Int. J. Production Economics 276 (2024) 109349

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Integrated cross-dock location and supply mode planning in retail networks☆

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ARTICLE INFO

Keywords:
Supply chain design
Location planning
Transportation
Integer optimization
Grocery retailing
Case study

ABSTRACT

This paper considers the problem of integrating cross-docks (CDs) into a given retail supply network with the aim of minimizing related logistics costs. These comprise transportation costs, costs for setting up and operating CDs, inventory holding and purchasing costs. We present a novel mixed integer program (MIP) for optimizing the number and locations of CDs within the supply network as well as the selection of flow type (cross-docking or direct-to-warehouse shipping) and the associated delivery pattern tailored to a specific supplier. A numerical study shows that the original problem is difficult to solve for real-sized instances using a standard MIP solver. We therefore develop a hierarchical decomposition approach that achieves cost-efficient results compared to heuristic approaches, which assume linear transportation costs. In order to demonstrate the model's applicability to real-life instances and to gain further practical insights we conducted a case study using data from a major European retail company. In this study we found that more than 6% of related logistics costs can be saved by setting up CDs within the supply network. We also show that existing approaches in literature may lead to unfavorable results in certain settings due to an overestimation of transportation bundling effects. Extensive numerical experiments and scenario analyses provide further managerial insights into the problem characteristics.

1. Introduction

A large-scale retailer's supply and distribution network, such as in grocery retailing, is generally characterized by a vast product assortment sourced from a plurality of suppliers, stored in retailer's warehouses and distributed to final customers and to the outlets operated by the retail company (Fernie et al., 2010; Kuhn and Sternbeck, 2013). The overall product flow – from a retail perspective – can therefore typically be divided into a two-stage transportation network (Klose and Drexl, 2005). The distribution aspect of this network, i.e., the link between warehouses and outlets, has been extensively studied in literature (Holzapfel et al., 2016; Taube and Minner, 2018; Hübner and Ostermeier, 2019; Frank et al., 2021; Kuhn et al., 2021). However, the link between suppliers and warehouses, i.e., the supply network of a retailer, has so far only been considered to a very limited extent, even though this link is of high practical relevance (Rode, 2017) and offers several possibilities for optimization and enhancement. This is primarily due to rising cost pressure and increasing product variety from an increasing number of suppliers. The marketing reasons for this development are often the introduction of additional product ranges and an accompanying more extensive store-specific differentiation of the products listed. The corresponding greater fragmentation of inbound shipment flows into retailer's warehouses requires greater bundling in order to achieve a better truck utilization rate for cost and CO_2 reasons. Practitioners in retail logistics report that the reduction of ramp dockings at the retailer's warehouses is one additional driver for upstream bundling concepts as the truck gates at the warehouses are limited and often becoming a bottleneck resource in retail supply networks (Rode, 2023). In general, retail companies are increasingly taking control of the flow of goods from the industrial partner to the shelf (Fernie et al., 2010). While efforts were initially more focused on the section from the warehouse to the store, the vertically integrated view is increasingly being extended to the transport section from the supplier to the retailer's warehouses.

In a common setting, the suppliers deliver their products to the retailer's warehouses via direct transport connections. This occurs in full truck load (FTL) shipments if the supplier delivers products in large volumes or a noticeable number of different products that regularly fill an entire truck. A considerable number of suppliers however supply

☆ We declare that one author (Tobias Potoczki) received funding of a doctoral scholarship from the Erich–Kellerhals–Stiftung (Foundation), Ingolstadt, Germany. No additional funding was received for conducting this study.

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https://doi.org/10.1016/j.ijpe.2024.109349
Received 17 January 2024; Received in revised form 3 June 2024; Accepted 24 July 2024
Available online 2 August 2024

products in low or moderate demand that do not fill up entire trucks to the different warehouses per order. These deliveries then often result in less than truck load (LTL) shipments, or they are aggregated over a longer time horizon with the resulting effect that storage space in the supplier's and retailer's warehouses is occupied to a larger extent. Substantial cost savings are therefore assumed, if the deliveries of medium- or low-volume suppliers can be coordinated and bundled into joint delivery tours (Kreng and Chen, 2008; Cortes and Suzuki, 2020). These bundling effects and corresponding cost savings can be realized with the help of cross-docks (CDs) that are set up at a comparatively early stage in the retail supply chain Vogt (2010), Hosseini et al. (2014).

Given the particular circumstances of a retail company – especially the multitude and disparity of suppliers – the decision on how to integrate CDs into an existing logistics network, however, poses a considerable challenge. This is especially true, since the possibility and extent of shipment consolidation within a CD depends on the sizes and frequencies of the deliveries of each supplier. The decision to set up a CD therefore requires that the delivery frequencies are determined simultaneously. Within this context, it also has to be decided, whether a supplier should deliver directly to the retailer's warehouses or via one of the possibly new established CDs of the supply network. The joint decision on delivery frequency and delivery path then constitutes the supply mode per supplier.

In this paper we address these interrelated decisions. The decision problem considered specifies the number and locations of CDs to be set up, decides on one of two alternative flow types for each supplier, i.e., direct-to-warehouse shipping or shipping via one of the CDs, and determines the frequencies and delivery days within a given planning cycle. Comparable decision problems have been studied extensively in the literature (Belle et al., 2012). However, the available approaches mostly focus on the link between suppliers and customers and do not consider the special features of a retail supply network.

We introduce a decision support model that configures the supply network of a retail company while taking retail specific-cost factors and restrictions into consideration. We propose a hierarchical decomposition approach for solving the decision problem for real-life instances. To demonstrate the applicability and benefits of the solution approach in retail practice, we conduct an extensive case study using data from a major European retail company. The study shows a considerable reduction of logistics costs when setting up and operating CDs within the supply network of that company. In addition, we perform diverse numerical experiments and scenario analyses that provide further managerial insights into the problem considered.

Our paper is structured as follows. Section 2 introduces the general problem setting, describes relevant structures, processes, and cost factors for implementing a cross-docking solution within a retailer's supply network. Section 3 then reviews the literature in the field of supply network design with cross-docking related decisions. Section 4 develops the integrative decision support model, and Section 5 describes the solution approach suggested. Section 6 presents numerical results from the real-life case study and further scenario analyses performed. Section 7 summarizes the findings and refers to future research opportunities.

2. Problem setting

Our study focuses on large-scale retail companies that have the general option to integrate CDs within their supply networks. In this section we characterize the typical logistics network design in retailing and the decision problem considered in our study.

2.1. Retail logistics network

Most large retail companies have established their own warehouses, where products are intermediately stored after the receipt from suppliers before being further transported downstream to stores or directly to end customers (Kuhn and Sternbeck, 2013). Such retail warehouses decouple industry supply from store/consumer demand and therefore make it possible to cushion short-term demand fluctuations and achieve bundling opportunities in transportation both in the inflow and in downstream shipments. Retail companies usually operate central warehouses and/or multiple regional as well as local warehouses with identical product mixes, multiple heterogeneous warehouses, or a mix between the latter two (Kuhn and Sternbeck, 2013; Holzapfel et al., 2018, 2023). In this paper, we build on a given warehouse network structure and take the number and the specific locations with the assigned products and stores as given. Accordingly, the average demand quantities per product and warehouse can be derived from this and are not part of the decision in our approach. The overall product flow – from a retail perspective – can therefore typically be divided into a two-stage transportation network (Klose and Drexl, 2005) where product flows from suppliers to warehouses can be classified as "supply transportation" and product flows from warehouses to points of sale or final customers as "distribution transportation." Equivalently, we denote the entire network from suppliers to the warehouses as "supply network" and the entire network from the warehouses to stores and/or final customers as "distribution network." Both networks could also include CDs that are used as transshipment points between the respective sources and sinks of both networks. The focus of our study is the supply network of a retail company.

Supply and distribution networks in retail reveal structural differences that need to be considered when developing modeling and solution approaches. Upstream flows typically involve many sources (suppliers) and few destinations (warehouses), resulting in a converging structure where consolidation effects are significant. In contrast, downstream flows are characterized by few sources (warehouses) and many destinations (stores), creating a divergent structure. The warehouses act as logistical buffers, allowing the retail company to focus on cost efficiency upstream and on logistics service downstream. For example, there is more tolerance for lead times and quantity deviations in deliveries to warehouses, where products are stored temporarily. However, lead times and delivery quantities are crucial for store deliveries to prevent out-of-stock situations and manage limited storage space at stores. These differences necessitate tailored modeling approaches that significantly impact the solution strategy.

2.2. Cross-docking in retail supply networks

The core of our study is the decision-supportive evaluation of the introduction of CDs in the supply network of a retail company. We define CD operations as the activity of receiving goods (CD-inbound) and transferring them without putting them into storage and without any manipulation onto the outgoing vehicles (CD-outbound). The CDs' task is then to consolidate medium- and low-volume supplier deliveries into FTL deliveries. We therefore generally assume that the retailer organizes entire trucks on the transport connection between CDs and warehouses.

On the one hand these CDs take over the "inter-supplier" function that bundles multiple deliveries of suppliers to one or several warehouses. These CDs are mainly located near to several suppliers. On the other hand CDs also take over the "intra-supplier" function to bundle multiple deliveries of a single supplier to different warehouses into a main leg and splitting it up in a so-called "break-bulk" CD (Apte and Viswanathan, 2000). These CDs are predominantly located near the respective target warehouses. In the latter case we assume that these deliveries are combined with inbound deliveries of other suppliers so that the onward carriage can mostly be performed in FTL mode. This illustrates that cross-docking also allows for more frequent deliveries in smaller quantities. This again reduces the average inventory levels at suppliers and in the retailer's warehouses. An integration of CDs into a retailer's supply network must therefore also consider delivery planning between suppliers and the retailer's warehouses.

2.3. Decision problem

Decisions. Four intertwined decisions have to be taken into consideration when retail companies plan to integrate CDs into their supply networks.

First, the number and locations of CDs have to be set. The specific locations selected for each of the CDs affect the possible savings in transportation costs. The candidate sites of CDs can be new facilities that have to be set up and/or already existing facilities of the retailer, e.g., warehouses or other logistics facilities belonging to the retail company, such as transshipment points of the distribution network.

Second, the possible delivery options have to be selected for each supplier. In general, the retailer could offer multiple delivery options to the supplier, i.e., deliveries direct to the warehouse, deliveries via one or more CDs, or a combination of both, depending on the particular products delivered and the associated warehouse locations (Aboueee-Mehrizi et al., 2014; Azizi and Hu, 2020). In our study we limit the possible delivery options for each supplier by two mutually exclusive delivery options that are valid for all products delivered by this supplier, i.e., direct-to-warehouse delivery or delivery via one of the CDs.

Third, the delivery frequency and the associated delivery quantity have to be chosen for every supplier, which ultimately determines the transportation lot size and the consolidation potential with other suppliers serving the same destination(s).

Finally, fourth, economically efficient means of transportation have to be selected depending on the delivery frequency, i.e., shipping options, e.g., FTL billing, (billing of the entire truck or an integer multiple of the truck size, respectively) vs. LTL billing (billing of individual pallets in general cargo tariffs).

Decision-relevant costs. Setting up CDs within the supply network affects several cost components of a retail company. CDs should reduce transportation and possibly inventory holding costs, however, it involves some additional efforts and expenditures. These for example are increased delivery times and travel distances, additional handling effort, and efforts related to setting up and operating the CDs.

The main leverage of reducing overall costs through the implementation of cross-docking lies in the gains of efficiency with regard to *transportation*. CDs that are located close to several suppliers enable the consolidation of small shipments into well utilized truck loads (source area bundling). This means transportation costs per unit decrease. The same applies for a single supplier that provides a total shipping volume that is large enough to fill a full truck load, but has to split up the quantities into several small deliveries, each with a distinct warehouse destination. Locating a CD close to the destination warehouses' area enables the supplier to cover most of the travel distance with well-utilized truck loads, while postponing the splitting point (destination area bundling).

Fixed and variable costs arise for each CD that has to be set up either for acquiring land and building the facility or for renting or providing cross-docking space in an existing facility, e.g., from a third party logistics provider or in a company owned facility. Besides those fixed costs, variable costs arise depending on the number of operations and volumes to be handled within the specific CDs (administrative costs per truck arrival and departure, and pallet-based costs for moving the shipping units through the CD facility).

Warehousing and inventory costs are essentially positively impacted by the introduction of cross-docking. Since cross-docking enables the delivery of smaller lot sizes via efficient bundling, a reduction in inventory costs at the warehouses can be realized (capital tie-up and space costs). Another positive effect of inbound cross-docking on warehousing is the reduction of the number of incoming trucks. This smaller number of ramp dockings reduces the overall fixed costs of processing incoming shipments, e.g., paperwork and setup costs for receiving a truck load.

Like the inventory costs, *purchasing costs or conditions* are usually based on the negotiated order quantities per order between the supplier and the receiving location of the retail company. If a supplier benefits from larger batch sizes being taken over from the retail company due to lower setup and handling costs, the supplier might pass some of these cost savings to the retailer. We regularly find this situation in the large-scale grocery setting. For other suppliers or in other branches, however, the opposite might be the case. Large batches may lead to higher inventory levels at the supplier's facility so that purchasing conditions may increase for longer delivery intervals and larger lot sizes. In summary, purchasing costs or conditions may vary with the delivery frequencies selected. However, the direction and impact of this effect depends on the respective supplier's situation.

