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Retail Logistics Network Design: Strategic Models for Distribution and Supply Structures

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1 Einleitung

1.1 Gesamtrahmen der Dissertation

Der Einzelhandel steht seit Jahren unter einem tiefgreifenden strukturellen Anpassungsdruck. Wachsende Sortimentsbreiten, eine zunehmende Heterogenität der Artikel, veränderte Nachfrage- und Serviceanforderungen, steigende Kosten in Transport und Lagerhaltung sowie die fortschreitende Verzahnung stationärer und online-basierter Vertriebskanäle führen dazu, dass die Gestaltung logistischer Netzwerke nicht mehr als rein infrastrukturelle Entscheidung verstanden werden kann. Vielmehr handelt es sich um ein zentrales strategisches Gestaltungsfeld, in dem langfristige Strukturentscheidungen über Bezugsquellen, Lager- und Umschlagspunkte, Distributionsstufen und Materialflussarchitekturen in hohem Maße die ökonomische und operative Leistungsfähigkeit eines Handelsunternehmens bestimmen.

Im Zentrum dieser Dissertation steht daher das *strategische Supply Chain Network Design* in der Handelslogistik. Darunter werden langfristig wirksame Entscheidungen über die Struktur, räumliche Konfiguration und funktionale Ausgestaltung von Beschaffungs- und Distributionsnetzwerken verstanden. Solche Entscheidungen betreffen unter anderem die Anzahl, Lage und Funktion von Lagern, die Segmentierung von Warenströmen auf unterschiedliche Distributionskanäle, die Einbindung von Umschlagspunkten wie Cross-Docks, die Zuordnung von Artikeln zu verschiedenen Netzwerkelementen sowie die Gestaltung der Schnittstelle zwischen Beschaffungs- und Distributionslogistik. Charakteristisch für diese Entscheidungen ist ihr hoher strategischer Bindungsgrad: Infrastrukturinvestitionen sind kapitalintensiv, organisatorisch tiefgreifend und nur begrenzt reversibel. Entsprechend können Fehlentscheidungen über lange Zeiträume hinweg zu strukturellen Ineffizienzen führen, während geeignete Netzwerkkonfigurationen nachhaltige Wettbewerbsvorteile ermöglichen.

Die Relevanz dieser Fragestellungen ist im Handel besonders ausgeprägt. Im Unterschied zu vielen industriellen Kontexten sind Handelsnetzwerke typischerweise durch breite und heterogene Sortimente, eine Vielzahl räumlich verteilter Lieferanten sowie ein dichtes Netz nachgelagerter Nachfragepunkte gekennzeichnet. Diese Nachfragepunkte können klassische Filialen, Umschlagspunkte, Fulfillment-Standorte oder im Omni-Channel-Kontext auch kundennähere Abhol- und Belieferungspunkte umfassen. Aus dieser Struktur resultieren ausgeprägte Interdependenzen zwischen vorgelagerten Beschaffungsentscheidungen, der Ausgestaltung mittlerer Distributionsstufen und der nachgelagerten Versorgung der Absatzpunkte. Gerade im Handel ist es deshalb nur begrenzt sinnvoll, einzelne Gestaltungsprobleme isoliert zu betrachten. Die Wirtschaftlichkeit eines Netzwerkelements hängt regelmäßig davon ab, welche Rolle es im Gesamtsystem übernimmt und wie es mit anderen Elementen des Netzes interagiert.

Vor diesem Hintergrund verfolgt die vorliegende kumulative Dissertation das Ziel, einen Beitrag zu einer integrierten Theorie und Modellierung des strategischen Netzwerkdesigns in der Handelslogistik zu leisten. Im Mittelpunkt steht die Frage, wie sich die strukturelle Logik von Handelsnetzwerken präziser konzeptualisieren und zugleich durch entscheidungsunterstützende Modelle operationalisieren lässt. Die Arbeit verbindet damit zwei komplementäre Erkenntnisinteressen. Erstens soll ein konzeptioneller Bezugsrahmen entwickelt werden, der die zentralen Entscheidungsebenen und Interdependenzen handelslogistischer Netzwerke systematisiert. Zweitens sollen spezifische Entscheidungsprobleme, die für reale Handelsnetzwerke von hoher Relevanz sind, formal modelliert und hinsichtlich ihrer Implikationen für die Netzwerkgestaltung analysiert werden. Die modellorientierten Beiträge entwickeln formale Optimierungsansätze für zentrale Strukturentscheidungen der Handelslogistik und kombinieren diese mit anwendungsnahen Lösungsverfahren sowie Fallstudien auf Basis realer Daten aus der Einzelhandelspraxis. Dadurch wird nicht nur die theoretische Modellierbarkeit der betrachteten Probleme adressiert, sondern auch ihre praktische Anschlussfähigkeit geprüft.

Die kumulative Dissertation umfasst vier Einzelbeiträge, die entlang dieser Forschungslogik unterschiedliche, aber komplementäre Perspektiven auf das strategische Supply Chain Network Design in der Handelslogistik entwickeln. Der erste Beitrag entwickelt einen konzeptionellen Bezugsrahmen für das strategische Supply Chain Network Design in der Handelslogistik. Er zeigt, dass handelslogistische Netzwerke als mehrschichtige und interdependente Systeme zu begreifen sind, in denen Kontextbedingungen, strategische Gestaltungsentscheidungen, resultierende Netzwerkkonfigurationen und Leistungswirkungen eng miteinander verschränkt sind. Damit schafft dieser Beitrag die theoretische Klammer der Dissertation.

Der zweite Beitrag widmet sich der Gestaltung von Distributionssystemen im Lebensmitteleinzelhandel. Im Fokus steht ein Netzwerk, in dem unterschiedliche Typen von Distributionszentren verschiedene Teilmengen des Sortiments bedienen. Analysiert wird insbesondere, wie die Wahl von Lagertypen und die artikelspezifische Zuordnung von Produkten zueinander in Beziehung stehen und welche Kostenwirkungen daraus entlang der Versorgungskette resultieren. Der Beitrag verdeutlicht damit, dass strategische Strukturentscheidungen im Handel nur dann adäquat bewertet werden können, wenn ihre Konsequenzen für nachgelagerte taktische Entscheidungen antizipiert werden.

Der dritte Beitrag erweitert diese Perspektive zu einer umfassenderen Analyse der Breite und Tiefe von Distributionsnetzwerken. Während der zweite Beitrag die funktionale Differenzierung von Lagertypen in den Mittelpunkt rückt, wird hier zusätzlich die Frage der Parallelisierung und damit des Zentralisierungsgrades systematisch integriert. Dadurch wird das Problem der Netzwerkgestaltung in eine allgemeinere Form überführt: Handelsunternehmen müssen nicht nur entscheiden, welche Netzsegmente sie benötigen, sondern auch, wie stark diese Segmente räumlich zentralisiert oder regionalisiert werden sollen. Der Beitrag zeigt damit, dass Differenzierung und Zentralisierung keine getrennten, sondern eng gekoppelte Dimensionen strategischer Netzwerkgestaltung darstellen.

Der vierte Beitrag verschiebt den Blick auf die vorgelagerte Seite des Handelsnetzwerks und behandelt die Integration von Cross-Docks in bestehende Versorgungsstrukturen. Damit wird die Dissertation um einen Aspekt ergänzt, der in der handelslogistischen Forschung bislang kaum berücksichtigt wurde: die strategische Ausgestaltung der Verbindung zwischen Lieferanten und Handelslagern. Die gemeinsame Betrachtung von Cross-Dock-Standorten, Belieferungsmodi und Lieferfrequenzen macht deutlich, dass auch die Beschaffungsseite nicht unabhängig von der übrigen Netzwerkarchitektur verstanden werden kann. Vielmehr zeigt sich, dass die Wirtschaftlichkeit vorgelagerter Bündelungskonzepte maßgeblich von ihrer Einbettung in das Gesamtnetz abhängt.

1.2 Zusammenfassung der einzelnen Beiträge

Übersicht

Die Beiträge dieser Dissertation basieren auf den Manuskripten der folgenden Publikationen. Der Konsistenz halber wurden geringfügige Änderungen im Vergleich zu den publizierten Studien vorgenommen.

