactive planning. Instead, incorporating the approximation into planning to facilitate a proactive approach is generally advantageous compared to neglecting it in reactive planning. Furthermore, the present study focuses on a hub-and-spoke network, where newly arriving parts are initially assigned to the central hub. Investigating alternative networks promises additional insights. Additionally, varying the technical parameter $\varepsilon$ can generate further insights. In the article at hand, it was chosen sufficiently small to emphasize the sequential (day-by-day) nature of the considered planning problem. Future studies should address these aspects. Further potential lies in developing machine learning approaches for predicting future customers. Challenges arise from the uniqueness of the parts considered in prototype logistics, which could make learning from historical data more difficult.

## Appendix A Considered logistics network

The locations of warehouses and customers are visualized in Fig. 7. The distances between the locations are calculated using the Euclidean norm. The cost rates are derived based on the distances, considering a rate of 0.96 EUR/km. The distances between locations are summarized in Table 7. The associated costs for one vehicle traveling the paths are reported in Table 8. The probabilities of customers to order parts are generated using a beta distribution with the parameters $\alpha = 10$ and $\beta = 1$ and are provided in Table 9. Please note that the ten probabilities are randomly allocated to the ten customers.

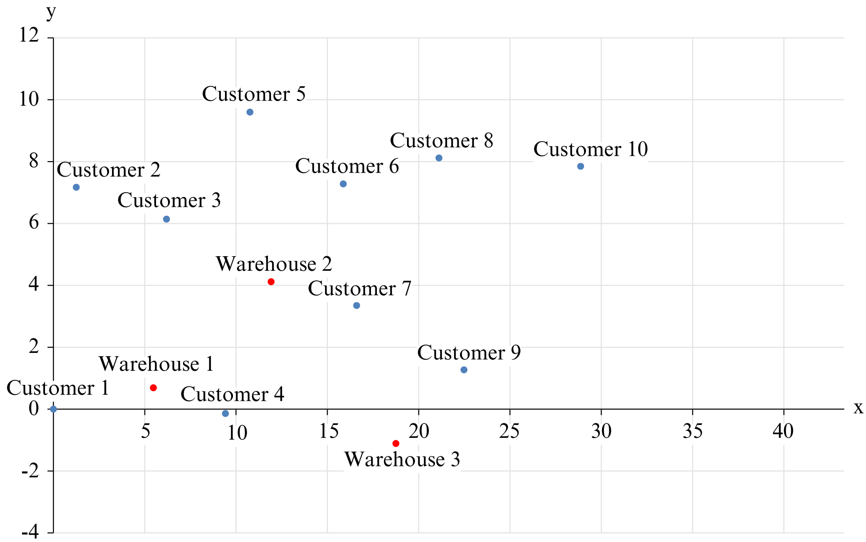



**Fig. 7** Visual representation of warehouses and customers

**Table 7** Distances between locations, from warehouses (W1-W3), to warehouses and customers (C1-C10), in km

| To | W1 | W2 | W3 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From W1 | 0 | 146 | 268 | 110 | 155 | 110 | 81 | 207 | 246 | 229 | 346 | 340 | 489 |
| From W2 | 146 | 0 | 172 | 252 | 222 | 122 | 99 | 112 | 101 | 95 | 200 | 219 | 347 |
| From W3 | 268 | 172 | 0 | 376 | 387 | 290 | 187 | 267 | 177 | 99 | 191 | 89 | 270 |

**Table 8** Costs between locations, from warehouses (W1-W3), to warehouses and customers (C1-C10), in EUR/vehicle

| To | W1 | W2 | W3 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From W1 | 0 | 140 | 257 | 106 | 148 | 106 | 77 | 199 | 236 | 220 | 332 | 327 | 470 |
| From W2 | 140 | 0 | 165 | 242 | 213 | 117 | 95 | 108 | 97 | 91 | 192 | 210 | 333 |
| From W3 | 257 | 165 | 0 | 361 | 372 | 278 | 180 | 256 | 170 | 95 | 183 | 85 | 260 |

**Table 9** Probabilities used to generate customer orders

| Probability # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | $\sum$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Probability [%] | 0.00 | 0.00 | 0.00 | 0.01 | 0.09 | 0.51 | 2.22 | 7.91 | 24.13 | 65.13 | 100.00 |

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**Data Availibility Statement** The data that support the findings of this study are available from the corresponding author upon request.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.



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