Restrictions. The scope for decision-making is limited regarding several constraints in retail practice. Supply deliveries from suppliers to retail warehouses via CD instead of direct transports are practically inevitably attached with increased lead times as the route from the supplier to the warehouse via CD is usually longer than the alternative direct route between supplier and warehouse. For lead time sensitive products this issue would be either a soft or hard constraint to consider during decision-making related to cross-docking. Negative effects of increased lead times are mainly a potentially decreased service level at demand points and increased pipeline inventory (Gümüş and Bookbinder, 2004; Berman and Wang, 2006; Benrqya et al., 2020). For inbound retail networks in grocery retailing, the longer lead times caused by cross-docking can generally be neglected from an economic perspective. This is justified by the situation that the comparatively cheap grocery products considered for cross-docking have a relatively constant demand rate and regular deliveries (Apte and Viswanathan, 2000; Vogt, 2010). In addition, retail warehouses are generally used to compensate for short-term fluctuations in end customers' demand, meaning that a longer delivery time for inbound deliveries does not necessarily affect the level of service for end customers.

If storage space at a warehouse is limited, delivery frequencies might have to be adapted such that the storage capacity is not exceeded. Since cross-docking naturally tends to lead to higher delivery frequencies due to transportation bundling, lot sizes correspondingly decrease, which reduces the required level of storage capacity at the warehouses. Still, the consideration of limited storage capacity is useful when, for instance, the company expands, a reduction in the number of warehouses is planned, demand levels are increasing or the product assortment is expanded. The degree to which different delivery frequencies can reduce the requirement for storage space depends on storage assignment policies (Malmborg, 1996). Typically, large-scale retailers use a randomized storage assignment in their warehouses for incoming pallets.

Further restrictions include potential lower and upper bounds regarding the overall throughput in CDs as well as a relatively balanced workload at the CDs over time such that peak days are avoided. Following the principles of lean logistics, a balanced workload increases the utilization of resources at a facility by reducing idle times, which also applies to CDs (Jones et al., 1997; Novoa et al., 2018; Abushaikha et al., 2018; Vogt, 2010).

3. Related literature

There has been a vast amount of literature regarding the planning and deployment of cross-docking operations within supply chains. Generic studies like the ones of Apte and Viswanathan (2000) and Vogt (2010) provide frameworks without suggesting mathematical modeling approaches. Apte and Viswanathan (2000) compare different consolidation strategies and discuss prerequisites for implementing a cross-docking system and expected benefits. Vogt (2010) derives success factors of cross-docking from field research. Focusing on modeling approaches, Belle et al. (2012) categorize cross-docking research into the following problem types: (1) strategic decision problems, i.e., planning the location of CDs and layout design of CDs, (2) tactical decision problems, i.e., planning the flow of goods through the CD network, and (3) operational decision problems, i.e., planning the vehicle routing, dock door assignment and detailed truck scheduling. The literature discusses in particular operational and organizational issues of cross-dock facilities and presents a variety of decision models and solution approaches, e.g., Maknoon et al. (2016), Serrano et al. (2017) and Dulebenets (2019). However, the strategic and tactical decision problems are rarely considered in literature. These problems are of special interest for our study. Section 3.1 therefore reviews CD location and network design contributions. Section 3.2 then provides an overview of literature that deals with the flow of goods through a CD network and particularly considers flow type decisions. Finally, Section 3.3 presents the reviewed literature in a comparative table, summarizes the findings obtained from the literature, and highlights the distinctive contribution of our work.

3.1. CD location and network design

There are numerous studies dealing with location problems ranging over several decades. For the sake of brevity we limit our review to CD location contributions and refer to the more general surveys on modeling approaches for location planning problems to Klose and Drexl (2005) and ReVelle et al. (2008). Facility location problems in the context of supply chain design are reviewed by Daskin et al. (2005), Shen (2007) and Melo et al. (2009). General hub location reviews are presented by O'Kelly (1992), Campbell (1994, 1996). However, more recent contributions are not available. Govindan et al. (2017) note, for example, that there currently exists a lack of scientific publications and surveys on models and methods for location planning problems in the context of SCM.

In the category of network design models with cross-docking there are several contributions that are related to our planning problem as they determine the location of CDs and the allocation of suppliers to those CDs. However, product flows are typically assumed to be routed exclusively via these CDs and direct shipping options to warehouses are not included. Sung and Song (2003) as well as Sung and Yang (2008) present a network design model that decides upon the number and location of CDs, the assignment of shipments to CDs on a source–destination basis and the type of truck per transport connection. Jayaraman and Ross (2003) and Ross and Jayaraman (2008) investigate a two-echelon network design problem where the number and location for both warehouses and outbound cross-dock facilities are decided upon. Similarly, Bachlaus et al. (2008) investigate a multi-echelon network design integrating the decision of the number and location of CDs. Additionally, they decide upon the location of production plants and warehouses and consider multi-objective optimization, including cost minimization and flexibility maximization. Mousavi et al. (2013b) propose a multi-period MIP formulation for the integrated decision of selecting locations for cross-dock facilities and assigning suppliers to the CDs as well as CDs to destinations. In their model, product flow is carried out exclusively via cross-docking. Mousavi et al. (2013a, 2014) extend this study by considering uncertainty in a fuzzy environment. The models of Hosseini-Nasab et al. (2023) and Nasrollahi et al. (2023) integrate the possibility of cross-dock linking, i.e., shipments can be transported via more than just one CD in succession. Both studies also consider a heterogeneous fleet. Battarra et al. (2022) examine a multi-terminal cross-docking problem focusing on the distribution of perishable goods, while also including cross-dock linking. They propose a MILP model that decides on the location and number of CDs and the routing of shipments through one or more CDs while excluding the possibility of direct shipping from suppliers to destinations.

The contributions discussed above correlate with our problem setting regarding the facility location aspect. However, their focus primarily lies on the strategic level while applying very aggregated modeling approaches. In particular, these approaches neglect the decision-relevant operational delivery planning dependencies. That is, they do not decide on the flow type, the frequency of delivery, and the specific day of delivery within the associated planning horizon. Notwithstanding, the flow type selection decision, i.e., direct shipments to destinations, can be included in these models by considering them as shipments via dummy CDs located directly at the respective destinations and having no fixed costs. However, this possibility is never mentioned in these papers and is explicitly excluded in the modeling assumptions of some papers (e.g., Battarra et al. 2022, Nasrollahi et al. 2023).

The following papers follow a more integrated approach by also considering flow type decisions in their CD facility location models. Abouee-Mehrizi et al. (2014) determine the number and location of cross-dock centers and allocate the product flow. Besides other diverging modeling assumptions, the main difference compared to our model is that they only consider linear transportation costs, whereas our model specifically integrates the combinatorial effects of bundling shipments in cross-dock centers and the consequences thereof, such as truck utilization and load balancing at the cross-docks. Instead, they include other aspects, e.g., sourcing decisions, which are excluded from our study. Shahabi et al. (2013) develop an integrated inventory control and facility location model for cross-docks and warehouses, considering assignments of suppliers to cross-docks and warehouses while assuming unit transportation costs. Gümüş and Bookbinder (2004) also combine the CD network design and flow type selection problem by deciding on CD locations and supplier-to-CD assignments. However, they do not consider warehouses as a further intermediate stage between suppliers and customers. They also do not consider the consequences of a CD stage on warehouse capacities. In addition, the modeling and solution approach presented by Gümüş and Bookbinder (2004) is only suitable for very limited problem sizes. Furthermore, they assume a fixed delivery quantity per period, i.e., they do not decide on the delivery frequencies within the planning cycle. They assume that the entire volume from a source (supplier) is jointly delivered within the planning period considered.

Another stream of literature addresses cross-docking location problems under the risk of disruption (e.g., Hasani Goodarzi et al. 2021). Selected cross-docks are assumed to be non-operational with certain independent probabilities. Therefore, supplying and receiving nodes seek the services of other operating cross-docks or use direct transport. The goal of these approaches is to determine the optimal location for a set of cross-docking stations that minimizes the costs of establishing cross-docks, the transportation costs both in the event of no failure and in the event of a failure, and the penalty costs if a delivery cannot be fulfilled at all. These models consider a single period and do not decide on the frequency of deliveries and the possible balancing of workload between different delivery days.

Mogale et al. (2023) propose a cross-docking location problem that minimizes the costs of establishing cross-docks as well as transportation, inventory, and carbon emission costs. Inventory costs include both pipeline inventory in the transportation system and inventory at the destination points. Equivalently to our case, they decide on the number of cross-dock locations, the flow type, i.e., direct delivery or delivery via cross-docks, and the frequency of inbound and outbound shipments at a cross-dock. However, they follow an approximation scheme suggested by Berman and Wang (2006), which assumes that transportation and inventory costs follow a linear behavior with respect to the number of products shipped and the demand at the destination points. This approximation scheme bases on several restrictive assumptions (Berman and Wang, 2006). It includes that the delivery frequency can be any positive (integer) number and is not limited to a range of possible (feasible) numbers and, most critically, that the coordination of inbound and outbound deliveries at the cross-dock is neglected.

Both approaches (Mogale et al. 2023 and Berman and Wang 2006) assume FTL deliveries for inbound and outbound connections in all cases. The frequency of these deliveries is determined by the number of FTLs required to fulfill the product flow for each respective link, such

Table 1
Overview of papers on cross-dock location. Solution approaches: B&P: branch&price, CG: column generation, CS: commercial solver, DA: decomposition approach, MDM: minimum deviation method, PP: possibilistic programming, PSO: particle swarm optimization, LR: lagrangian relaxation, SA: simulated annealing, TS: tabu search, VNS: variable neighborhood search.

	Number and locations of CDs	Multi-supplier	Flow type selection	Delivery frequency	Delivery pattern on daily basis	Transportation cost modeling	Limited warehouse capacities	Balanced workload at the CDs	Solution approach
Own approach	✓	✓	✓	discrete	✓	truck	✓	✓	matheuristic (DA)
Sung and Song (2003)	✓	✓	–	–	–	truck	–	–	metaheuristic (TS)
Sung and Yang (2008)	✓	✓	–	–	–	truck	–	–	exact (B&P)
Jayaraman and Ross (2003)	✓	–	–	–	–	linear	✓	–	metaheuristic (SA)
Bachlaus et al. (2008)	✓	✓	–	–	–	linear	–	–	metaheuristic (PSO)
Mousavi et al. (2013b)	✓	✓	–	–	–	truck	–	–	metaheuristic (SA/TS)
Mousavi et al. (2013a)	✓	✓	–	–	–	truck	–	–	exact (PP)
Mousavi et al. (2014)	✓	✓	–	–	–	truck	–	–	exact (PP)
Battarra et al. (2022)	✓	✓	–	–	–	truck	–	–	matheuristic (CS)
Hosseini-Nasab et al. (2023)	✓	✓	–	–	–	linear	–	–	not specified
Nasrollahi et al. (2023)	✓	✓	–	–	–	linear	–	–	matheuristic (MDM)
Abouee-Mehrizi et al. (2014)	✓	✓	✓	continuous	–	linear	–	–	exact (CG)
Shahabi et al. (2013)	✓	✓	–	continuous	–	linear	–	–	exact (CS)
Gümüş and Bookbinder (2004)	✓	✓	✓	–	–	truck	–	–	exact (CS)
Hasani Goodarzi et al. (2021)	✓	✓	✓	–	–	truck	–	–	matheuristic (LR)
Mogale et al. (2023)	✓	✓	✓	continuous	–	truck	–	–	metaheuristic (VNS)

as the link between supplier and CD, CD and demand point, and the direct supply link from source to sink. This is a valid approach when taking a long-term perspective. However, it neglects the situation at the operational level, and typically results in cost approximation errors or intractable operational scenarios, where cross-dock operations are not possible anymore without building stocks at the consolidation point, as this approach cannot ensure that the inbound and outbound flows at a CD are coordinated in terms of arrival times (see also Assumption 4 of Berman and Wang 2006).

The following example illustrates the problem. Let us assume a network with two suppliers, one CD and two warehouses. Both suppliers deliver products for both warehouses. A bundling advantage is achieved at the CD if the deliveries of both suppliers are consolidated and then delivered together to each of the warehouses. Let us now assume that supplier #1 delivers every fifth day and supplier #2 every seventh day. Then only every 35th day the deliveries of both suppliers arrive on the same day and would allow two FTL outputs from CD to warehouses on the same day. In the other cases, the products must be stored in the CD until both outbound trucks are completely filled, or the delivery cycles are adjusted during operation, which in turn changes the storage costs and/or leads to less utilized trucks.

In contrast, our approach coordinates the inbound and outbound quantities on each day and limits the delivery frequencies to feasible and practicable numbers that ensure a cyclic supply of products from suppliers.

In summary, the existing literature mostly neglects operational decisions when deciding on the CD network design. Those approaches that include operational decisions in their modeling and solution approach all assume continuous or arbitrary delivery frequencies. However, this assumption significantly complicates the generation of feasible and practically realizable delivery schedules. In the following we therefore analyze the CD delivery planning approaches proposed in literature to see whether these approaches meet the practical requirements.