1. Potoczki, T., 2026, **Supply Chain Network Design in Retail Logistics - A Conceptual Review**, *SSRN*, `https://doi.org/10.2139/ssrn.6653679`
2. Holzapfel, A., Kuhn, H., Potoczki, T., 2020, **Design of distribution systems in grocery retailing**, *Operations Research Proceedings 2019: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR)*, Springer, `https://doi.org/10.1007/978-3-030-48439-2_85`

3. Holzapfel, A., Potoczki, T., Kuhn, H., 2023, **Designing the Breadth and Depth of Distribution Networks in the Retail Trade**. *International Journal of Production Economics*, Elsevier, `https://doi.org/10.1016/j.ijpe.2022.108726`

4. Potoczki, T., Holzapfel, A., Kuhn H., Sternbeck, M., 2024, **Integrated cross-dock location and supply mode planning in retail networks**, *International Journal of Production Economics*, Elsevier, `https://doi.org/10.1016/j.ijpe.2024.109349`

Beitrag 1: Supply Chain Network Design in Retail Logistics - A Conceptual Review

Der Beitrag *Supply Chain Network Design in Retail Logistics: A Conceptual Review* entwickelt einen konzeptionellen Bezugsrahmen für das strategische Supply Chain Network Design in der Handelslogistik und ordnet die einschlägige Literatur aus einer explizit handelsspezifischen Perspektive. Ausgangspunkt ist die Beobachtung, dass bestehende Forschungsarbeiten zu Standort- und Netzwerkentscheidungen zwar umfangreich sind, die besonderen Strukturmerkmale des Handels jedoch nur unzureichend integrieren. Gerade breite und heterogene Sortimente, geografisch verteilte Lieferantenstrukturen, dichte nachgelagerte Filial- bzw. Nachfragepunktnetze sowie Omni-Channel-Anforderungen führen zu ausgeprägten Interdependenzen zwischen Beschaffung, Infrastruktur und Warenfluss. Methodisch stützt sich die Arbeit auf einen semi-systematischen Literaturreview und überführt die bislang fragmentierte Forschung in ein mehrschichtiges Rahmenmodell. Dieses unterscheidet vier miteinander verknüpfte Ebenen: erstens den handelslogistischen Kontext und die zentralen Designtreiber, zweitens die strategischen Gestaltungsentscheidungen, drittens die resultierende Netzwerkkonfiguration und Flussarchitektur sowie viertens die daraus entstehenden Performanzwirkungen. Ergänzend werden Resilienz, Nachhaltigkeit, Kollaboration und E-Commerce bzw. Omni-Channel-Retailing als Querschnittsdimensionen konzeptualisiert, die mehrere Ebenen gleichzeitig beeinflussen und klassische Zielkonflikte des Netzwerkdesigns verändern. Auf dieser Grundlage systematisiert der Beitrag die Literatur zu Lieferantenauswahl, Filialstandortplanung, strategischer Lagerplanung und Cross-Dock-Planung. Die zentrale Schlussfolgerung lautet, dass strategisches Netzwerkdesign im Handel nicht als Summe isolierter Teilentscheidungen verstanden werden darf, sondern als integriertes, mehrdimensionales und langfristig wirksames Strukturproblem. Der Beitrag leistet damit vor allem einen theoretisch-konzeptionellen Beitrag: Er schafft eine übergreifende Ordnung des Forschungsfeldes, macht zentrale Interdependenzen sichtbar und formuliert eine Grundlage für zukünftige Forschung zu integrierten, resilienten und zukunftsorientierten Handelsnetzwerken.

Beitrag 2: Design of Distribution Systems in Grocery Retailing

Der Beitrag *Design of Distribution Systems in Grocery Retailing* untersucht ein strategisches Netzwerkgestaltungsproblem des Lebensmitteleinzelhandels, bei dem nicht nur die Anzahl von Distributionszentren (DC), sondern zugleich deren funktionaler Typ bestimmt wird. Ausgangspunkt ist die in der Handelspraxis verbreitete Struktur mehrstufiger Distributionssysteme, in denen unterschiedliche DC-Typen (beispielsweise zentrale, regionale oder lokale Lager) jeweils spezifische Sortimentssegmente versorgen. Die zentrale Forschungsfrage lautet, wie ein solches Netz so gestaltet werden kann, dass die langfristige Strukturentscheidung die nachgelagerte taktische Produktzuordnung bereits antizipiert. Zu diesem Zweck wird ein gemischt-ganzzahliges Optimierungsmodell (*NDPA - Network Design with Product Allocation*) entwickelt. Dieses bestimmt, welche DC-Typen eingerichtet werden sollen, und weist jedem Produkt genau einen DC-Typ zu. In die Zielfunktion gehen nicht nur Lagererrichtungs- und Betriebskosten ein, sondern auch Beschaffungstransporte, Bestandskosten, ausgehende Transporte zu den Nachfragepunkten sowie In-Store-Logistikkosten. Damit verfolgt der Beitrag eine explizit ganzheitliche Supply-Chain-Perspektive, die über klassische Standortmodelle hinausgeht. Für den Fall nicht vorgegebener Lagerstandorte (Greenfield Ansatz) wird ergänzend ein p-Median-Ansatz zur Vorbestimmung geeigneter Standorte vorgeschlagen. Die Anwendbarkeit des Ansatzes wird anhand einer Fallstudie mit Daten eines großen europäischen Handelsunternehmens demonstriert. Für das betrachtete Bestandsnetzwerk mit rund 9.000 Produkten, etwa 300 Lieferanten und 36 Nachfragepunkten zeigt sich, dass eine Umgestaltung von einem Drei-Typen-Netz auf eine Zwei-Typen-Struktur zu Kostenvorteilen führt. Die beste Lösung umfasst ein zentrales und fünf parallele regionale Lager und reduziert die gesamten entscheidungsrelevanten Supply-Chain-Kosten um rund 4 %. Besonders vorteilhaft wirken sich dabei verbesserte Bündelungseffekte im Eingangstransport und Entlastungen in der Filialogistik aus. Der Beitrag zeigt damit, dass die integrierte Betrachtung von Netzwerkstruktur und Produktallokation erhebliche Effizienzpotenziale im Handelskontext erschließen kann.

Beitrag 3: Designing the breadth and depth of distribution networks in the retail trade

Der Beitrag *Designing the breadth and depth of distribution networks in the retail trade* erweitert die strategische Netzwerkplanung im Handel um eine integrierte Betrachtung zweier grundlegender Gestaltungsdimensionen: der *Breite* des Netzwerks, also der Zahl unterschiedlicher Typen von Distributionszentren (DC), und der *Tiefe* des Netzwerks, also der Zahl parallel betriebener Lager je Typ. Ausgangspunkt ist die Beobachtung, dass Handelsunternehmen mit heterogenen Sortimenten weder allein über den Zentralisierungsgrad noch allein über funktionale Lagerdifferenzierung zu einer effizienten Lösung gelangen; vielmehr sind beide Dimensionen gemeinsam zu optimieren. Der Beitrag adressiert damit eine Forschungslücke, da bestehende Modelle diese beiden Strukturmerkmale bislang nicht simultan abbilden. Methodisch wird ein gemischt-ganzzahliges Optimierungsmodell (*NDDCT - Network Design with different DC Types*) entwickelt. Dieses bestimmt, welche DC-Typen eingerichtet werden, wie viele parallele Lager je Typ betrieben werden, an welchen Standorten sie liegen und welchen DC-Typen die einzelnen Produkte zugeordnet werden. Berücksichtigt werden fixe Standortkosten und variable Handling- und Lagerkosten, Inbound- und Outboundtransporte, Bestandskosten sowie Kosten der Filiallogistik. Damit verbindet der Beitrag strategische Netzwerkgestaltung mit den Folgewirkungen der Produktsegmentierung und geht deutlich über klassische Standortmodelle hinaus. Da das Gesamtproblem für praxisrelevante Instanzen komplex ist (*NP-hard*), wird es anhand eines hierarchischen Dekompositionsverfahren in zwei Teilmodelle zerlegt und mithilfe eines iterativen Verfahrens (*Iterated Local Search*) heuristisch gelöst. Eine Fallstudie mit Realdaten eines großen europäischen Einzelhändlers zeigt bei Anwendung des vorgeschlagenen Lösungsverfahrens ein erhebliches Optimierungspotenzial: Gegenüber der bestehenden Netzwerkstruktur lassen sich bis zu 15 % der gesamten entscheidungsrelevanten Supply-Chain-Kosten (darunter Filiallogistikkostenreduktionspotenziale von bis zu 50 %) einsparen. Die Sensitivitätsanalysen verdeutlichen zudem, dass die vorgeschlagenen Lösungen innerhalb realistischer Kostenintervalle weitgehend robust bleiben. Der Beitrag liefert somit einen substanziellen methodischen und inhaltlichen Fortschritt für die integrierte Gestaltung differenzierter Handelsnetzwerke.