3.2. CD delivery planning

The papers discussed in this subsection present quantitative approaches for planning the flow of goods through the CD network. These models determine whether certain products should be distributed directly to destination points (typically stores), or whether to use cross-docking operations in-between. One stream of literature uses empirical case studies assessing the potential of reducing supply chain costs through cross-docking (see, e.g., Kreng and Chen 2008, Benrqya 2019, Benrqya et al. 2020). The authors develop detailed cost models that quantify the resulting logistics costs of a direct delivery versus a delivery via an existing CD facility. A second stream of literature develops combinatorial optimization models that decide on the assignment of products to a specific delivery mode, i.e., flow type (Galbreth et al., 2008; Li et al., 2009; Hosseini et al., 2014; Soleimaninanadegany et al., 2017). In summary, the papers mentioned here focus exclusively on tactical problems, i.e., assume a given network and do not consider the decision of where to locate the CDs, but decide on the flow type of goods. They usually also neglect to determine the delivery frequency and day-based delivery patterns, except the contribution of Lim et al. (2005). Modeling these issues is however relevant for quantifying period-based capacity levels of CDs and warehouses. The papers reviewed therefore miss a practically important aspect that is addressed in this paper. Moreover, the available tactical approaches are not suitable as part of a sequential approach that first determines the number and locations of CDs and then the frequency and patterns of deliveries. Assumption 4 (“Inbound-outbound coordination at the cross-dock is ignored.”) from Berman and Wang (2006) applies to these approaches.

3.3. Summary, research gap and contribution

Table 1 differentiates the literature analyzed from the problem setting we are considering and illustrates the novelty of our approach.

Literature on cross-docking mostly considers CDs as a substitute for traditional warehousing with the main benefit of reducing inventory while replacing the warehouse’s consolidation function. In our study, however, cross-docking serves as an upstream supplement to subsequent warehouses, which thereby constitutes a two-echelon supply network structure. An important strategic decision that has to be made within this network concerns the number and position of CDs. This problem cannot be handled independently from the decisions that determine how the goods flow through the network (Belle et al., 2012). Existing literature usually neglects the interdependence between CD network planning and operational planning. Only very few approaches consider both problems in an integrative manner. However, the available integrative approaches are still modeled in such an aggregated manner that crucial operational implications (such as actual shipment bundling effects) are not considered. Very few contributions include the delivery frequency decision in their modeling and solution approach. These approaches all assume continuous or arbitrary delivery frequencies (see Table 1). However, this assumption contradicts the usual procedure in retail practice. Here it is standard that suppliers deliver their goods in certain predefined delivery cycles and delivery patterns, e.g., twice a week, once a week, every other week, etc. Thus,

Table 2
Example of delivery patterns, the corresponding frequency mode m, delivery frequency $freq_m$, delivery interval $\frac{|D|}{freq_m}$, and delivery quantity $q_{s,w,j}$ on the designated day, respectively, for $q_{s,w} = 240$.

j\d	1	2	3	4	5	⋯	21	22	23	24	m	$freq_m$	$\frac{\lvert D\rvert}{freq_m}$	$q_{s,w,j}$
1	1	1	1	1	1	⋯	1	1	1	1	1	24	1	10
2	1	0	1	0	1	⋯	1	0	1	0	2	12	2	20
3	0	1	0	1	0	⋯	0	1	0	1	2	12	2	20
4	1	0	0	1	0	⋯	0	1	0	0	3	8	3	30
5	0	1	0	0	1	⋯	0	0	1	0	3	8	3	30
6	0	0	1	0	0	⋯	0	0	0	1	3	8	3	30
7	1	0	0	0	1	⋯	1	0	0	0	4	6	4	40
⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

our approach differs significantly from the approaches proposed in the literature, as we assume a limited number of delivery frequencies and delivery patterns that allows us to generate an executable delivery schedule on each day of the planning horizon. Furthermore, the assumption of a limited number of possible delivery frequencies allows the modeling of non-linear transportation costs for the links between suppliers and CDs. The respective costs can then be calculated in advance and can, for example, relate to the respective required size of the trucks and/or to specific billing methods (truck-based, pallet-based). This is generally not possible in the approaches proposed in the literature. Even the vast majority of the tactical approaches that focus on the flow of goods through the CD network (see Section 3.2) neglect the determination of day-based delivery patterns, which are relevant in our problem setting. Thus, all the papers studied leave out at least one aspect that is important from a practical point of view, which is addressed in our paper.

Regarding solution methods, it is evident from Table 1 that a wide variety of approaches has been applied in studies addressing CD location planning. The approaches can be categorized into exact algorithms, matheuristics, and metaheuristics. A deeper examination reveals that the choice of solution approach is highly dependent on the specific problem setting, which varies across the existing studies. Consequently, no single solution approach has emerged as dominant for solving CD location problems in general. This underscores the need for a tailored approach, whether it be an exact algorithm, a matheuristic, or a metaheuristic, depending on the unique characteristics of the problem and the modeling approach used.

Our study therefore fills an existing gap in the literature by proposing a decision support model that, for the first time, explicitly considers a retailer's supply network and decides how CD facilities can be integrated into that network to improve the cost efficiency of diverse deliveries from multiple suppliers to different destination warehouses. In addition, the study demonstrates the applicability of the modeling and solution approach proposed using a real-world case of a large European grocery retail company.

The approach suggested integrates the strategic decisions on the number and locations of cross-docking facilities, the tactical decision on the flow of goods through the network, i.e., direct-to-warehouse shipping or shipping via one of the CDs, and the decisions on the delivery frequency with which each supplier delivers its products to retailer's warehouses. A subsequent model then decides on the specific delivery day, ensures a balanced workload on each working day in the CDs, and accounts for integer truck deliveries on the link between CDs and the retailer's warehouses. The modeling and solution approach also implicitly decides on different shipping options depending on the selected flow type and delivery frequency, e.g., FTL assuming multiple truck sizes vs. LTL billing. The decision support framework developed thus fulfills the specific requirements of a large-scale retail company.

4. Model

The given supply network of a retail company consists of a set of suppliers, $S = \{1, 2, \dots, s, \dots |S|\}$, a set of (potential) cross-dock points (CDs), $I = \{1, 2, \dots, i, \dots |I|\}$, and a set of warehouses, $W = \{1, 2, \dots, w, \dots |W|\}$. The warehouses in turn are responsible for supplying the stores of the retailer with the products respectively assigned. The set of warehouses W represents the demand points (sinks) of the supply network. Within the planning horizon under investigation, we consider a planning cycle of fixed length that consecutively repeats one after the other. Each planning cycle includes a given set of working days, $D = \{1, 2, \dots, d, \dots |D|\}$. The model parameters are assumed to be time-independent, which implies a static planning situation.

Supplier s delivers $q_{s,w}$ quantity units on average (measured in pallets per planning cycle) exclusively via one out of two alternative shipping options (flow types) to warehouse w. The quantity $q_s = \sum_{w \in W} q_{s,w}$ then quantifies the total shipping volume of supplier s. Each supplier has to be assigned to either direct-to-warehouse shipping (flow type $i = 0$) or to a particular CD, $i \in I$, through which all shipments of this supplier have to be processed. Set $I_0 = I \cup \{0\}$ then defines all possible paths a shipment of supplier s can take to warehouse w, from which exactly one has to be selected.

Additionally, the delivery frequency and the associated delivery day within the planning cycle of |D| days has to be defined for each supplier. For practical reasons we assume constant and discrete time intervals for delivery. We define the respective time intervals by their associated delivery frequencies $freq_m$, $m \in M = \{1, 2, \dots, m, \dots |M|\}$ within the planning cycle, where m denotes a particular delivery frequency mode. Frequency modes having a delivery interval greater than 1 ($\frac{|D|}{freq_m} > 1$) can be realized in different patterns. Suppose a delivery should be done every other day, then the delivery can be made on Monday, Wednesday, Friday and so on, or on Tuesday, Thursday, Saturday, and so on. We therefore create a discrete set of possible delivery patterns $J = \{1, 2, \dots, j, \dots |J|\}$, which specifies the possible combinations of the exact delivery days for each of the possible frequency modes. Table 2 illustrates some examples of delivery patterns associated with the respective frequency mode m, i.e., delivery frequencies $freq_m$, assuming a cycle length of $|D| = 24$ days. Table 2 also shows the associated delivery intervals $\frac{|D|}{freq_m}$ and the delivery volume per delivery day $q_{s,w,j} = \frac{q_{s,w}}{freq_m}$, $\forall\ j \in J_m$ for one supplier s assuming a total delivery volume of $q_{s,w} = 240$ quantity units and neglecting weekly seasonality. Set J_m then defines the subset of all delivery patterns that have the delivery frequency mode m. The column of a particular day d defines the set of patterns with a delivery on day d, $d \in D$. We denote this set as J_d.

The decision problem mainly decides on three issues: (a) the number and locations of CD facilities to be selected from the set of potential candidate sites $I = \{1, 2, \dots, i, \dots |I|\}$, (b) the delivery path i, $i \in I_0$, of supplier s, $s \in S$, and (c) the delivery pattern j, $j \in J$. Note that with a given combination of delivery path and delivery pattern, a cost-optimal option of the transportation mode for each supplier-to-CD and direct supplier-to-warehouse transport link can be precalculated. This includes, for instance, the decision to use a fleet of your own vs. a third-party logistics service provider (3PL), truck sizes and according billing methods (truck-based, pallet-based). To solve decision (a), the binary decision variable $z_i \in \{0, 1\}$ is used indicating whether the CD site i, $i \in I$, is selected or not. The assignment of supplier s to delivery path i, i.e., decision (b), and delivery pattern j, i.e., decision

Table 3
Notation for model SNDP-FT.

Index sets	
D	Days of the planning cycle, $D = \{1, 2, \dots, d, \dots \lvert D\rvert\}$
I_0	Shipping options: direct shipping ($i = 0$) or via one of the possible CD locations, $I_0 = I \cup \{0\}$
I	Candidate sites for CD locations, $I = \{1, 2, \dots, i, \dots \lvert I\rvert\}$
J	Delivery patterns, $J = \{1, 2, \dots, j, \dots \lvert J\rvert\}$
J_d	Delivery patterns including a delivery on day d, $J_d \subseteq J$
J_m	Delivery patterns using the same delivery frequency mode m
M	Delivery frequency modes, $M = \{1, 2, \dots, m, \dots \lvert M\rvert\}$
S	Suppliers, $S = \{1, 2, \dots, s, \dots \lvert S\rvert\}$
W	Warehouses, $W = \{1, 2, \dots, w, \dots \lvert W\rvert\}$
Parameters	
$c^{\text{assign}}_{s,i,m}$	Costs for assigning supplier s to delivery path i and frequency mode m
c^{setup}_i	Fixed costs for setting up and operating a CD at candidate site i
$c^{\text{outb}}_{i,w}$	Transportation costs from CD i to warehouse w per truck
$cap^{\text{truck,out}}$	Truck capacity for CD-to-warehouse shipments
cap_w	Maximum storage capacity of warehouse w
lb_i	Lower bound factor for daily deviation from average utilization at CD i
$q^{\min}_i$	Minimum quantity to be processed through CD i within the entire planning cycle
$q^{\max}_i$	Maximum quantity to be processed through CD i within the entire planning cycle
q_s	Total delivery quantity of supplier s, $q_s = \sum_{w\in W} q_{s,w}$
$q_{s,w}$	Delivery quantity of supplier s to warehouse w
$q_{s,w,j}$	Delivery quantity from supplier s to warehouse w per delivery applying delivery pattern j
$q^{\text{min,out}}$	Minimum number of pallets required for CD-to-warehouse transportation, if there is any transport from a particular CD to a particular warehouse
ub_i	Upper bound factor for daily deviation from average utilization at CD i
Decision and auxiliary variables	
$f_{i,w,d}$	Integer variable quantifying the number of truck shipments required to fulfill the transport volume between CD i and warehouse w on day d
$y^{\text{out}}_{i,w}$	Binary variable, 1 if there is any transport from CD i to warehouse w; otherwise 0
$y_{s,i,j}$	Binary variable, 1 if supplier s is assigned to delivery path i with delivery pattern j; otherwise 0
z_i	Binary variable; 1 if CD i is opened; otherwise 0

(c), is represented by the binary decision variable $y_{s,i,j}$. Given the three decisions just-mentioned, auxiliary variable $f_{i,w,d} \in \mathbb{Z}^+_0$ quantifies the number of truck shipments required from CD i to warehouse w on day d of the planning cycle. This leads to a step-fixed (non-linear) transportation cost function, which distinguishes our approach from many other approaches assuming linear (continuous) transportation costs. In that latter case, the transportation costs depend only on the quantity transported.

Cost parameters. The model's objective is to minimize all supply chain costs that are affected by the decision and auxiliary variables. Related to the decision on the number and locations of CD facilities, i.e., decision (a), cost parameter c^{setup}_i quantifies the fixed costs for setting up and operating a CD at candidate site i.

The selection of delivery path i and delivery pattern j for supplier s, i.e., decisions (b) and (c), is associated with costs for the entire delivery volume supplied by supplier s. These costs depend on the associated frequency mode m and are therefore identical for all $j \in J_m$. These costs are quantified by $c^{\text{assign}}_{s,i,m}$. Cost parameter $c^{\text{assign}}_{s,i,m}$ can be precalculated and includes costs for direct-to-warehouse shipping (in the cases of $i = 0$) or inbound transportation processes to CD i and the associated operational process within the CD (in the case of $i \neq 0$). Particularly, the handling of pallets, as well as frequency related costs, i.e., ramp contact costs for incoming trucks, inventory costs and purchasing costs have to be considered. The costs associated with the delivery frequency depend on the selected frequency mode m. This parameter also reflects the inventory costs and the space required in the warehouses. We assume a constant product flow from the warehouses to the stores or customers. The average stock level per product in the respective warehouses therefore corresponds to half of the product's delivery quantity. More frequent delivery of products therefore reduces the amount of capital tied up and the space required in the warehouses. In addition, comparable to the approach of Berman and Wang (2006), pipeline inventories can also be integrated into cost parameter $c^{\text{assign}}_{s,i,m}$, which are influenced by the respective shipping option and frequency mode.

The cost rate per truck traveling from CD i to warehouse w is denoted by $c^{\text{outb}}_{i,w}$. It includes a truck-based transportation rate valid for the respective travel distance. It additionally includes costs for ramp contacts at the CD (outgoing) and the warehouse.

Constraints. The model considers several constraints motivated from retail practice. First, the trucks delivering goods from CDs to warehouses are assumed to have a limited loading capacity, $cap^{\text{truck,out}}$. Second, the storage space in warehouse w, cap_w, is usually limited. The storage space required at a warehouse is influenced by the frequency mode a supplier delivers its products to the warehouse and by the storage assignment policy applied at the warehouse (Malmborg, 1996). Third, the overall throughput of a newly opened CD i should fulfill a lower and upper bound within the entire planning cycle, i.e., $q^{\min}_i$ and $q^{\max}_i$. Fourth, CDs should be utilized evenly over time to avoid peak days.

Formal model. In the following we formulate the decision support model denoted as *Supply Network Design Problem with Flow Type Selection (SNDP-FT)*. It minimizes total costs for a retailer's supply network, while deciding on the number and locations of CDs to be set up. It additionally decides on the delivery path and delivery pattern selected for each supplier. The decision on the delivery path also defines the flow type used, i.e., direct-to-warehouse or delivery via CD. Table 3 summarizes the notation used.

Model SNDP-FT

$$\min \quad Z = \sum_{i\in I} c^{\text{setup}}_i \cdot z_i + \sum_{s\in S}\sum_{i\in I_0}\sum_{m\in M} c^{\text{assign}}_{s,i,m} \cdot \sum_{j\in J_m} y_{s,i,j} + \sum_{i\in I}\sum_{w\in W}\sum_{d\in D} c^{\text{outb}}_{i,w} \cdot f_{i,w,d} \tag{1}$$

s.t.

$$\sum_{i\in I_0}\sum_{j\in J} y_{s,i,j} = 1 \qquad \forall\, s \in S \tag{2}$$

$$\sum_{s\in S}\sum_{i\in I_0}\sum_{j\in J} y_{s,i,j} \cdot q_{s,w,j} \le cap_w \qquad \forall\, w \in W \tag{3}$$

$$\sum_{s\in S}\sum_{j\in J_d} y_{s,i,j}\cdot q_{s,w,j} \le cap^{truck,out}\cdot f_{i,w,d} \qquad \forall\, i\in I, w\in W, d\in D \quad (4)$$

$$q_i^{\min}\cdot z_i \le \sum_{s\in S}\sum_{j\in J} y_{s,i,j}\cdot q_s \le q_i^{\max}\cdot z_i \qquad \forall\, i\in I \quad (5)$$

$$lb_i\cdot \sum_{s\in S}\sum_{j\in J} q_s\cdot y_{s,i,j} \le \sum_{s\in S}\sum_{j\in J_d}\sum_{w\in W} q_{s,w,j}\cdot y_{s,i,j} \le ub_i\cdot \sum_{s\in S}\sum_{j\in J} q_s\cdot y_{s,i,j} \qquad \forall\, i\in I, d\in D \quad (6)$$

$$\sum_{j\in J} y_{s,i,j} \le z_i \qquad \forall\, s\in S, i\in I \quad (7)$$

$$y_{s,i,j}\in\{0,1\} \qquad \forall\, s\in S, i\in I_0, j\in J \quad (8)$$

$$z_i\in\{0,1\} \qquad \forall\, i\in I \quad (9)$$

$$f_{i,w,d}\in\mathbb{Z}_0^+ \qquad \forall\, i\in I, w\in W, d\in D \quad (10)$$

The model's objective function (1) minimizes total costs consisting of setup and operating costs for CDs, costs related to selected delivery paths and delivery patterns for the suppliers, and total transportation costs from CDs to warehouses. Please note that the transportation cost term is a step-fixed cost function, as we define the decision variable $f_{i,w,d}$ as an integer variable. We therefore refer to this modeling approach as one that assumes "non-linear transportation costs."

Constraints (2) ensure that exactly one delivery path and pattern is assigned to each supplier. Constraints (3) ensure that the capacity per warehouse is not exceeded. Constraints (4) determine the daily number of trucks needed per CD-to-warehouse connection. Constraints (5) keep the total throughput volumes per CD within site-specific ranges. The maximum capacity constraint (even if unlimited) also links the assignment of supplier s to CD i with the set-up necessity of i. Constraints (6) balance the daily workload per CD. Constraints (7) connect the two types of binary variable. This leads to sharper bounds through the relaxed problem, which will speed up solving the model with standard methods. Constraints (8) to (10) define the model's variables.

In retail practice it is often the case that 3PL service providers are responsible for the fulfillment of certain transportation links between CDs and warehouses. If so, it is likely that they will ask for a minimum carriage per period. The SNDP-FT model could then be extended by a minimum quantity required on each CD-to-warehouse link (see Constraints (11) and (12)).

$$\sum_{s\in S}\sum_{j\in J} q_{s,w,j}\cdot y_{s,i,j} \ge q^{\min,out}\cdot y_{i,w}^{out} \qquad \forall\, i\in I, w\in W \quad (11)$$

$$\sum_{j\in J} y_{s,i,j} \le y_{i,w}^{out} \qquad \forall\, i\in I,\ (s,w)\in S\times W,\ \text{where } q_{s,w}>0 \quad (12)$$

Constraints (11) and (12) enforce a minimum delivery quantity from an established CD i to warehouse w only if the CD i is assigned at least one supplier that provides deliveries for that warehouse w. We will use these additional constraints later in the context of our hierarchical decomposition approach (see Section 5.2). Note that in case these constraints are added to model SNDP-FT, the formulation can be further strengthened, if Constraints (7) are replaced by $y_{i,w}^{out}\le z_i$, $\forall\, i\in I, w\in W$.

The SNDP-FT generalizes the simple plant location problem (SPLP) and can therefore be classified as $\mathcal{NP}$-hard (Krarup and Pruzan, 1983). The huge set of possible delivery patterns within a planning cycle additionally complicates the identification of an optimal solution to the problem in manageable computation time. The theoretical number of possible supplier and delivery pattern combinations is given by $|J|^{|S|}$. For instance, a planning cycle of $|D| = 24$ days, which yields 60 possible delivery patterns and $|S| = 100$ suppliers would result in $|J|^{|S|} = 60^{100} \approx 6.53\cdot 10^{177}$ supplier-pattern combinations. Note that in this example we assume constant delivery intervals and a repetition of all possible patterns in each subsequent planning cycle. That means, only integer divisors of 24 form valid delivery intervals in this case, i.e., $\{1,2,3,4,6,8,12,24\}$, which add up to a total of 60 different delivery patterns.

5. Solution approach

Model SNDP-FT is hard to solve with exact algorithms due to its combinatorial complexity. This is especially true since real-life instances in the problem context are expected to be relatively large, featuring a high variety of products, a multitude of suppliers and several warehouses. As discussed in Section 3, no standard solution method has emerged for CD location problems, since each problem setting requires a tailored approach. We therefore present a heuristic decomposition approach to solve the SNDP-FT problem. The approach hierarchically decomposes the original problem formulated into a master and several independent sub-problems that can be resolved in a sequential manner. While this approach does not guarantee optimal solutions, it provides near-optimal results (see Section 6). We outline the general approach in Section 5.1, while addressing the master and sub-models in Sections 5.2 and 5.3, respectively.

5.1. General approach

The major combinatorial challenge in solving the SNDP-FT model is due to the fact that we exactly model each individual day of the planning cycle using length |D|. This is relevant since the integer number of FTL trucks required for each CD-to-warehouse connection on each day of the planning cycle has to be quantified and the workload at the CDs established should be balanced between the working days of the planning cycle. We assume that we can abstract from day-to-day decisions taking a long-term perspective. We therefore aggregate the allocation of resources, i.e., workload assigned to CDs and the number of trucks required for CD-to-warehouse deliveries, over the entire planning cycle, and assume that a subsequent operational planning model can be used to create a satisfying resource allocation at a daily level.

Large-scale retailers, e.g., in the grocery setting, exhibit an extensive sales volume and usually operate only a limited number of warehouses, such that a high truck utilization (i.e., close to FTL) can be assumed when bundling shipments from different suppliers in CDs. This allows the assumption that all CD-to-warehouse deliveries can be made in FTL mode, regardless of the exact day of execution and supplier-to-CD allocation decisions. Outbound transportation costs can then be linearized and total transportation costs can be pre-calculated independently per supplier for each possible delivery path.

We therefore propose a hierarchical decomposition of the SNDP-FT model into a CD and Flow Type Selection Problem (CDFTSP), see Section 5.2, and a CD-individual Operational Problem (CDOP$^{(i)}$), see Section 5.3, that can each be optimally solved by standard MIP solvers for real-life instances.

5.2. CD and flow type selection problem

The CD and Flow Type Selection Problem (CDFTSP) determines the number and locations of CDs, and selects the flow type for each supplier, i.e., direct-to-warehouse shipping or shipping via one of the selected CDs. The model additionally decides on the delivery frequency per supplier, but ignores the concrete delivery days within the planning cycle. I.e., a set of possible delivery frequency modes $M = \{1,2,\dots,m,\dots|M|\}$ replaces the delivery patterns $J = \{1,2,\dots,j,\dots|J|\}$ used in model SNDP-FT, see Section 4. The shipping volume per delivery when applying delivery frequency mode m is then specified by $q_{s,w,m} = \frac{q_{s,w}}{freq_m}$. This quantity becomes relevant when quantifying the required level of capacity in warehouses W.

The newly introduced binary decision variable $x_{s,i,m}$ that assigns supplier s to delivery path i and delivery frequency m replaces the variable $y_{s,i,j}$ of model SNDP-FT, which considers delivery patterns based

Table 4
Additional notation used for model CDFTSP.

Parameters	
$\hat{c}^{\text{assign}}_{s,i,m}$	Costs for assigning supplier s to delivery path i and delivery frequency mode m including the associated linear transportation costs for shipments on the CD-to-warehouse links
$q_{s,w,m}$	Delivery quantity from supplier s to warehouse w per delivery applying delivery frequency mode m
Decision variables	
$x_{s,i,m}$	Binary variable, 1 if supplier s is assigned to delivery path i with delivery frequency mode m; otherwise 0

on daily granularity. Note that the following relation exists between both variables since a maximum of one delivery pattern corresponding to the same frequency mode, $j \in J_m$, may be selected.

$$x_{s,i,m} = \sum_{j \in J_m} y_{s,i,j} \qquad \forall\, s \in S,\ i \in I_0,\ m \in M \qquad (13)$$

The associated cost parameter $\hat{c}^{\text{assign}}_{s,i,m}$ is quantified for a delivery via CD i as follows.

$$\hat{c}^{\text{assign}}_{s,i,m} = c^{\text{assign}}_{s,i,m} + \sum_{w \in W} q_{s,w} \cdot c^{\text{outb-lin}}_{i,w} \qquad \forall\, s \in S, i \in I, m \in M \qquad (14)$$

The cost parameter $\hat{c}^{\text{assign}}_{s,i,m}$ is quantified by its associated cost parameter for the supplier-to-CD link of the original problem (SNDP-FT), $c^{\text{assign}}_{s,i,m}$, and adding the resulting (linear) transportation costs for the subsequent shipments of supplier s to all potential warehouses W. Please note that linear transportation costs are hereby assumed for each connection between CD i and warehouse w. The corresponding cost parameter is calculated by a linearization of the transportation costs per truck, $c^{\text{outb-lin}}_{i,w} = \frac{c^{\text{outb}}_{i,w}}{cap^{\text{truck,out}}}$.