Beitrag 4: Integrated cross-dock location and supply mode planning in retail networks

Der Beitrag *Integrated cross-dock location and supply mode planning in retail networks* untersucht die strategische und taktische Einbindung von Cross Docking in das Beschaffungsnetz eines Handelsunternehmens. Ausgangspunkt ist die Beobachtung, dass vorgelagerte Warenströme im Handel häufig durch eine Vielzahl von Lieferanten, heterogene Liefergrößen und fragmentierte Anlieferungen an mehrere Lager geprägt sind. Insbesondere bei Lieferanten mit niedrigen oder mittleren Volumina entstehen dadurch Less-than-Truckload-Lieferungen, die zu erhöhten Transport- und Bestandskosten führen. Der Beitrag adressiert daher die Frage, wie Cross Docking so in ein bestehendes handelstypisches Beschaffungsnetzwerk integriert werden kann, dass Bündelungseffekte systematisch generiert und die damit verbundenen Logistikkosten minimiert werden. Methodisch wird ein gemischt-ganzzahliges Optimierungsmodell entwickelt, das vier eng miteinander verknüpfte Entscheidungen simultan berücksichtigt: die Anzahl und Standorte potenzieller Cross-Docks, die Wahl des Belieferungsmodus je Lieferant (Direktbelieferung versus Belieferung über ein Cross-Dock), die Lieferfrequenz sowie das konkrete Liefermuster innerhalb eines Planungszyklus. Der Beitrag geht damit über bestehende Literatur hinaus, weil nicht nur aggregierte Flusszuweisungen modelliert werden, sondern auch operative Implikationen wie tatsächliche Bündelungseffekte, ganzzahlige Lkw-Transporte und eine ausgeglichene Auslastung der Cross-Docks über die Arbeitstage hinweg berücksichtigt werden. Da das integrierte Problem für realistische Instanzen mit Standard-MIP-Solvern schwer lösbar ist, wird ein hierarchischer Dekompositionsansatz vorgeschlagen, der das Problem in zwei aufeinander aufbauende Teilmodelle zerlegt. In einer empirischen Fallstudie mit Realdaten eines großen europäischen Einzelhändlers wird die praktische Relevanz des Ansatzes aufgezeigt. In der Fallstudie werden über 8.000 Produkte von mehr als 300 Lieferanten sowie ein Netz aus 9 bestehenden Lagern und 36 Umschlagspunkten betrachtet. Die Ergebnisse zeigen, dass durch eine geeignete Implementierung von vorgelagertem Cross-Docking mehr als 6 % der entscheidungsrelevanten Logistikkosten eingespart werden können. Die Studie leistet damit einen wesentlichen Beitrag für die integrierte Gestaltung von Beschaffungsnetzwerken im Handel, da sie strategische Standortplanung, Transportorganisation und operative Liefermuster in einem gemeinsamen Entscheidungsrahmen zusammenführt.

2 Contribution 1: Supply Chain Network Design in Retail Logistics: A Conceptual Review

This chapter is based on the following manuscript:
Tobias Potoczki. „Supply Chain Network Design in Retail Logistics: A Conceptual Review". Preprint, SSRN, 2026.
https://doi.org/10.2139/ssrn.6653679.

2.1 Introduction

Retail supply chains have undergone profound structural change in recent years. Increasing product variety, the expansion of e-commerce, growing exposure to disruptions, and ongoing technological advances have substantially increased the complexity of retail operations and heightened the need for adaptive and robust logistics systems (W. Liu et al., 2026). In this environment, the design of a retailer's supply chain network has become a critical strategic lever for balancing cost efficiency, service responsiveness, and long-term competitiveness.

Strategic supply chain network design (SCND) in retail comprises long-term decisions about sourcing structures, distribution infrastructure, fulfillment configurations, and the organization of product flows. These decisions arise not only in greenfield settings, but also in response to structural change, such as shifting demand patterns, market expansion, assortment adaptation, new channel configurations, or evolving cost conditions (Holzapfel et al., 2023). Because many of these choices require substantial investment and are only partially reversible, especially with respect to logistics infrastructure, they must be approached as strategic design decisions with long-term performance implications.

A substantial body of literature has examined facility location and network design in supply chains. Foundational reviews by Klose and Drexl, 2005, Melo et al., 2009, and ReVelle and Eiselt, 2005 provide comprehensive overviews of location-analysis and facility-design models, while more recent work highlights the benefits and methodological challenges of integrating network design with transportation, inventory, and production planning (Jalal et al., 2021). However, much of this literature adopts a generic or manufacturing-oriented perspective and therefore only partially captures the structural logic of retail distribution systems.

Retail supply chains differ in several important respects. Retailers typically manage broad assortments of heterogeneous products, source from geographically dispersed supplier bases, and serve dense downstream networks of stores, fulfillment nodes, or end customers (Kuhn and Sternbeck, 2013). These characteristics increase the need for differentiated distribution concepts, shipment consolidation, segmented infrastructure, and coordination across multiple facility types (Holzapfel et al., 2023; Potoczki et al., 2024). At the same time, the growing integration of online and offline channels changes the role of stores, warehouses, and fulfillment facilities and expands the design space of retail logistics (Tahirov and Glock, 2022).

Despite these specificities, research on retail network design remains fragmented. Core decision problems are often examined in isolation and within different research traditions, which limits understanding of how they interact to shape the structure and performance of retail distribution networks. As a result, the literature still lacks a coherent conceptual perspective that integrates the major design decisions of retail logistics and relates them to broader design requirements such as resilience, sustainability, collaboration, and omnichannel retailing.

This paper addresses that gap by developing a conceptual framework for strategic supply chain network design in retail logistics and by synthesizing the relevant literature from a retail-specific perspective. The paper makes three contributions. First, it develops a structured framework that conceptualizes retail SCND as a layered and interdependent system linking retail context and design drivers, strategic design decisions, network configuration and flow architecture, and performance outcomes. Second, it synthesizes fragmented research streams within this common structure and thereby develops a more integrated understanding of retail network design as a strategic decision problem. Third, it shows how major contemporary developments reshape traditional network design trade-offs by altering sourcing choices, facility requirements, flow structures, and the performance logic of retail distribution networks.

Methodologically, the study follows a semi-systematic literature review approach as outlined by Snyder, 2019, combining structured literature identification with a concept-driven synthesis. The conceptual framework developed in this paper provides the basis for positioning, relating, and synthesizing the existing literature.

The remainder of the paper is structured as follows. Section 2 develops the conceptual framework for strategic network design in retail logistics. Sections 3 to 5 review the main structural decision domains of retail SCND, while Section 6 discusses the broader design dimensions that increasingly reshape these decisions. Section 7 concludes with the central insights of the review and outlines directions for future research.

2.2 Conceptual Framework for Strategic Network Design in Retail Logistics

Strategic retail network design is characterized by strong interdependencies between upstream sourcing, intermediate distribution structures, and downstream demand fulfillment. Warehouses, cross-docks, stores, and e-commerce fulfillment nodes cannot be effectively designed in isolation because their roles, capacities, and economic viability depend on how they interact within the broader network (Kuhn and Sternbeck, 2013; Andrejić, 2023). Yet, as outlined in the introduction, existing research largely treats the relevant decision domains separately, and a comprehensive conceptual structure tailored specifically to retail SCND remains lacking (Hübner et al., 2013; Jalal et al., 2021).

To address this gap, this section develops a conceptual framework that organizes strategic network design in retail logistics as a layered system of interdependent elements. The framework distinguishes between (1) retail context and design drivers, (2) strategic design decisions, (3) network configuration and flow architecture, and (4) performance outcomes.

2.2.1 Retail Context and Design Drivers

Retail supply chains exhibit structural characteristics that distinguish them from manufacturing oriented supply networks and strongly shape strategic network design decisions. A defining feature of retail logistics is the multi-product environment, in which firms manage broad assortments of heterogeneous products with different demand patterns, value densities, storage requirements, and service expectations (Holzapfel et al., 2018). Closely related is the multi-supplier structure, where retailers source from a large and often geographically dispersed supplier base (Kalchschmidt et al., 2020). On the demand side, retail networks are characterized by multiple sinks, traditionally represented by stores, but increasingly also by end customers in e-commerce and omni-channel settings (Wollenburg et al., 2018). Together, these characteristics increase network complexity and require differentiated planning approaches. In addition, the upstream and downstream parts of the retail network differ structurally: upstream flows are typically convergent and bundling-oriented, whereas downstream flows are divergent and service-oriented, implying different planning logics across network tiers (Potoczki et al., 2024).

At the same time, retailing is not a homogeneous context. Different retail sectors are subject to distinct logistical, regulatory, and service requirements (Onstein et al., 2022). Grocery retail, for example, differs markedly from pharmaceutical or fashion retail with respect to perishability, delivery frequency, assortment dynamics, and product handling requirements (Lagorio and Pinto, 2021; Fani et al., 2025; Luo et al., 2026). In the present framework, such sectoral variation is captured primarily through product characteristics and associated planning requirements, although sector-specific conditions may additionally affect the relevance and feasibility of particular design options. From a supply chain perspective, these structural characteristics can be interpreted as fundamental attributes of network topology and material flow structure that define relevant planning requirements and the feasible design space (Fleischmann and Meyr, 2003). In retail, they are reinforced by strong interdependencies between logistics subsystems, particularly between distribution structures and store operations (Kuhn and Sternbeck, 2013), and by the need to align product characteristics with differentiated distribution concepts (Holzapfel et al., 2023). Beyond these structural features, strategic positioning acts as a central design driver. Retailers typically face persistent trade-offs between cost efficiency and service responsiveness, which directly influence network structure decisions (Esmizadeh and Mellat Parast, 2021). The preferred network design therefore depends not only on technical parameters such as shipment volumes or facility costs, but also on the retailer's competitive positioning and service strategy (Fisher, 1997).