There are no combinatorial effects of assigning different suppliers to a certain CD anymore due to the linearization of CD-to-warehouse transportation. Thus, CD-to-warehouse costs are now included in this cost parameter. Overall, the parameter considers supplier-to-CD transportation, CD-to-warehouse transportation, processing costs at the CD and warehouses, purchasing costs and inventory holding costs. The direct-to-warehouse delivery costs, i.e., costs associated with flow type $i = 0$, do not change. These costs are equivalent to the corresponding cost parameters of the original problem (SNDP-FT).

$$\hat{c}^{\text{assign}}_{s,i=0,m} = c^{\text{assign}}_{s,i=0,m} \qquad \forall\, s \in S,\ m \in M \qquad (15)$$

In order to ensure that the assumption of fully utilized trucks for CD-to-warehouse transportation largely holds in solving the CD operational problem (see subsequent Section 5.3), we set a minimum quantity of pallets $q^{\text{min,out}}$ for each transport link actually used. This corresponds to the practical requirement formulated in Constraints (11) and (12) of the original model SNDP-FT. Binary variable $y^{\text{out}}_{i,w} \in \{0,1\}$ indicates whether a transport connection between CD i and warehouse w is used or not. This measure allows for CDs with low overall throughput to be opened without breaching the FTL assumption, which is not ensured in comparable studies.

All remaining sets (I, I_0, S, W), decision variables (z_i) and cost parameters (c^{setup}_i) are equivalent to model SNDP-FT. Table 4 summarizes the additional notation used.

Model CDFTSP

$$\min \quad Z = \sum_{i \in I} c^{\text{setup}}_i \cdot z_i + \sum_{s \in S} \sum_{i \in I_0} \sum_{m \in M} \hat{c}^{\text{assign}}_{s,i,m} \cdot x_{s,i,m} \qquad (16)$$

s.t.

$$\sum_{i \in I_0} \sum_{m \in M} x_{s,i,m} = 1 \qquad \forall\, s \in S \qquad (17)$$

$$\sum_{s \in S} \sum_{i \in I_0} \sum_{m \in M} x_{s,i,m} \cdot q_{s,w,m} \le cap_w \qquad \forall\, w \in W \qquad (18)$$

$$q^{\min}_i \cdot z_i \le \sum_{s \in S} \sum_{m \in M} x_{s,i,m} \cdot q_s \le q^{\max}_i \cdot z_i \qquad \forall\, i \in I \qquad (19)$$

$$\sum_{s \in S} \sum_{m \in M} q_{s,w} \cdot x_{s,i,m} \ge q^{\text{min,out}} \cdot y^{\text{out}}_{i,w} \qquad \forall\, i \in I,\ w \in W \qquad (20)$$

$$\sum_{m \in M} x_{s,i,m} \le y^{\text{out}}_{i,w} \qquad \forall\, i \in I,\ (s,w) \in S \times W, \text{ where } q_{s,w} > 0 \qquad (21)$$

$$y^{\text{out}}_{i,w} \le z_i \qquad \forall\, i \in I,\ w \in W \qquad (22)$$

$$x_{s,i,m} \in \{0,1\} \qquad \forall\, s \in S,\ i \in I_0,\ m \in M \qquad (23)$$

$$y^{\text{out}}_{i,w} \in \{0,1\} \qquad \forall\, i \in I,\ w \in W \qquad (24)$$

$$z_i \in \{0,1\} \qquad \forall\, i \in I \qquad (25)$$

The objective function (16) of model CDFTSP minimizes total costs consisting of setup and operating costs for CDs and costs related to the delivery path and delivery frequency selected for the suppliers. Like the integrative model (SNDP-FT), the CDFTSP model minimizes all decision-relevant costs in Eq. (16), the only difference being that it omits discrete consolidation effects. Constraints (17) assign exactly one flow type and one mode of delivery frequency to each supplier. Constraints (18) ensure that the warehouses' capacities are not exceeded. Constraints (19) ensure that total CD throughput is within the specified range. Constraints (20) and (21) ensure a minimum quantity of transportation units for each CD-to-warehouse transport link that is used. The maximum capacity constraints also inherently connect the two decision variables. Constraints (22) strengthen the LP relaxation of the problem. Constraints (23), (24) and (25) define the decision and auxiliary variables, respectively.

CDFTSP as lower bound of model SNDP-FT. Model CDFTSP represents a relaxation of the original model SNDP-FT for the case where the integrality condition of the variable $f_{i,w,d}$ is relaxed, i.e., $f_{i,w,d} \ge 0$, $f_{i,w,d} \in R^+_0$, and the balancing constraints of the daily workload per CD, i.e., Constraints (6), are excluded from model SNDP-FT. This relaxation applies in both cases, if the minimum shipping volume on each CD-to-warehouse link is (a) included or (b) excluded, i.e., Constraints (11) and (12) of model SNDP-FT as well as Constraints (20) and (21) of model CDFTSP, respectively.

5.3. CD operational problem

Master model CDFTSP ignores the individual days of the planning cycle and aggregates the outgoing truck shipments and the workload at the CDs selected over the entire planning cycle. The actual costs, however, depend on the number of trucks required for the CD-to-warehouse connections on each day of the planning cycle. In addition, the workload at the CD should be balanced between the working days of the planning cycle. Thus, subsequent models for each of the CDs selected in the higher-level (master) model CDFTSP are required that generate a solution that corresponds to the assumptions of the original model SNDP-FT. In the following we formulate these models that are denoted as CDOP$^{(i)}$, $(i \in I | z_i = 1)$. Model CDOP$^{(i)}$ solves the operational planning problem for CD i on a daily basis. It selects one of the possible delivery patterns for those suppliers that have been assigned to CD i, $s \in S^{(i)}$. Binary decision variable $y^{(i)}_{s,j} \in \{0,1\}$ indicates the selected pattern $j \in J_s$ for supplier s. Set J_s denotes the possible delivery patterns of supplier s that correspond to the delivery frequency mode selected for supplier s in model CDFTSP $(m \in M | x_{s,i,m} = 1)$. The

Table 5
Additional notation used for model CDOP$^{(i)}$.

Index Sets	
J_s	Set of delivery patterns available for supplier s
$S^{(i)}$	Set of suppliers assigned to CD i in the higher-level model CDFTSP ($s \in S \mid \sum_{m \in M} x_{s,i,m} = 1$), $S^{(i)} \subseteq S$
Parameters	
$c_w^{\text{out},(i)}$	Transportation costs from the CD to warehouse w per truck; superscript (i) indicates the CD being considered of sub-model i
$lb^{(i)}$	Lower bound factor for daily deviation from average utilization at the CD; superscript (i) indicates the CD being considered of sub-model i
$q^{\text{total},(i)}$	Total quantity of pallets being shipped via CD i within the planning cycle
$q_{s,w}^{(m)}$	Delivery quantity from supplier s to warehouse w per delivery; superscript (m) indicates the delivery frequency mode defined for supplier s in the higher-level model CDFTSP
$ub^{(i)}$	Upper bound factor for daily deviation from average utilization at the CD; superscript (i) indicates the CD being considered of sub-model i
Decision variables	
$f_{w,d}^{(i)}$	Integer variable quantifying the number of truck shipments required to fulfill the transport volume between the CD and warehouse w on day d; superscript (i) indicates the CD being considered of sub-model i
$y_{s,j}^{(i)}$	Binary variable, 1 if delivery pattern j is assigned to supplier s; otherwise 0; superscript (i) indicates that this variable is set for all suppliers previously assigned to CD i, $S^{(i)}$

corresponding delivery quantities from supplier s to warehouse w per delivery are denoted $q_{s,w}^{(m)}$.

Since the delivery quantity from supplier s to warehouse w is already determined in the higher-level model CDFTSP, model CDOP$^{(i)}$ only decides on the specific delivery days with respect to the given frequency. The required number of trucks per CD-to-warehouse connection and day is determined based on the joint decision of assigning delivery patterns to suppliers. Auxiliary variable $f_{w,d}^{(i)}$ defines this number.

The remaining sets and parameters of model CDOP$^{(i)}$ are equivalent or directly associated with the sets and parameters of model SNDP-FT. The sets W (warehouses of the retailer) and D (days of the planning cycle) are identical to model SNDP-FT. The parameters $c_w^{\text{out},(i)}$, $lb^{(i)}$, $ub^{(i)}$ are subsets of the original model parameters since they only concern the individual CD i that is part of model CDOP$^{(i)}$. We indicate this by setting index i as superscript (i). $q^{total,(i)}$ denotes the total quantity of pallets being shipped via CD i within the planning cycle and is obtained by $\sum_{s \in S} \sum_{m \in M} x_{s,i,m} \cdot q_s$ with the respective results for $x_{s,i,m}$ in model CDFTSP. Table 5 summarizes the additional and modified notation used within model CDOP$^{(i)}$.

Model CDOP$^{(i)}$

$$\min \quad Z^{(i)} = \sum_{w \in W} \sum_{d \in D} c_w^{\text{out},(i)} \cdot f_{w,d}^{(i)} \tag{26}$$

s.t.

$$\sum_{s \in S^{(i)}} \sum_{j \in J_d} y_{s,j}^{(i)} \cdot q_{s,w}^{(m)} \leq cap^{\text{truck,out}} \cdot f_{w,d}^{(i)} \qquad \forall\, w \in W,\ d \in D \tag{27}$$

$$\sum_{j \in J_s} y_{s,j}^{(i)} = 1 \qquad \forall\, s \in S^{(i)} \tag{28}$$

$$\sum_{s \in S^{(i)}} \sum_{j \in J_d} \sum_{w \in W} q_{s,w}^{(m)} \cdot y_{s,j}^{(i)} \geq lb^{(i)} \cdot q^{\text{total},(i)} \qquad \forall\, d \in D \tag{29}$$

$$\sum_{s \in S^{(i)}} \sum_{j \in J_d} \sum_{w \in W} q_{s,w}^{(m)} \cdot y_{s,j}^{(i)} \leq ub^{(i)} \cdot q^{\text{total},(i)} \qquad \forall\, d \in D \tag{30}$$

$$f_{w,d}^{(i)} \in \mathbb{Z}_0^+ \qquad \forall\, w \in W,\ d \in D \tag{31}$$

$$y_{s,j}^{(i)} \in \{0,1\} \qquad \forall\, s \in S^{(i)},\ d \in D \tag{32}$$

The objective function (26) minimizes outbound transportation costs from CD i considering the number of outgoing trucks per day and warehouse and the destination-specific cost rates. The minimum number of trucks required for each destination and day is determined by Constraints (27). Constraints (28) ensure that a delivery pattern is selected for each supplier. Constraints (29) and (30) ensure that the actual throughput neither exceeds the maximal nor falls below the minimal predetermined throughput on each day. The respective limits are denoted by a percentage deviation from the daily average. Constraints (31) and (32) define the decision variables.

5.4. Lower bound and benchmark approach

Our approach can easily be benchmarked against existing approaches in literature for the CD location problem. A common method for dealing with the complexity of the CD location problem is the relaxation of the integrality of the variable $f_{i,w,d}$ of model SNDP-FT, assuming constant truck utilization between CDs and destinations. This leads to the assumption of linear transportation costs of the CD-to-warehouse links and gives a lower bound on the optimal objective value of the original model SNDP-FT. We denote this lower bound as LB1. An additional lower bound (denoted as LB2) can be calculated based on model CDFTSP when balancing constraints of the daily workload per CD, i.e., Constraints (6) are excluded from model SNDP-FT. Note that also LB2 assumes linear transportation costs, but might lead to a weaker bound than LB1, if workload balancing at the CDs (Constraints (6)) is relevant. In contrast, if the balancing constraints are omitted, LB1 and LB2 lead to the same result.

The relaxed problem's solution consequently serves two purposes. First, it provides a lower bound for our original problem and thus serves as a performance indicator for our decomposition approach. Second, it provides the basis for benchmark comparisons with other approaches in the literature that generally assume linear transportation costs (see Section 3.1). The relaxed problem's solution generates a feasible solution with regard to the number and locations of CDs and the assignments of suppliers to CDs. Our approach, however, explicitly includes the operational implications of the network configuration decision, i.e., actual utilization of trucks and daily workload per CD. These effects therefore also have to be considered via model CDOP$^{(i)}$ for each CD selected of the benchmark solution.

6. Numerical results

In this section we present results from applying the model and solution approach to a practical case study. The aim of the case study is to demonstrate the model's applicability in a real-life setting and its dynamics for different scenarios. In Section 6.1 we describe the case setting, followed by a scenario analysis in Section 6.2.

6.1. Case setting

We gathered data from a major European grocery retail company that sources over 8000 different products within the ambient segment from more than 300 suppliers located in Central Europe. In the core market Germany, the company operates eight warehouse locations. Each location belongs to one of three warehouse types, with the exception of one location that serves two warehouse types. In total, the case study considers nine different warehouses: one central warehouse for the entire German market (where 53% of the stock keeping units (SKUs) are stored which covers around 15% of supply and sales volume measured in number of pallets), two parallel "regional" warehouses (36% of SKUs, 30% of pallets) and six parallel "local" warehouses (11% of SKUs, 56% of pallets). Products that are not applicable to be considered for cross-docking (e.g., due to seasonal or highly fluctuating demand) have been excluded from this analysis. The case company already has 36 transshipment points in place, which are used for cross-docking operations in the distribution system between the warehouses and stores. Currently, no supply-side cross-docking is implemented. This case study aims at evaluating the efficiencies of implementing inbound cross-docking for this company.