Finally, external developments increasingly reshape the design space of retail logistics. The rise of e-commerce and omni-channel retailing introduces additional fulfillment structures and more complex flow patterns (Tahirov and Glock, 2022). At the same time, disruption risks and sustainability pressures require retailers to incorporate resilience and environmental objectives into strategic network design. These developments expand the traditional cost-service trade-off and increase the need for more flexible and adaptive network structures (Aldrighetti et al., 2021).

2.2.2 Strategic Design Decisions

Within this context, strategic network design can be conceptualized as a set of interrelated decision domains that jointly determine the long-term structure of the retail distribution system (Chopra, 2003). In retail, these decisions can be grouped into four main areas: upstream structure decisions, downstream demand-node decisions, intermediate facility decisions, and flow-architecture decisions.

First, upstream structure decisions define the sourcing side of the network. They include supplier selection, sourcing strategies, and the geographical configuration of the supplier base. These choices influence inbound transport structures, supply risk exposure, and the feasibility of shipment consolidation (Kalchschmidt et al., 2020). In particular, supplier-specific shipment volumes, delivery frequencies, and handling requirements affect whether direct shipping, warehousing, or cross-docking is economically and operationally viable (Potoczki et al., 2024).

Second, downstream demand-node decisions concern the structure of the retail demand network. In traditional store-based retailing, this primarily includes store location, store format, and the spatial distribution of outlet demand (Reynolds and Wood, 2010). In omni-channel settings, it also includes the role of stores as potential fulfillment nodes and the position of end customers as decentralized demand points (Wollenburg et al., 2018). The spatial distribution of demand shapes these decisions, which in turn affect service requirements and transportation needs.

Third, intermediate facility decisions address the design of the distribution infrastructure between suppliers and demand nodes. This includes decisions on the number, location, capacity, specialization, and technological configuration of warehouses, fulfillment centers, and cross-docking facilities. Because such facilities require substantial capital investment and have long-term implications for transportation, inventory positioning, and service responsiveness, they represent a central component of strategic SCND (Melo et al., 2009; Holzapfel et al., 2023).

Fourth, flow-architecture decisions determine how products move through the network. These decisions include the choice between alternative distribution concepts, such as direct shipping, warehousing, and cross-docking, as well as decisions on shipment consolidation, allocation of product segments to specific distribution channels, transportation modes, and outsourcing structures (Chopra, 2003; Melo et al., 2009). In contrast to the preceding decision areas, which concern the structural elements of the network, flow-architecture decisions define the logic by which these elements are connected and utilized.

These decision domains are strongly interdependent. Supplier structures affect the feasibility of consolidation concepts; downstream demand patterns influence the attractiveness of centralized versus decentralized facilities; and facility decisions must be coordinated with transportation and inventory considerations to achieve overall system efficiency (Melo et al., 2009; Jalal et al., 2021). This interdependence is also evident in integrated location-routing and direct-shipment models, which show that jointly optimizing structural and flow-related decisions can outperform sequential planning approaches (Azizi and Hu, 2020). Strategic retail network design should therefore be conceptualized as an integrated planning problem rather than as a set of isolated decision tasks.

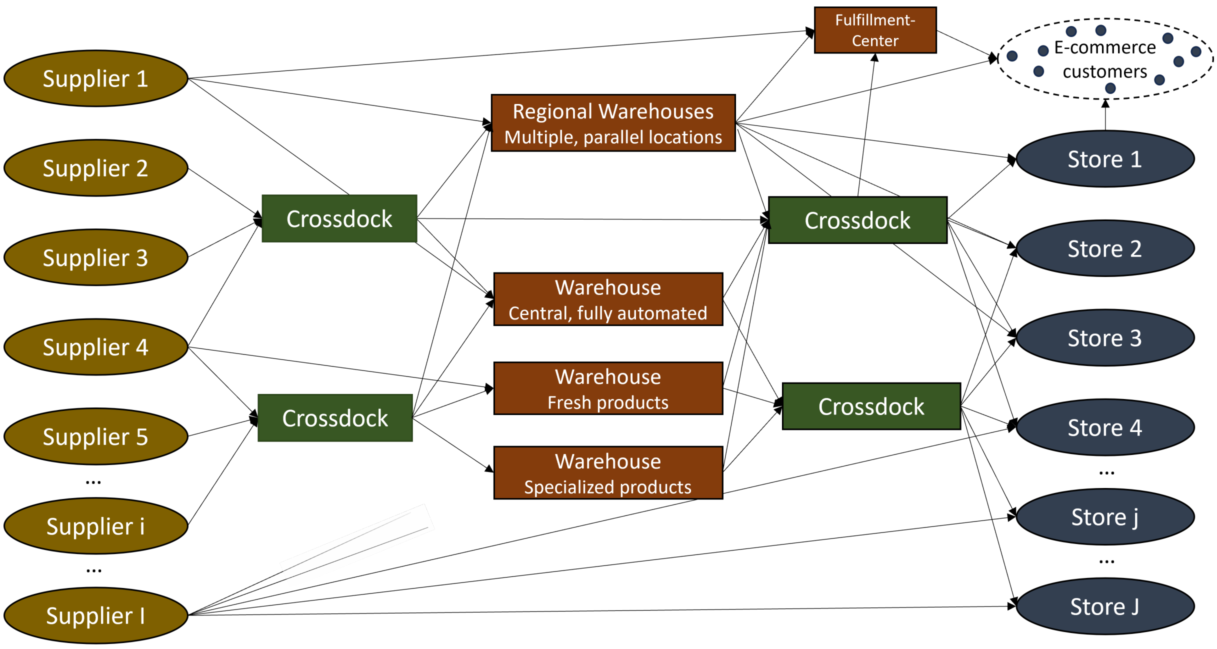

Figure 2.1: Schematic example of a hybrid retail distribution network

2.2.3 Network Configuration and Flow Architecture

The combination of strategic design decisions results in a specific network configuration and flow architecture, which together represent the structural manifestation of the retail distribution system. From a topological perspective, retail supply chain networks consist of suppliers, intermediate facilities, and downstream demand nodes. A key design issue concerns the number, type, and arrangement of intermediate facilities within this topology. In retail logistics, three fundamental distribution concepts are commonly distinguished: direct shipping, warehousing, and cross-docking. In practice, however, hybrid and multi-echelon structures are frequent (Kuhn and Sternbeck, 2013). Figure 2.1 illustrates such a hybrid retail distribution system by showing how suppliers, cross-docks, warehouses, fulfillment centers, stores, and e-commerce customers may be connected within one network.

Network configuration is not only a matter of topology, but also of facility typology and the degree of centralization. Retailers must decide whether to rely on a small number of highly centralized facilities, a more decentralized regional network, or a multi-echelon combination of both. Centralized structures enable inventory pooling and economies of scale, whereas decentralized configurations improve local responsiveness and reduce transport distances to demand points (Fleischmann, 2016; Holzapfel et al., 2023). In many retail settings, this trade-off leads to differentiated multi-echelon systems that combine central and regional facilities with distinct operational roles (Onstein et al., 2022).

In addition, the resulting network must be interpreted in terms of product flow architecture.

A central question is whether all products should follow a standardized distribution logic or whether different product segments should be assigned to different network pathways. Such segmentation is particularly relevant in retail due to heterogeneous assortments and varying service requirements (Holzapfel et al., 2018). Flow design therefore concerns not only which facilities exist, but also which suppliers, products, or shipment types are routed through them. In particular, retail flow design often requires assigning suppliers or product flows to alternative transport concepts, such as direct-to-warehouse delivery versus routing via cross-docks, under heterogeneous shipment-volume and delivery-frequency conditions (Potoczki et al., 2024).

2.2.4 Performance Outcomes and Strategic Trade-offs

The resulting network configuration affects performance along several dimensions central to strategic retail logistics. At the most fundamental level, network design shapes total logistics cost and service performance (Fisher, 1997). Facility number and location influence fixed infrastructure costs and transportation distances; flow architecture affects shipment consolidation and handling costs; and the degree of centralization affects both inventory pooling and delivery responsiveness (Esmizadeh and Mellat Parast, 2021). However, strategic retail network design should not be evaluated solely in terms of cost and service. Network configuration also influences resilience, sustainability performance, and structural adaptability (Aldrighetti et al., 2021; Govindan et al., 2015; Tai et al., 2023; Holzapfel et al., 2023). For example, redundancy in suppliers or facilities may improve robustness against disruptions but increase fixed costs. Similarly, centralized structures may lower inventory and facility costs while increasing transport-related emissions or reducing responsiveness in certain service environments. The framework therefore conceptualizes performance outcomes as multidimensional and shaped by trade-offs rather than by a single optimization criterion. In retail settings, the central trade-offs typically arise between efficiency and responsiveness, consolidation and flexibility, centralization and proximity, as well as robustness and cost minimization.