The planning cycle is set to four weeks, which corresponds to the maximum delivery interval given by the retailer. The following delivery frequencies are available for selection: once (delivery every four weeks), twice (delivery every two weeks), four times (weekly delivery) and eight times (delivery twice per week). The reasoning for this selection is that a common denominator enables more effective shipment consolidation between frequencies. Transportation costs for direct-to-warehouse shipping have been precalculated for each supplier and destination, considering the optimal combination of frequency and truck combination. For supplier-to-CD shipments, transportation costs are precalculated accordingly, but, without determining the frequency selection. We set the truck size to a fixed capacity of 36 pallets for CD-to-warehouse transportation, which corresponds to a standard European truck (40t) with trailer. All decision-relevant cost parameters were provided by the retailer except for the frequency dependency of purchasing costs, which is excluded in our analysis as a result.

We implemented our solution approach in Python and solved the models CDFTSP and CDOP using Gurobi v9.1.2. as a solver on an AMD Ryzen 5 4500U CPU @ 2.38 GHz with 16 GB RAM. The runtime for both the CDFTSP and CDOP model did not exceed 30 min for finding the optimal solution in all our numerical experiments. We benchmark our decomposition approach using Gurobi on the SNDP-FT model. However, solving the SNDP-FT model for real-sized instances requires a significant amount of RAM (in our practical instances usually more than 100 GB). Therefore, we use an AMD Ryzen 9 3950X @ 3.49 GHz with 128 GB RAM to solve the SNDP-FT problem.

6.2. Scenario analysis

In this section we analyze varying scenarios that differ in the availability and setup costs of potential cross-docking sites. This differentiation demonstrates the different outcomes of the solution approach when existing facilities in the retailer's logistics network can easily be used for inbound cross-docking compared to the situation where new facilities have to be built (or external facilities rented) for cross-docking. We provide detailed analyses on the cost savings potential, truck utilization and structural findings with regard to CD locations and quantity-related results.

6.2.1. Scenario descriptions

Scenario A. The first analysis (Scenario A) consists of a greenfield scenario without the possibility of utilizing existing facilities for cross-docking. Each potential cross-docking location exhibits fixed set-up costs that represent the acquisition of property and building costs for a new facility. The potential fixed costs are written off linearly by the case company over a period of 10 years, of which we take into account the proportion corresponding to the case's four-week planning cycle. We use a grid-like structure for the candidate CD sites, with potential CDs at equal distances. The grid spans the company's sourcing and trading area in Central Europe as defined by the suppliers' geographical coordinates. In total, 625 candidate sites (resulting from a 25×25 rectangular grid) are available for setting up a CD. Regarding the workload balancing at the CDs, the relative deviation of pallet throughput per day from the daily average is desired to be a maximum of 10% in order to be able to create efficient rosters at the CDs. A minimum and maximum total throughput per CD is not initially specified. The CDs are supposed to be operated six days per week. In order to avoid an unfavorable assignment of suppliers to CDs leading to poorly utilized CD-to-warehouse truck loads, we set the minimum number of pallets for a CD-to-warehouse transport connection at 400, if the respective transport connection is to be used. We derived that parameter considering truck capacities, desired truck utilization, and delivery frequencies. The value has proven expedient across different scenarios.

Scenario B. The remaining scenarios constitute a brownfield approach, where existing facilities can be utilized for cross-docking while keeping open the possibility of building supplementary new facilities. In Scenario B, each of the eight warehouses can take on the function of a CD. The estimated fixed costs for setting up a warehouse for cross-docking operations were provided by the retail company and are roughly 12.5% relative to the set-up costs for a new facility (grid point).

Scenario C. The third scenario additionally includes the retailer's 36 transshipment points of the distribution network between warehouses and stores. The company's estimate for the corresponding fixed costs for extending the on-site operations to supplier cross-docking are roughly 7.5% relative to the set-up costs for a new facility.

6.2.2. General results

Table 6 summarizes the main results of the scenario analysis, which we discuss in detail in the following paragraphs focusing on the table's section "Decomposition approach." Please note that unless otherwise indicated, the cost savings for the solutions are reported without workload balancing constraints at the operational level for ease of comparison between the different scenarios. In Scenario B and C, CDs may be integrated into existing facilities and the current operations would thus have to be considered and could be rearranged in order to accommodate cross-docking while ensuring processes that are balanced overall.

Scenario A. For the greenfield scenario our decomposition approach generates a solution with two relatively equally sized CDs. In this scenario 54% of all suppliers are assigned to one of the CDs, whereas the remaining suppliers ship their quantities directly to the warehouses as before without utilizing the CDs. Compared to the original setting without cross-docking operations, the cost savings potential considering all decision-relevant costs is 4.4%. When applying a workload balancing constraint with a maximum deviation of 10% of the daily throughput, the cost savings would decrease only slightly to 4.1%. The truck utilization for CD-to-warehouse deliveries is 97% on average. The average number of suppliers merged per CD-to-warehouse connection and day is 6.9.

Scenario B and C. Since setup costs for CDs are much lower in the brownfield scenarios (Scenario B and C) compared to Scenario A, the number of CDs to be set up as suggested by the model results increases. Scenario B leads to 7 CDs (six warehouses with dual function and one newly set up CD) and Scenario C to 9 CDs (all integrated in existing CDs of the distribution system). Scenario B achieves an overall cost reduction of 5.4% compared to the original setting without cross-docking, while Scenario C achieves 6.3%. The share of suppliers delivering via CD is at 71% and 72% respectively, which represents a dramatic increase compared to Scenario A. This increase is due to the wider spread of CDs, which makes it cost-efficient for more suppliers to deliver via CD. However, since the overall CD throughput is not

Table 6
Scenario analysis: results of decomposition approach, lower bounds and benchmark comparison.

	Scenario A	Scenario B	Scenario C
Decomposition approach			
Number of CDs	2	7	9
Share of CD suppliers [%]	54	71	72
Cost savings [%]	4.4	5.4	6.3
Cost savings lower bound [%]	4.9	7.4	9.8
Mean truck utilization CD-to-warehouse [%]	97	93	90
Runtime in minutes (CDFTSP | CDOP)	14.8 | 9.3	11 | 9.1	18.6 | 4.3
Linear transportation costs			
Number of CDs	2	8	18
Share of CD suppliers [%]	54	72	76
Cost savings [%]	4.2	2.7	−2.7
Mean truck utilization CD-to-warehouse [%]	95	81	67
Runtime in minutes (CDFTSP | CDOP)	0.7 | 5.25	0.6 | 4.75	0.3 | 0.1
Model SNDP-FT, MIP solver, 24h			
Number of CDs	2	8	–
Cost savings [%]	4.4	6.6	–
MIP-gap [%]	0.46	0.53	–

as concentrated within two CDs as in Scenario A, the consolidation effectiveness slightly decreases, with a mean truck utilization of 93% and 90% for CD-to-warehouse shipments, respectively.

6.2.3. Performance of the decomposition approach

In order to evaluate the performance of our decomposition approach, we benchmark our approach threefold using the base scenarios A, B, and C. First, we assess lower bound gaps of our decomposition approach (see Table Section "Decomposition approach" of Table 6). Second, we compare our results to common approaches that use linear transportation costs but do not consider operational implications (see Table Section "Linear transportation costs" of Table 6). Third, we solve the original model SNDP-FT using the Gurobi MIP solver (see Table Section "Model SNDP-FT, MIP solver" of Table 6). Finally, we provide further benchmark comparisons on a variety of additional instances generated based on Scenario C (see Tables 7 and 8).

Lower bound assessment. As stated in Section 5.4, a lower bound for the original problem can be obtained by relaxing the integrality of the number of outgoing trucks ($f_{i,w,d} \in \mathbb{R}$). We calculate the corresponding lower bound gap of our decomposition approach in order to assess the theoretical potential for further cost improvement. The relative gap to the lower bound, i.e., the difference of the objective value of the decomposition approach and the lower bound in relation to the lower bound's value, is 0.5%, 2.2% and 3.9% for the different scenarios, respectively. This shows that the results of our decomposition approach in Scenario A cannot be significantly improved anymore. However, the results of scenarios B and C indicate further potential for improvement. Please note that both lower bounds (LB1 and LB2) lead to identical values since in the considered cases the balancing constraints are omitted.

Benchmark based on linear transportation costs. The lower bound provided for our original problem can also serve as a basis for a benchmark to similar approaches in previous research where it is common to assume that trucks can always be fully utilized and thus unit transportation costs can be applied. Since the results of our decomposition approach rely on truck-based transportation costs, we evaluate the solution generated as a lower bound with linearized transportation costs (see previous paragraph) with regard to its operational implications. I.e., we determine the optimal decisions for the transportation problem based on the lower bound's CD locations and supplier assignments and compare its performance with the results of our decomposition approach. The latter heuristic approach then serves as a benchmark to comparable studies suggested in literature and assuming linear transportation costs, see our literature review in Section 3. Both the heuristic approach based on linear transportation costs and our decomposition approach yield similar cost savings in Scenario A in which the linearization assumption approximately holds. However, it is apparent that the solutions based on linear transportation costs do not perform well considering the operational implications on a daily basis in Scenarios B and C. In fact, when applying linear-transportation-cost models in Scenario C, there is even an overall cost increase of 2.7% compared to the status quo without cross-docking when considering operational effects. In that case the cost savings potential for cross-docking is highly overestimated for individual CDs on a strategic level. The benchmark approach would thus suggest that no CDs should be established, even though the case company could achieve noticeable cost benefits by setting up CDs amounting to more than a million euro p.a. In the end, overall costs in our decomposition approach are 2.8% (Scenario B) and 8.7% (Scenario C) lower compared to the benchmark results when considering operational effects.

Benchmarks based on exact methods. Due to the combinatorial complexity of model SNDP-FT, the problem is hard to solve with exact methods. We used the Gurobi solver to produce results close to optimality based on exact methods with a time limit of 24 h (see Table Section "Model SNDP-FT, MIP solver" of Table 6). For Scenario A, the difference in cost savings between this approach and our decomposition approach is only marginal, while the decisions are basically the same. The MIP-gap of the exact approach after 24 h is 0.46%. In Scenario B the Gurobi solver produces results which are slightly better, achieving cost savings of 6.6% (MIP-gap of 0.53%) whereas our decomposition approach yields only 5.4% of cost savings compared to the status quo without cross-docking. For Scenario C Gurobi runs into memory problems before generating feasible results. This might be explained by the relatively low set-up costs for CDs in this scenario which increases the problem's complexity due to a higher number of viable CD combinations.

Additional benchmark comparisons. In the following we concentrate our analyses on a variety of instances that are generated based on Scenario C. First, we focus on the analysis of instances with a varying number of potential cross-dock locations. Second, we provide benchmark comparisons for instances based on subsets of the supplier set, focusing on four different supplier clusters.

We generate the first set of instances by starting with two potential CD sites with low setup-costs and increase this number until the Gurobi MIP solver runs into memory problems, i.e., more than 16 sites. The locations of the newly added potential CD sites are determined by applying a k-means approach. In this approach we partition the company's demand centers with an increasing number of clusters. The cluster centers serve as the additional potential CD sites in the respective instances. Note that all coordinates of the low-cost CD sites deviate between instances due to a regrouping of clusters. For those

Table 7
Benchmark comparisons of instances based on Scenario C.

Number of low-cost CD locations	2	4	6	8	10	12	14	16
Decomposition approach								
Number of CDs	8	6	8	7	9	8	8	9
Cost savings [%]	5.50	5.93	5.16	4.56	4.29	5.06	4.59	4.28
Runtime [min]	8	8	10	6	5	7	8	11
Linear transportation costs								
Number of CDs	9	11	10	10	12	11	12	14
Cost savings [%]	2.09	0.61	3.33	1.22	−0.58	1.73	−2.09	−2.25
Runtime [min]	<1	<1	<1	<1	<1	<1	<1	<1
Model SNDP-FT, MIP solver, 24h without minimum shipment constraints								
Number of CDs	9	10	9	10	12	11	11	12
Cost savings [%]	6.72	6.97	7.26	6.49	6.05	7.14	6.59	6.77
MIP-gap [%]	0.87	1.13	0.97	1.17	1.85	1.77	1.75	1.51
Model SNDP-FT, MIP solver, 24h with minimum shipment constraints								
Number of CDs	9	8	7	4	5	5	–	–
Cost savings [%]	6.27	6.05	6.42	5.43	5.41	5.36	–	–
MIP-gap [%]	0.65	1.08	1.23	1.10	1.44	2.09	–	–

instances, we apply the same solution approaches as mentioned above, i.e., our decomposition approach, the approach that assumes linear transportation costs, and an MIP solver solving the original model SNDP-FT in two versions, i.e., with and without minimum shipment constraints on CD-to-warehouse links (see Constraints (11) and (12)). The results are listed in Table 7.

The results show that assuming linear transportation costs leads to the highest number of CDs to be set up, but also to the lowest cost savings. In the instances with 10, 14 and 16 applicable low-cost CD sites, the results even lead to a cost increase compared to the status quo without cross-docking, when operational effects are evaluated for those configurations.