2.2.5 Cross-cutting Design Dimensions

In addition to the core structural and flow-related decisions, several cross-cutting dimensions influence multiple layers of the framework simultaneously. These dimensions do not constitute separate planning areas in the same sense as supplier selection or warehouse design; rather, they modify decision criteria, alter feasible configurations, and reshape performance trade-offs.

Resilience influences network design by increasing the importance of redundancy, diversification, and flexibility. This affects sourcing choices, such as multi-sourcing, as well as infrastructure decisions regarding backup capacity, redundant facilities, and alternative transport structures (Aldrighetti et al., 2021). Resilience therefore modifies both strategic decisions and the evaluation of performance outcomes.

Sustainability affects network design by introducing environmental objectives and constraints into facility placement, transportation planning, and consolidation logic. This includes considerations such as emissions from transport and facility operations, carbon pricing, load factor improvements, and the trade-off between transportation intensity and facility consolidation (Govindan et al., 2015; Colicchia et al., 2015; Tai et al., 2023). Sustainability thus changes both the objective structure of network design and the desirability of particular configurations.

Omni-channel integration changes the structure of the retail network by introducing additional fulfillment pathways, new node types, and new interactions between channels. Stores may serve not only as demand points but also as fulfillment nodes; dedicated e-fulfillment centers may complement traditional distribution centers; and direct-to-customer flows become strategically relevant. Omni-channel retailing therefore affects context conditions, decision domains, network configuration, and the resulting performance trade-offs (Ishfaq et al., 2016; Wollenburg et al., 2018; Tahirov and Glock, 2022).

Collaboration represents an additional cross-cutting dimension because it changes the organizational boundaries within which network design takes place. Shared facilities, pooled transportation resources, and outsourcing arrangements with logistics service providers can expand the feasible design space and alter the economics of centralization, capacity utilization, and spatial coverage (Quintero-Araujo et al., 2017; Ouhader and El Kyal, 2017; Ben Jouida et al., 2021). As a result, collaboration affects the structure of strategic decisions and the set of attainable network configurations.

2.2.6 Framework Synthesis

The proposed framework conceptualizes strategic retail network design as a layered and interdependent system. Retail-specific context characteristics and external drivers define the environment in which strategic decisions are made. These decisions jointly shape network configuration and flow architecture, which in turn determine multidimensional performance outcomes. Cross-cutting design dimensions modify this logic by influencing both the choice of design options and the criteria by which alternative configurations are evaluated.

Table 2.1: Strategic planning areas in retail supply chain network design

Planning area	**Key decisions**	**Selected aspects**
Supplier selection	Upstream structure	Geographical sourcing structure, product portfolio fit, delivery reliability, shipment volumes and frequencies, contractual constraints, sustainability and resilience criteria
Store location planning	Downstream demand-node design	Number and location of outlets, store formats, market potential, competitor proximity, service coverage, omni-channel role of stores
Warehouse planning	Intermediate facility design	Number, location, capacity, and specialization of DCs; degree of centralization; automation and warehouse design; differentiated DC types
Cross-dock planning	Intermediate facility and flow integration	Number and location of CDs; consolidation type; process variant; interaction with warehouse structures and inbound shipment patterns
Flow architecture	Distribution concept and transport design	Direct shipping vs. warehousing vs. cross-docking; product-flow segmentation; shipment consolidation; transport mode; outsourcing decisions
Cross-cutting design dimensions		
Resilience	Robustness and flexibility	Multi-sourcing, facility redundancy, safety stock positioning, scenario-robust design, recovery capability
Sustainability	Environmental performance	Emission minimization, green transport modes, facility consolidation trade-offs, carbon pricing integration
Omni-channel	Multi-channel fulfillment integration	E-fulfillment center placement, ship-from-store, click-and-collect, returns integration, inventory pooling
Collaboration	Shared network structures	Shared warehouses and transport, pooled volumes, outsourcing, coalition-based infrastructures, governance and coordination requirements
Performance outcomes	Strategic evaluation criteria	Total logistics cost, service level, lead time, resilience, sustainability performance, adaptability and complexity

Table 2.1 summarizes the principal strategic planning areas and cross-cutting dimensions captured by the framework and provides orientation for the remainder of the paper. The subsequent sections review the literature along the key strategic decision domains: Section 3 examines supplier selection and store location planning as the design of upstream and downstream network structures; Section 4 addresses strategic warehouse planning as the central intermediate-facility problem; Section 5 analyzes cross-docking as a strategic option at the interface of facility design and flow architecture; and Section 6 discusses cross-cutting dimensions that reshape retail network design beyond traditional cost–service considerations.

2.3 Supplier Selection and Store Location Planning

Supplier selection and store location planning define the upstream and downstream anchors of retail distribution networks and therefore constitute a foundational part of strategic supply chain network design. While supplier-related decisions shape the geography, reliability, and fragmentation of inbound flows, store location decisions determine the spatial distribution of demand and the service requirements imposed on the network. Together, these decision domains delimit the feasible set of distribution structures, influence the attractiveness of centralization versus decentralization, and condition the design of warehouses, cross-docking systems, and transport concepts.

2.3.1 Supplier Selection

The supplier base represents a key determinant of the upstream structure of retail supply chains. It shapes inbound transport patterns, affects risk exposure, and constrains the set of feasible distribution concepts. For this reason, supplier selection should not be treated solely as an isolated procurement problem, but as an integral component of strategic network design (Kalchschmidt et al., 2020). From a network-design perspective, the most relevant supplier characteristics are those that affect the spatial and operational structure of inbound flows. These include supplier location, product portfolio characteristics, shipment volumes and delivery frequencies, delivery reliability, lead times, purchase prices, and specific handling or storage requirements. Additional considerations include expansion potential, contractual constraints such as minimum order quantities or delivery frequencies, and exclusivity arrangements (Weber et al., 1991; Wetzstein et al., 2016; Heese, 2025). Such factors influence transport distances, bundling potential, inventory-buffering needs, and the economic viability of alternative distribution concepts. In particular, recent retail-specific research shows that supplier shipment structures can be decisive for the choice between direct deliveries and cross-dock-based inbound consolidation (Potoczki et al., 2024).

The supplier selection problem has been extensively studied in the literature, as reflected in major review contributions by Zimmer et al., 2015, Fahimnia et al., 2015, Wetzstein et al., 2016, and Chai and Ngai, 2020. Much of this literature addresses supplier evaluation from a multi-criteria or procurement perspective, often focusing on trade-offs among cost, quality, delivery reliability, flexibility, and sustainability. For retail network design, however, the key issue is not only how suppliers are evaluated individually, but how supplier structures propagate through the logistics system and shape the architecture of the network. Despite these interdependencies, supplier selection and network design are often treated separately in the literature, partly because both problem classes are analytically complex and have evolved in different research streams. Nevertheless, integrated approaches show substantial benefits in terms of overall supply chain performance. Benyoucef et al., 2013 and Kuderinova et al., 2021, for example, demonstrate that jointly considering supplier-related and network-related decisions can improve logistics efficiency relative to sequential planning. Even where decisions are made sequentially, the dynamic evolution of supplier portfolios should be reflected in long-term facility and flow design choices (Emirhüseyinoğlu and Ekici, 2019).

Recent research has also increasingly incorporated resilience and sustainability considerations into supplier selection, although much of this work remains rooted in manufacturing rather than retail settings (Zimmer et al., 2015; Fahimnia et al., 2015). These dimensions are nevertheless highly relevant for retail network design because supplier-related risks and environmental impacts influence the downstream logistics system and affect the value of redundancy, diversification, and consolidation (Dolgui and Ivanov, 2021). From a strategic SCND perspective, supplier selection can therefore be understood as a structural design decision that shapes inbound flow characteristics, affects the need for differentiated facilities, and helps determine the feasible architecture of the retail supply network.

2.3.2 Store Location Planning

In traditional retail systems, stores constitute the primary demand nodes, and their number, location, format, and market positioning directly affect transport requirements, service expectations, and the design of the distribution infrastructure (Huff, 1963; Brown, 1994; Reynolds and Wood, 2010). Store location planning differs from many other SCND decisions in that it is strongly influenced by market-facing considerations. Store locations determine customer access, local demand capture, and competitive positioning, and are therefore closely tied to revenue generation. From a supply chain perspective, however, these market-oriented objectives must be reconciled with logistics efficiency, resulting in a strategic trade-off between maximizing market coverage and ensuring cost-efficient replenishment and service provision (Brown, 1994). This tension is particularly important in retail, where store networks often evolve incrementally and where expansion, restructuring, and downsizing decisions coexist (Wood and Reynolds, 2011).