Using the Gurobi solver for the SNDP-FT model without minimum shipment constraints produces slightly better results than our decomposition approach throughout the instances with a minimum difference of 1.04 and a maximum of 2.49 percentage points. A higher number of low-cost CD sites thereby makes the problem harder to solve, since more CD combinations are viable. This becomes apparent by the (in tendency) increasing MIP-gaps and by the fact that the solver cannot produce any results for a number of low-cost CD sites higher than 16 in our analyses (or even higher than 12 when applying the minimum shipment constraints). The results of model SNDP-FT that includes minimum shipment constraints on CD-to-warehouse links are directly comparable to the results of our decomposition approach since our approach also assumes this type of constraints. The solution of model SNDP-FT provided by the MIP solver results in cost savings for the instances considered that are between 0.3% and 1.26% higher than the cost savings obtained with the decomposition approach. These deviations appear to be acceptable, since solving model SNDP-FT requires high-end computing facilities (128 GB RAM) and a significant amount of computation time (24 h). In addition, users cannot be sure that a feasible solution can be achieved at all for real-sized problem instances. In many cases of our analyses, the Gurobi solver terminates before it could even generate a feasible solution. Comparing the results of model SNDP-FT with and without minimum shipment constraints shows that including these constraints leads to slightly less cost savings, i.e., between 0.48% and 1.78% for the instances considered, as the constraints limit the possible solution space.

To further test the performance of our decomposition approach, we generated additional instances with a smaller number of suppliers based on geographical subregions. We again benchmark the results of the decomposition approach against the solutions of an approach that assumes linear transportation costs and the solutions of model SNDP-FT with and without minimum shipment constraints (see Table 8).

The decomposition approach yields noticeably better results than the approach that assumes linear transportation costs for the cases denoted as Cluster2, Cluster3, and Cluster4. In two cases, the latter approach even leads to an increase in costs compared to the status quo of our case company. Compared with the approach that directly solves the SNDP-FT model, the decomposition approach again achieves competitive results. However, the computation time for solving the SNDP-FT model is much longer than for the decomposition approach. In two of the tested cases (Cluster2 and Cluster3), the strategic results, i.e., the number and/or coordinates of the selected CDs, differ slightly between the decomposition approach and solving model SNDP-FT. However, the cost savings achieved in each case are quite similar. Comparing the results of the SNDP-FT model with and without minimum transportation constraints confirms the results shown in Table 7. Considering these constraints again leads to slightly lower cost savings.

We also analyzed the supplier clusters assuming Scenarios A and B and found that the differences between the decomposition approach and the exact approaches are only marginal in terms of cost savings and strategic decisions.

Comparison of LB1 and LB2 with workload balancing at the CD. So far, we focused the analysis on settings without balancing constraints (Constraints (6)) for the CDs to be established to be able to provide benchmarks with the original model SNDP-FT. In such a setting, the two lower bound approaches lead to the same results as explained in Section 5.4. In the following, we examine the difference of the two approaches when considering balancing at the CDs. We find that the calculation of LB1 requires a large amount of RAM, since LB1 is based on the integrated model SNDP-FT and relies solely on relaxing the integrality of variable $f_{i,w,d}$. For this reason, we cannot produce a feasible result for LB1 with our equipment (128 GB RAM) for the original scenarios in our case study, as well as for the instance of Cluster 3. In general, LB1 does not seem practical for larger instances due to its computing requirements. However, a computation for the instances featuring a smaller set of suppliers (Clusters 1, 2, and 4) is possible. For these instances we find that for tight balancing constraints (e.g., with a maximum allowed deviation from the daily mean of throughput volume of 10%) the LB1 approach produces equal or stronger bounds compared to the LB2 approach as illustrated in Table 9. This is due to the fact that LB1 incorporates the balancing constraints (Constraints (6)) in contrast to LB2. For all instances presented in Table 9 the minimum daily throughput at a CD is set to 0, the sensitivity factor provided represents the upper limit for the allowed daily throughput as a factor

Table 8
Benchmark comparisons for supplier clusters based on Scenario C.

Instance	Cluster1	Cluster2	Cluster3	Cluster4
Number of suppliers	51	36	148	74
Decomposition approach				
Number of CDs	1	0	6	2
Cost savings [%]	2.1	0	2.6	11.4
Runtime [min]	<1	<1	14	6
Linear transportation costs				
Number of CDs	1	4	9	4
Cost savings [%]	2.0	−9.3	−6.3	3.1
Runtime [min]	<1	<1	<1	<1
Model SNDP-FT, MIP solver, MIP-gap 0.3% without minimum shipment constraints				
Number of CDs	1	1	7	2
Cost savings [%]	2.6	0.6	4.1	13.6
Runtime [min]	7	4	418	648
Model SNDP-FT, MIP solver, MIP-Gap 0.3% with minimum shipment constraints				
Number of CDs	1	0	5	2
Cost savings [%]	2.6	0	3.1	13.1
Runtime [min]	13	4	632	491

Table 9
Comparison of lower bounds with varying balancing constraints. The lower bounds are expressed as cost savings [%] relative to the status quo without CDs. The sensitivity factor is expressed as a factor of the mean daily throughput at the CDs.

Sensitivity factor	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Cluster 1										
Decomposition approach	0.3	0.3	0.5	1.6	1.7	1.7	1.7	1.7	1.7	1.7
LB1 (SNDP-FT)	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
LB2 (CDFTSP)	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Cluster 2										
Decomposition approach	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LB1 (SNDP-FT)	12.7	14.8	16.3	16.8	16.9	17.1	17.1	17.3	17.6	18.2
LB2 (CDFTSP)	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Cluster 4										
Decomposition approach	–	7.2	8.4	10.1	10.2	10.4	10.4	10.4	10.5	10.5
LB1 (SNDP-FT)	16.2	16.2	16.3	16.3	16.3	16.3	16.3	16.4	16.4	16.4
LB2 (CDFTSP)	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4

of the mean (e.g., factor 1.1 allows a 10% deviation per day from the daily mean of throughput).

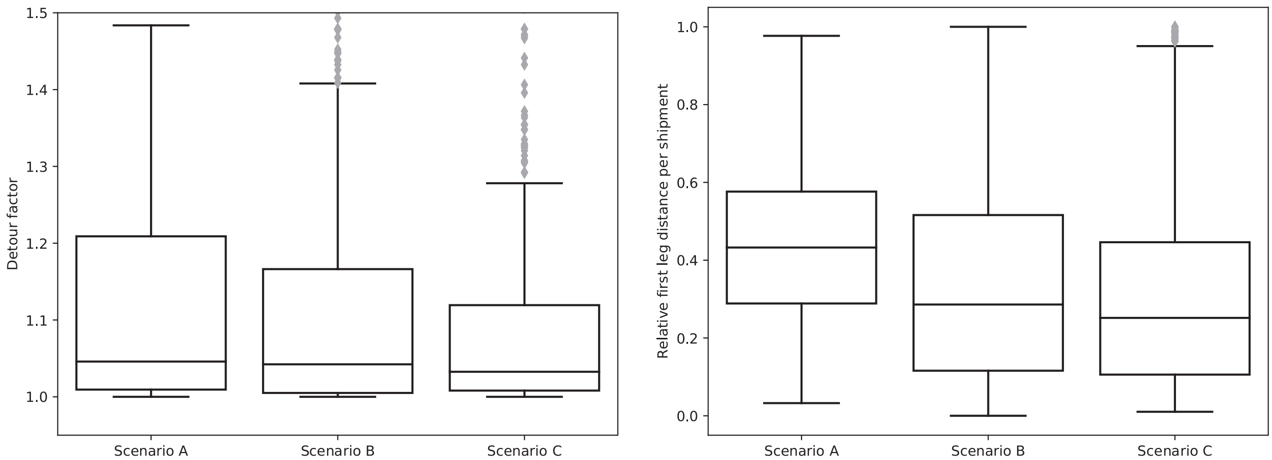
6.2.4. Structural results

After this first generic view on the three basic and further derived scenarios, we provide further insights in the solution structures of the base scenarios A, B and C. To do this, we first analyze the variation of the additional distances suppliers are willing to accept when bundling potentials through the CDs are offered, and how these vary between the different scenarios. Second, we analyze the CD positioning in the different settings, addressing which kind of CDs (i.e., located in closer proximity to suppliers or to warehouses) are primarily established under which conditions.

Detour factors for CD suppliers. One main setback of cross-docking is that the travel distance per shipment is stretched due to the detours required via CD. It is thus worth knowing to what extent detours occur, such that overall cost savings can still be realized via bundling effects at the CDs. Fig. 1(a) depicts the detour factor per shipment relative to direct-to-warehouse shipping. While 50% of shipments take on a detour of less than 5% across all scenarios, there is a noteworthy number of suppliers where the CD consolidation effect outweighs a considerable detour factor. This applies especially for Scenario A, where 25% of shipments have a detour factor of 1.2 or higher compared to the direct-to-warehouse route. Additionally, the analysis shows that for a scenario with a larger number of CDs (as in Scenario C) the detour factor is comparatively low. This reflects the fact that the CD coordinates are located closer to the respective suppliers' coordinates, since each CD serves a more restricted set of suppliers in those scenarios.

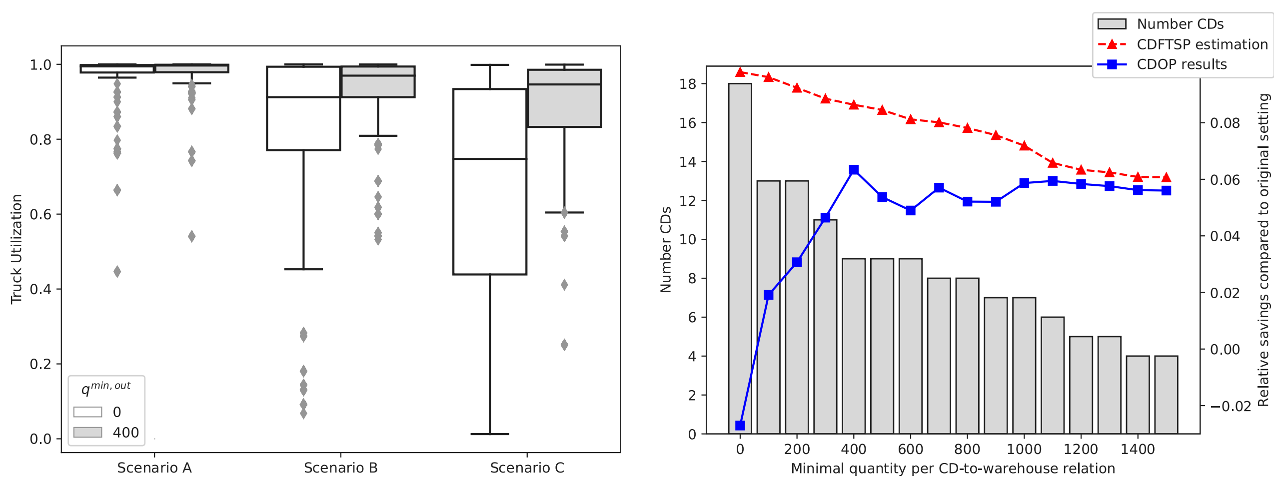
Relative CD positioning. CDs that are mainly used to consolidate deliveries from multiple suppliers (inter-supplier function) tend to be located near suppliers. CDs that are mainly used to split a single delivery from one supplier to multiple destinations (intra-supplier function) tend to be located near warehouses (see also Section 2). We therefore analyze the travel distance per shipment from the suppliers to the CDs relative to overall travel distance, i.e., the transport connection supplier-CD-warehouse (see Fig. 1(b)). A higher number of CDs not only reduces the detour per shipment (see Fig. 1(a)), but also the distance from the suppliers to CDs.

In Scenario C with nine CDs, the supplier-to-CD distance is less than 25% of total travel distance for 50% of CD shipments, i.e., the majority of CDs can be characterized as primarily in close proximity to the suppliers in this case. The median for Scenario A with only two CDs is 45%, which means that the first transportation leg is longer than the second leg for approximately half of the shipments, and vice versa. I.e., relatively long runs to the CDs are acceptable too for a considerable proportion of suppliers that greatly benefit from consolidation. Furthermore, the maximum outliers show that for certain shipments the CDs are used exclusively as a break-bulk facility, that is, the CD is located close to the target warehouses. A separate analysis of each CD of Scenario C has further exemplified this phenomenon. Some CDs mainly operate as a consolidation center in close proximity to their respective suppliers such that the second leg is the dominant section of the travel in terms of distance. In contrast, other CDs can be characterized as



(a) Detour factors (truncated) (b) Relative CD positioning

Fig. 1. Structural results of scenarios A, B, and C.



(a) Box plot: Truck utilization per CD-to-warehouse shipment, scenario comparison (b) Number of CDs and cost savings (Scenario C)

Fig. 2. Analysis results for $q^{\text{min,out}}$.

break-bulk facilities as the first leg is more often than not the dominant section of travel for the shipments that are routed via those CDs.