The key strategic decisions in this domain concern the number, location, size, and format of stores, as well as their role within the broader retail system. Store formats may differ substantially in terms of assortment breadth, service concept, and logistics requirements, implying that store network design is closely linked to distribution structures and segmentation logics (Arrigo, 2015). More generally, store location planning is often structured along a macro–micro distinction (Brown, 1994): macro-level decisions concern the selection of regions, cities, or districts, whereas micro-level decisions address the exact positioning of individual outlets. Both levels require robust demand assessment and an understanding of local competitive conditions. A broad body of literature examines the determinants of store performance and location attractiveness. Particularly relevant factors include market potential, demographic and socio-economic conditions, accessibility, visibility, real-estate constraints, and the local competitive environment (Reynolds and Wood, 2010; Wood and Reynolds, 2012; Wieland, 2017; Formánek and Sokol, 2022). The competitive effects of store clustering are especially important. While proximity to other retailers may increase demand through agglomeration and shared footfall, empirical evidence suggests that these benefits diminish once competition exceeds a critical threshold (Seong et al., 2022). In addition, retailers must account for internal network effects, especially cannibalization between outlets and the role of stores within a broader spatial portfolio (Reynolds and Wood, 2010).

Methodologically, store location planning has generated a diverse body of work. Traditional approaches include gravity-based and market-area models, most prominently the Huff model (Huff, 1963), as well as analog methods and regression-based site evaluation (Brown, 1994; Reynolds and Wood, 2010; Wood and Reynolds, 2011). More recent work complements these approaches with optimization models, multi-criteria decision-making methods, GIS-based analyses, and machine-learning techniques for location assessment and sales forecasting (Formánek and Sokol, 2022; Lin et al., 2022). Although these methods differ in emphasis, they share the objective of linking expected demand and competitive positioning to a feasible spatial store network. In practice, analytical approaches are often combined with managerial judgment and experience-based decision-making (Reynolds and Wood, 2010).

The growing importance of multi- and omni-channel retailing has further increased the strategic relevance of store location planning. Stores are no longer evaluated solely as customer-facing sales outlets, but also as potential logistics nodes for online demand. Concepts such as ship-from-store and click-and-collect mean that outlet locations can affect not only market access but also local fulfillment capability, delivery responsiveness, and inventory deployment (Wollenburg et al., 2018; J. Chen et al., 2022; Lin et al., 2022). As a result, stores may simultaneously function as demand nodes and decentralized operational nodes within the retail distribution system.

2.4 Strategic Warehouse Planning

Warehouses constitute the central intermediate infrastructure of retail distribution networks. They connect upstream sourcing structures with downstream demand nodes and thereby translate strategic network design decisions into logistics performance. In retail, warehouse planning extends beyond storage capacity decisions to the design of an infrastructure that positions inventory, consolidates flows, supports differentiated service requirements, and links heterogeneous product segments to appropriate distribution concepts (Gu et al., 2010; Holzapfel et al., 2023).

Functionally, warehouses decouple supply and demand by providing inventory buffers and enabling the temporal and spatial coordination of material flows (Boysen et al., 2021). This role is particularly important in retail, where demand is fragmented across many stores or end customers and supply originates from multiple suppliers with heterogeneous shipment structures. By holding inventory at intermediate facilities, retailers can stabilize service levels, shorten replenishment lead times, and mitigate upstream uncertainty (Erlebacher and Meller, 2000; Shen and Qi, 2007). Warehouses also facilitate consolidation, sorting, and assortment-building processes essential for efficient downstream distribution (De Koster et al., 2017). Their strategic importance therefore lies in their simultaneous impact on transportation structures, inventory positioning, and service responsiveness.

2.4.1 Core Strategic Decision Areas

Strategic warehouse planning comprises three interrelated decision areas: network structure, warehouse differentiation, and facility configuration.

First, retailers must determine the overall structure of the warehouse network, including the number of facilities, their roles within the system, and the degree of centralization. These choices shape the balance between inventory pooling, transportation effort, and responsiveness. Highly centralized systems allow economies of scale and lower aggregate inventory levels, but often increase outbound transport distances and reduce local responsiveness

(Fleischmann, 2016). More decentralized structures shorten lead times and improve service proximity, but require duplicated inventories and higher fixed infrastructure costs. In practice, many retailers adopt hybrid multi-echelon systems that combine central and regional facilities to balance these competing objectives (Holzapfel et al., 2020; Holzapfel et al., 2023).

Second, warehouse planning involves differentiation across facility types. Retail assortments are typically heterogeneous with respect to demand characteristics, value density, handling requirements, perishability, and service expectations, making a single standardized warehouse concept inefficient for the entire product portfolio (Holzapfel et al., 2018). Recent retail-specific research therefore emphasizes that strategic warehouse planning concerns not only the depth of the network, that is, the number of facilities, but also its breadth, meaning the number of different warehouse types assigned to different product segments (Holzapfel et al., 2023). Differentiated structures may include specialized facilities for temperature-sensitive products, high-throughput facilities for fast-moving items, or channel-specific facilities for e-commerce demand (Boysen et al., 2019; Boysen et al., 2021; Schorung et al., 2024). Warehouse planning is thus closely linked to product segmentation and the broader flow architecture of the network.

Third, facility configuration concerns warehouse design, process structure, and automation. These decisions define the technological and organizational setup of individual facilities and shape their long-term role within the network. Strategic warehouse design has long been recognized as a multi-dimensional planning problem involving systems, resources, equipment, and internal process flows (Rouwenhorst et al., 2000; Baker and Halim, 2007). More recent research highlights that automation is not merely a tactical process issue but a strategic configuration choice because it interacts with network centralization, throughput structure, product segmentation, and channel strategy (Dubey and Veeramani, 2017; Boysen et al., 2019; Boysen et al., 2021; Zhen and H. Li, 2022; Fatima et al., 2022; Kembro and Norrman, 2025). Highly automated facilities may be particularly attractive in centralized and high-volume settings, whereas more flexible and labor-intensive solutions may be preferable in differentiated or uncertain environments.

2.4.2 Warehouse Location Planning

Within this broader infrastructure-design problem, warehouse location planning captures the spatial dimension of strategic warehouse design. It addresses where warehouses should be placed, how many should be operated, and which demand nodes and product flows should be assigned to them. Because these decisions require substantial long-term investment and affect transportation costs, service levels, and inventory deployment, they have long been central to SCND research (Klose and Drexl, 2005; Melo et al., 2009).

The analytical literature on warehouse location planning builds on classical facility location models. At the most fundamental level, the problem can be represented by continuous formulations such as multi-source Weber-type models or by discrete formulations such as the p-median problem introduced by Hakimi, 1964. A central distinction concerns capacitated versus uncapacitated facility location problems, depending on whether warehouse capacities are modeled explicitly (Melo et al., 2009). Many contributions also extend the problem from single-echelon to multi-echelon structures to reflect the hierarchical architecture of distribution systems (Tcha and B.-I. Lee, 1984; Şahin and Süral, 2007).

Subsequent research has incorporated a broader set of practically relevant considerations. Dynamic and stochastic formulations account for temporal change and uncertainty in demand or supply conditions (Ballou, 1968; Mirchandani et al., 1985; Canel et al., 2001). Multi-commodity formulations explicitly consider multiple products with heterogeneous characteristics, building on early contributions such as Warszawski and Peer, 1973 and Geoffrion and Graves, 1974 and later extensions including Pirkul and Jayaraman, 1998, Jayaraman and A. Ross, 2003, Keskin and Üster, 2007, and Camm et al., 1997. These developments are especially relevant in retail, where broad assortments and product-specific constraints may strongly affect feasible facility structures. A distinctive feature of retail warehouse location planning is that facilities often differ not only in location and capacity, but also in functional role and technological design. Retailers may operate different distribution center types for different product groups, service requirements, or channels. In such settings, location planning must be linked to decisions about facility typology and product allocation (Holzapfel et al., 2023). This perspective is particularly useful in retail because it captures the fact that warehouse location decisions are inseparable from assortment structure, channel differentiation, and distribution logic.