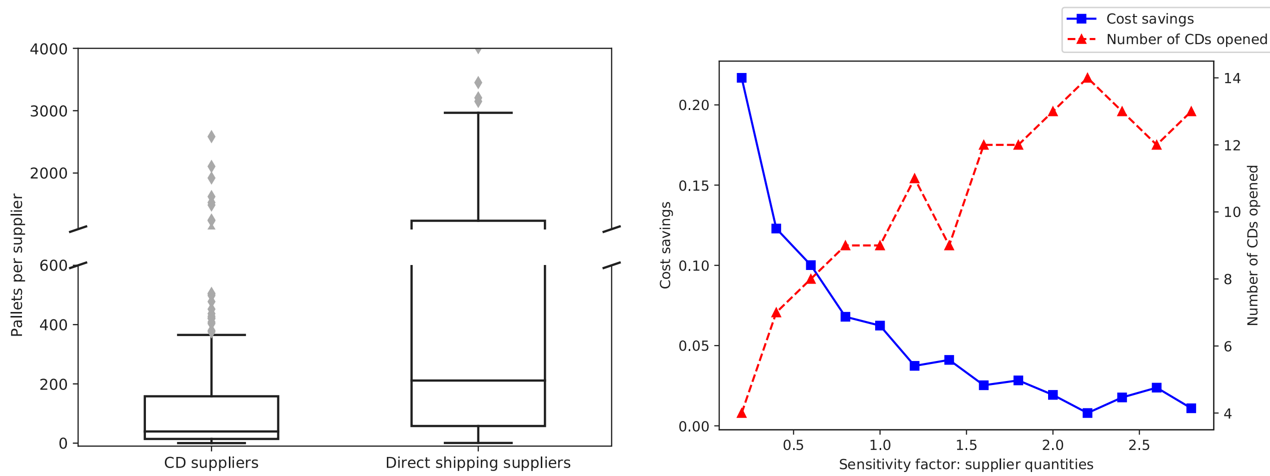
6.2.5. Effectiveness of shipment consolidation

The primary benefit of cross-docking is shipment consolidation. To ensure effective shipment consolidation, we have introduced parameter $q^{\text{min,out}}$ in our model, designed to facilitate efficient bundling. In the subsequent analyses, we will therefore examine the effectiveness of this parameter.

Truck utilization and total shipping volume per CD-to-warehouse connection. At first it is important to know under what conditions a minimum quantity per CD-to-warehouse connection is especially relevant. The box plots in Fig. 2(a) show the truck utilization per CD-to-warehouse shipment comparing the setting in which no minimal quantity per CD-to-warehouse connection is applied ($q^{\text{min,out}} = 0$) to a setting with $q^{\text{min,out}} = 400$ that has demonstrated good performance in terms of truck utilization and total cost savings in precalculations for our case. In Scenario A, where all CD shipments are concentrated within only two CDs, the median truck utilization is close to 100% and the first quartile at 98%, with only some outlier trucks at less than 95% utilization. In Scenario B, where 7 CDs are operated, the first quartile decreases to 91%. And finally in Scenario C, where 9 CDs are operated, 25% of trucks between CDs and warehouses show a truck utilization of less than 83%.

The effect of including parameter $q^{\text{min,out}}$ is evident when comparing the results to the setting of $q^{\text{min,out}} = 0$. Whereas the results for Scenario A remain relatively similar, the distributions of truck utilization in Scenarios B and C decrease significantly for $q^{\text{min,out}} = 0$ compared to $q^{\text{min,out}} = 400$. In Scenario C, the first quartile for truck utilization drops from 83% to 44% when no minimum quantity per CD-to-warehouse connection is given. The low truck utilization for $q^{\text{min,out}} = 0$ is due to the insufficient assumption that the trucks can be fully utilized after consolidation of the shipments in the CDs. This confirms the problematic character of the modeling approaches that have been proposed in the literature so far, see Section 3.3 (Summary, research gap and contribution) as well as Berman and Wang (2006).

Sensitivity analysis on the minimum quantity per CD-to-warehouse connection. Since it is evident that $q^{\text{min,out}}$ has a decisive impact on transport consolidation efficiency in scenarios with relatively low setup costs (as Scenario C in our case), we conduct a deeper assessment of the parameter's effect in Scenario C with varying calibrations of $q^{\text{min,out}}$.



(a) Quantity distributions (truncated)

(b) Sensitivity analysis on supplier quantities

Fig. 3. Quantity-related results for Scenario C.

Without any limitations on the parameter, the results from the CDFTSP model on a strategic level suggest a cost savings potential of nearly 10%, as depicted in Fig. 2(b). However, after calculating total costs with actual bundling effects from the results of the operational CDOP model, it is evident that the supply network as suggested by the CDFTSP model would result in an increase of total costs by 2% compared to the original setting without cross-docking. Note that the CDFTSP model gives an estimate that is a lower bound or best possible cost value of the results of the SNDP-FT model. The subsequent solutions of models CDOP$^{(i)}$, $(i \in I | z_i = 1)$, however, present a feasible but not necessarily optimal solution to the SNDP-FT model. We therefore denote the results achieved by the CDFTSP model as "CDFTSP estimation" and the results achieved by the hierarchical approach as "CDOP results."

Assuming $q^{\min,\text{out}} = 0$ leads to a large number of CDs – 18 locations (see Fig. 2(b)) – since in Scenario C the costs for setting up and operating a CD are relatively low. This also results in a relatively low average workload for each of the CDs established, which again does not allow for an efficient transportation consolidation at the CDs for outgoing trucks. The average utilization of outbound trucks is only about 56%. Nevertheless, under certain circumstances, the solution could also be realized in a cost-efficient manner. This might be the case for example if storage overnight is allowed that would enable bundling between days, or when empty trucks that are traveling back from the transshipment points to the warehouses in order to pick up new store shipments could potentially be loaded with deliveries intended for the warehouse. Regardless of those possibilities to achieve higher utilization of trucks traveling between CDs and warehouses, the actual cost savings realizable as determined by the CDOP model improve with increased minimum quantities per CD-to-warehouse connection, up to a parameter setting of 400 pallets, that is, $q^{\min,\text{out}} = 400$. At this value, the average utilization of outgoing trucks approaches 90%.

Compared to the setting with $q^{\min,\text{out}} = 0$, fewer poorly utilized trucks are deployed and the number of CDs established is halved from 18 to 9 CDs. The number of CDs established continues to decline with a further increase of $q^{\min,\text{out}}$. This however would also exclude various suppliers from cross-docking operations. It should be noted again that these large fluctuations are linked to the fact that setup costs for CDs in Scenario C are comparatively low, resulting in low-throughput, cost-effective CDs unless the strategic CDFTSP model ensures a minimum CD-to-warehouse transfer volume.

Setting $q^{\min,\text{out}}$ between 400 and 1000 leads to roughly similar results with regard to cost savings, since the remaining CD-to-warehouse links exhibit such a high volume that the minimum quantity restriction does not make a decisive difference anymore. Eventually, with minimum quantities of around 1000 pallets per destination, the cost savings as anticipated by the CDFTSP almost correspond to the actual cost savings quantified by the operational CDOP model. Working from this assumption, the average utilization of outgoing trucks is about 98%.

Overall, these findings highlight the relevance of our modeling and solution approach. In general, existing models in literature assume that highly utilized trucks can always be guaranteed on all transportation links such that transportation costs can be linearized. Based on our analysis it is evident that the cost savings calculated after linearizing transportation costs without anticipating actual bundling effects ($q^{\min,\text{out}} = 0$) might not be realized on an operational level.

6.2.6. *Supplier shipment quantity related results*

In addition to the efficiency of transport volume consolidation, the individual suppliers' shipment sizes also highly impact the benefits realizable when setting up a cross-docking system. We therefore analyze the quantity distributions (pallets per supplier during the planning cycle) for CD and direct suppliers as well as the impact of variations in shipment sizes on general results. In the following we present the analyses for Scenario C. The findings are, however, similar in the other two scenarios, too.

Quantity distribution: CD vs. direct suppliers. As expected, cross-docking is mainly used by small suppliers, as shown in Fig. 3(a). Nonetheless, there are some suppliers with a relatively large volume (more than 1000 pallets per supplier during the planning cycle) that use the CD as a break-bulk location. On the other hand, there are several suppliers shipping directly to the warehouses, although their small shipment volumes would have been generally applicable for cross-docking. On closer examination, those suppliers are already close to their destination warehouse, otherwise the detour via a CD would be too long.

Sensitivity analysis on suppliers' shipment quantities. A sensitivity analysis of the supplier's shipment sizes for Scenario C provides insights into the structural changes considering a supply network with suppliers that tended to be larger or smaller (see Fig. 3(b)). Although this analysis is hypothetical since the retailer's warehouse network is tailored to the current quantities, the results clearly show the substantial benefits of cross-docking for a setting with smaller suppliers and correspondingly low shipment sizes. The possible cost savings when setting up CDs within the supply network would considerably increase from 6% to over 20% if the shipment sizes of the suppliers go down to 20% of their original values. On the contrary, the positive consolidation effects on total costs decrease with larger suppliers and shipment sizes. Nevertheless, we observe an increase of CDs in the respective optimal solutions when increasing the shipment sizes. This might be due to the circumstance that CD setup costs relative to overall costs are decreasing since the share of transportation costs is growing. Since there are several very small suppliers in our data set, setting up an inbound CD system would be cost-optimal even when increasing the individual supplier quantities by a factor of 100. Of course, the number of CDs will then be reduced considerably to only two facilities and the overall cost savings effect would further decrease as already indicated by Fig. 3(b).

7. Conclusion

Concluding remarks. A well-designed logistics system is an indisputable backbone to the competitiveness of a retail company. Particularly for large-scale retailers with a heterogeneous mix of suppliers, transport efficiency is a crucial factor for logistics costs and poses a challenge for optimization. This article contributes to this field of research by conceptualizing the retail-specific problem of using cross-docking on the supply side between suppliers and retail warehouses. We furthermore developed a modeling approach and proposed a heuristic solution procedure that decomposes the model into two sequential sub-models that can each be solved optimally: a network design problem with flow type selection and an operational model that specifies CD operations in finer granularity. In this regard, it enhances previous modeling approaches for the CD location problem, specifically by simultaneously considering the flow type decision per supplier, frequency related costs through delivery patterns, and actual bundling effects in transportation. We showed in a numerical study that our decomposition approach achieves competitive results in solving the original problem compared to heuristic approaches currently proposed in the literature assuming linear transportation costs, and compared to standard MIP solvers, e.g., Gurobi. The numerical analysis also shows that the original problem is hard to solve for real-sized instances even with high-end computing facilities. In several cases of our analyses, the MIP solver terminates before it could even generate a feasible solution. In a case study conducted with data from a major European grocery retail company we demonstrated that the decision-relevant logistics costs can be reduced significantly by applying our modeling and solution approach. For the retailer examined in the case study, we found that more than 6% of decision-relevant costs could be saved by implementing an efficient cross-docking solution compared to the current situation where each supplier ships the corresponding volume directly to the destination warehouses. The following practical implications for our case company can be derived from the results of the study conducted. The results obtained give the company an indication of how many CDs it should set up, where to place them, and how to assign suppliers to either direct shipping or a specific CD. In addition, the results provide guidance on which delivery patterns should be preferred. Currently, the case company is in an advanced evaluation phase to determine the extent to which supplier CDs should be established and whether there are opportunities to begin with a promising preliminary CD setup.

Limitations and future research possibilities. Even though the proposed modeling and solution approach applied within a real case study demonstrates meaningful insights, it offers several opportunities for improvement and extensions, leading to new prospects for further research. The present study assumes that the transportation from suppliers to the retailer's warehouse is within the retailer's scope. In practice, however, the suppliers often bear the full transportation costs. In these cases a collaborative planning approach should be developed defining how cost savings are shared among the respective business partners (Vogt, 2010). The model also assumes that all incoming deliveries leave the CD on the same day. In practice, however, it is possible that residual outgoing deliveries that do not fill up an entire truck are postponed until the next working day. This study focuses on a retailer's supply network. Considering the supply and distribution network simultaneously could yield additional cost savings when setting up shared cross-dock facilities. The modeling approach also assumes that product allocations to warehouses are predetermined. Setting up CDs may influence these assignments. An integrated solution approach that solves both problems simultaneously may therefore be sensible. Furthermore, we assume that all a supplier's shipments have to be either routed via a single CD or transported directly to the respective warehouses. In the event that a supplier offers a heterogeneous range of products, the modeling and solution approach should allow different delivery paths and/or frequencies per supplier. A dynamic modeling approach becomes relevant when the products offered have a noticeable seasonal demand pattern. Finally, stochastic demand can be considered, for example, by a two-stage stochastic program. The first stage would then determine the CD locations, the flow type and the delivery mode, while the second stage would consider the detailed delivery schedules in relation to a range of demand scenarios. Both stages could be developed in a similar way to our decomposition approach, but would require an iterative procedure due to the stochastic demand scenarios.

CRediT authorship contribution statement

Tobias Potoczki: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Andreas Holzapfel:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Heinrich Kuhn:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Michael Sternbeck:** Writing – review & editing, Supervision, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

The authors gratefully acknowledge the doctoral scholarship from the Erich–Kellerhals–Stiftung (Foundation), Ingolstadt, Germany, for one of the authors. In addition, we would like to thank the anonymous reviewers and the editor for their valuable recommendations, which have significantly improved our paper.

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