From an objective-function perspective, warehouse location models traditionally emphasize the trade-off between fixed facility costs and transportation costs (Klose and Drexl, 2005; Melo et al., 2009). For retail networks, however, this view is often too narrow. The number and location of warehouses also affect inventory consolidation, replenishment frequency, and service responsiveness, implying that inventory-related and service-related considerations should be incorporated into strategic design. Important extensions therefore integrate inventory costs and replenishment decisions, for example through the square-root law logic in Erlebacher and Meller, 2000 building on Maister, 1976, or through joint location–inventory models such as Teo and Shu, 2004. Further work incorporates transport discounts and routing-related effects into strategic facility decisions (Tsao and Lu, 2012; Shen and Qi, 2007). Collectively, these extensions reflect a broader shift from isolated facility-location analysis toward integrated network design.

2.5 Strategic Cross-dock Planning

Cross-docking constitutes a major design option in retail distribution networks and complements traditional warehousing and direct-shipping concepts. From a strategic perspective, it affects both the physical network configuration and the flow architecture of the supply chain by enabling the consolidation, sorting, and redirection of shipments without long-term storage. In retail settings, cross-docking is particularly relevant where inbound shipment structures are fragmented, supplier deliveries are frequent but small, and downstream distribution requires efficient consolidation and synchronization of flows. Recent retail-specific work therefore suggests that cross-docking should be understood not as a stand-alone facility concept, but as an integrated element of retail supply chain network design that interacts closely with sourcing structures, warehouse configurations, and transport decisions (Apte and Viswanathan, 2000; Belle et al., 2012; Kuhn and Sternbeck, 2013; Potoczki et al., 2024).

2.5.1 Role of Cross-docking in Retail Distribution Networks

The strategic rationale for cross-docking lies in its ability to improve transport utilization and to reduce inefficiencies associated with fragmented material flows. In retail supply chains, especially in grocery and other high-frequency replenishment environments, suppliers often generate less-than-truckload inbound shipments destined for a limited number of downstream warehouses or retail locations. Cross-docking enables such fragmented flows to be consolidated into more efficient line-haul transports and redistributed without the need for long-term storage (Apte and Viswanathan, 2000; Potoczki et al., 2024).

Two fundamental consolidation logics can be distinguished. First, inter-supplier consolidation bundles shipments from multiple suppliers at an upstream cross-docking facility in order to create high-utilization transports to downstream facilities. Second, intra-supplier consolidation allows a supplier serving multiple destinations to deliver in larger loads to a cross-dock, where the shipment is subsequently split and redirected to individual destinations (Potoczki et al., 2024). Figure 2.2 illustrates these mechanisms schematically. It shows how fragmented inbound shipments can be consolidated into high-utilization line-haul transports at an upstream cross-dock and later disaggregated into destination-specific outbound flows at a downstream cross-dock. The same concept can be (inversely) applied for the distribution of products from warehouses to demand points. In this case, shipments from different warehouses can be bundled in cross-docks to achieve inter-warehouse

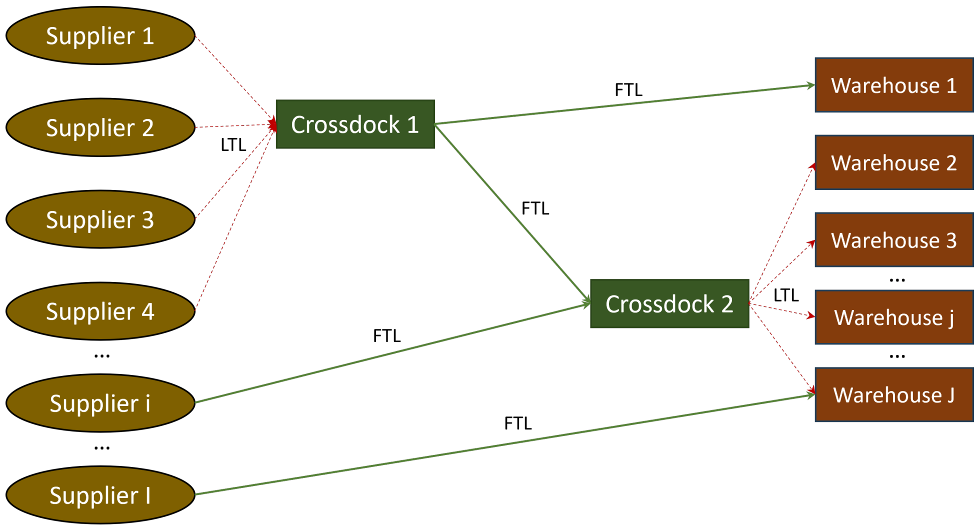

Figure 2.2: Schematic illustration of two cross-docking consolidation mechanisms: LTL-to-FTL consolidation at an upstream cross-dock and break-bulk from FTL to LTL at a downstream cross-dock

consolidation effects; likewise intra-warehouse consolidation effects can be achieved when shipments from one warehouse with multiple destinations are jointly transported on the main leg and broken up at a cross-dock that is situated close to major demand points. Beyond transportation consolidation, cross-docking also affects inventory positioning and the role of intermediate facilities in the network. By enabling more frequent replenishment in smaller lot sizes, it may reduce average inventory levels at downstream warehouses and thereby lower holding costs. At the same time, the use of cross-docks introduces additional handling operations and may increase lead times if detours or synchronization requirements become substantial (Gümüş and Bookbinder, 2004; Benrqya et al., 2020). Recent retail-specific analysis further shows that inbound cross-docking may reduce warehouse ramp contacts and associated receiving effort, thereby creating operational benefits beyond pure transportation savings (Potoczki et al., 2024).

A defining characteristic of cross-docking is the absence of long-term storage. Goods typically remain in the facility for less than 24 hours and are dispatched on the same day (Belle et al., 2012). Importantly, this functionality does not necessarily require dedicated facilities; cross-docking processes may also be embedded within conventional warehouses, resulting in mixed warehouse concepts (Apte and Viswanathan, 2000). This underlines the close relationship between warehouse planning and cross-dock planning in retail network design.

The suitability of cross-docking depends strongly on product and demand characteristics. It is particularly attractive for products with stable demand, predictable replenishment cycles, and substantial bundling potential, as often found in grocery retailing (Apte and Viswanathan, 2000; Vogt, 2010). Conversely, highly irregular or low-volume flows may limit its effectiveness. This product selectivity also links cross-dock planning to warehouse planning, since smaller and more frequent replenishment may reduce storage requirements, while the magnitude of this effect depends on the underlying storage policy. Cross-docking should therefore be conceptualized as a selective and context-dependent design option rather than as a universally superior alternative to warehousing (Potoczki et al., 2024).

2.5.2 Success Factors and Operational Preconditions

The effectiveness of cross-docking depends on several structural and operational prerequisites. A central requirement is sufficient bundling potential, which is determined by shipment volumes, supplier structure, delivery frequencies, and the degree of demand aggregation. Without adequate shipment density and synchronization, the transport benefits of cross-docking may not compensate for the additional handling effort introduced at the facility (Apte and Viswanathan, 2000; Belle et al., 2012; Vogt, 2010). A second prerequisite is the operational feasibility of delivery patterns. Cross-docking performance depends not only on aggregate flow volumes but also on the temporal structure of inbound and outbound shipments. In this context, Potoczki et al., 2024 show that models relying on overly aggregated or linearized transport assumptions may substantially overestimate bundling effects and therefore the economic value of cross-docking. This observation is highly relevant for strategic planning, as it indicates that cross-dock design must remain grounded in operationally feasible transport patterns. A third success factor is information transparency and coordination across supply chain actors. Because cross-docking requires tight synchronization of inbound and outbound flows, delays, forecast errors, or poor information exchange may propagate rapidly through the system and undermine consolidation benefits (Apte and Viswanathan, 2000; Belle et al., 2012; Benrqya et al., 2020). Consequently, cross-docking is closely linked to planning capabilities and information-system support.

The economic attractiveness of cross-docking also depends on how transportation responsibilities are allocated between retailers and suppliers. If inbound transportation is supplier-managed, part of the consolidation benefit may accrue upstream and therefore require contractual coordination; by contrast, under EXW-type arrangements (Ex Works: transport responsibility transfers to the buyer at the supplier's premises), transportation savings directly benefit the retailer (Potoczki et al., 2024). At the same time, the benefits of cross-docking must be weighed against its drawbacks. Additional transshipment operations increase handling complexity and cost, while detours via cross-docks may lengthen transport paths and increase pipeline inventory (Gümüş and Bookbinder, 2004; Benrqya et al., 2020). These trade-offs imply that cross-docking is not a purely cost-saving mechanism;

rather, its strategic attractiveness depends on whether transport consolidation, inventory effects, and operational implications jointly support the overall network design.

2.5.3 Process Variants and Cross-dock System Design

Cross-docking is not a homogeneous concept but encompasses several operational variants that differ in the allocation of sorting and consolidation tasks. The literature commonly distinguishes between alternative process configurations that vary in complexity, supplier involvement, and facility requirements (Napolitano, 2000; Yan and Tang, 2009; Vogt, 2010; Benrqya et al., 2020).

In pre-allocated supplier consolidation, suppliers pre-sort shipments according to their final destinations before delivery to the cross-dock. This allows pallets or shipments to be transferred quickly from inbound to outbound vehicles with limited handling effort at the facility. Such a design reduces processing complexity at the cross-dock but requires strong upstream coordination and supplier process capabilities (Napolitano, 2000; Vogt, 2010).

In contrast, CD operator consolidation shifts sorting and consolidation activities to the cross-docking facility. Suppliers deliver undifferentiated shipments, which are then sorted, broken down, and reassembled by the operator according to downstream destinations. This variant offers greater flexibility but requires more handling effort, more sophisticated process design, and higher operational coordination (Yan and Tang, 2009; Benrqya et al., 2020). Depending on whether pallets remain intact or are reconfigured at the facility, additional differences in labor intensity, equipment needs, and process complexity arise. In retail settings, pre-allocated supplier consolidation may be a particularly plausible starting configuration when cross-docking is introduced for the first time, because suppliers often already prepare shipments for specific warehouse destinations in direct-shipping systems.

These process variants have direct strategic implications. They affect facility design, labor requirements, information-system needs, and the division of tasks between suppliers and the retailer or logistics service provider. As a result, the choice of cross-docking variant should be treated as part of strategic network design rather than as a purely operational issue. It determines how cross-docks can be embedded into the wider distribution system and which upstream and downstream structures are compatible with their effective use.

2.5.4 Cross-dock Location Planning

From a strategic perspective, the placement of cross-docking facilities represents a location problem that is tightly linked to transportation and flow design. The relevant literature distinguishes between strategic decisions on the number and location of facilities, tactical decisions on flow allocation, and operational decisions on scheduling and dock assignment (Belle et al., 2012). In retail contexts, these levels are strongly interdependent because the economic value of cross-docking depends on both spatial consolidation opportunities and temporally feasible transshipment processes.

Conceptual contributions emphasize that cross-dock locations should be aligned with shipment structures and bundling potential. Upstream cross-docks are typically located close to supplier clusters in order to facilitate early consolidation, whereas downstream cross-docks may be positioned nearer to demand points or downstream facilities in order to support efficient regional distribution (Apte and Viswanathan, 2000; Vogt, 2010). In contrast to traditional warehouse location planning, however, cross-dock location decisions must explicitly account for synchronization requirements and transshipment logic. Their attractiveness is therefore shaped not only by distances and volumes, but also by timing constraints and the direction of consolidation flows.

Recent retail-specific work extends this perspective by jointly considering cross-dock location, supplier-specific flow assignment, and delivery-frequency decisions in an existing warehouse network. Potoczki et al., 2024 show that cross-dock location in retail cannot be separated from shipment structure and transport organization, since the profitability of a cross-dock depends critically on which suppliers use it, at what frequency, and under which shipment-size conditions. This further reinforces the view that cross-dock location planning is part of a broader network and flow design problem. In addition, the viability of a cross-dock location depends not only on spatial consolidation opportunities but also on whether sufficient throughput can be sustained: very small facilities may be difficult to justify organizationally, whereas existing sites may also impose effective upper bounds due to limited space and handling capacity (Potoczki et al., 2024).

2.5.5 Integrated Cross-dock Location and Network Design Models

A substantial body of analytical research integrates cross-docking decisions into broader supply chain network design models. These studies typically extend classical facility-location formulations by introducing cross-docks as additional intermediate nodes and jointly optimizing facility decisions, transport allocation, and shipment routing.

Early contributions include Sung and Song, 2003, who develop a model that simultaneously determines the number and location of cross-docks, shipment allocations, and transportation modes while minimizing fixed and transport-related costs. Sung and W. Yang, 2008 build on this line of work by proposing a branch-and-price solution approach. Other contributions embed cross-docking into multi-echelon distribution systems and jointly optimize warehouses and cross-docks. For example, Jayaraman and A. Ross, 2003 analyze a two-level distribution network in which both warehouses and cross-docking facilities are located strategically under capacity and transportation constraints. Related integrated approaches are developed by Bachlaus et al., 2008 and Mousavi et al., 2013b, who incorporate stochastic and multi-objective elements into the design problem.

Another important research stream explicitly links cross-dock design with transport-flow decisions. Gümüş and Bookbinder, 2004 propose a model that jointly determines whether flows should be routed directly or via cross-docks, thereby capturing trade-offs among facility costs, transportation costs, and inventory-related effects. This line of work is particularly relevant for retail settings because it recognizes that cross-docking changes not only facility structures but also the logic of product flow through the network. The cross-docking literature also spans broader review and classification work. Belle et al., 2012 provide an overview of decision problems across strategic, tactical, and operational planning levels. Benrqya et al., 2020 review cross-docking system design and highlight the interplay between facility location, process design, and scheduling decisions. Together with earlier conceptual contributions such as Apte and Viswanathan, 2000 and Vogt, 2010, this literature establishes cross-docking as a multi-level planning problem with strong interactions between operational feasibility and strategic design.

2.6 Cross-cutting Topics

The preceding sections have examined the core structural decision domains of retail supply chain network design, namely the design of upstream and downstream network structures, intermediate distribution infrastructure, and cross-docking-based flow architectures. However, contemporary retail network design can no longer be understood solely in terms of classical trade-offs between facility costs, transportation efficiency, and service levels. Several cross-cutting dimensions reshape these trade-offs by altering both the objectives of network design and the set of configurations that are strategically attractive.

In the retail context, four such dimensions are particularly salient: resilience, collaboration, sustainability, and online and omni-channel retailing. These do not constitute independent planning areas in the same sense as warehouse or store network design. Rather, they act as modifying forces that affect multiple layers of the conceptual framework developed in Section 2. They influence sourcing structures, facility decisions, flow architectures, and performance outcomes simultaneously. As a result, they expand the traditional design space of retail logistics and strengthen the need for integrated network design approaches.

2.6.1 Resilient Network Design

Resilience has become a central concern in supply chain network design due to increasing exposure to disruptions such as technological failures, pandemics, geopolitical conflicts, and natural disasters (Fahimnia et al., 2015; Ribeiro and Barbosa-Povoa, 2018; S. Hosseini et al., 2019; Aldrighetti et al., 2021). In retail logistics, where distribution systems are often asset-intensive and only partially adaptable in the short term, disruptions can have severe implications for transportation, replenishment, and service continuity. Resilience therefore introduces an additional strategic objective into network design that goes beyond cost efficiency and service responsiveness. From a structural perspective, resilience affects both network configuration and sourcing decisions. A network optimized under stable conditions may become highly vulnerable if suppliers, facilities, or transport links fail. Ignoring such risks may result in substantial recovery costs, increased transportation effort, and lost sales due to unmet demand (Aldrighetti et al., 2021). Consequently, resilience must be incorporated into strategic design either as an explicit objective or through constraints reflecting disruption scenarios and recovery requirements.

The literature identifies several structural mitigation strategies. These include facility fortification and physical protection (Aldrighetti et al., 2021; S. Hosseini and Barker, 2016), increased capacity redundancy and safety stock (Schmitt et al., 2015), parallel or redundant network structures (Maharjan and Kato, 2022; Obermair et al., 2022; Holzapfel et al., 2023), and sourcing strategies such as dual or multi-sourcing (Yildiz et al., 2015). Other approaches aim to reduce network complexity or to increase the geographical diversification of suppliers in order to avoid correlated risks (Adenso-Diaz et al., 2012; S. Hosseini and Barker, 2016). Taken together, these measures typically improve robustness but may reduce efficiency by increasing fixed cost, inventory, or structural complexity.

Methodologically, resilience is commonly incorporated into SCND models through stochastic programming, dynamic optimization, robust optimization, or simulation-based scenario analysis (Sadghiani et al., 2015; Alikhani et al., 2021; Mohamed et al., 2020; Maharjan and Kato, 2022). These approaches allow researchers to assess how alternative network structures perform under disruption risk and to evaluate the trade-off between expected efficiency and robustness. In retail settings, where supply and demand structures are often highly interconnected, this trade-off is particularly relevant because resilience measures frequently affect multiple parts of the network at once.

Overall, resilience modifies strategic retail network design by making redundancy, diversification, and recovery capability more valuable. It therefore shifts the design logic away from purely lean configurations toward structures that can maintain or restore service under adverse conditions.

2.6.2 Collaboration

Collaboration alters network design by changing the organizational boundaries within which logistics structures are configured. In particular, horizontal collaboration between firms at the same supply chain tier enables the joint use of logistics resources such as warehouses, transportation capacity, and consolidation facilities. In retail and distribution systems, such collaboration can fundamentally change the economics of network design by pooling demand, increasing asset utilization, and reducing duplication of infrastructure.

A central mechanism through which collaboration affects network design is volume pooling. By combining shipment volumes or demand across firms, collaborative arrangements can improve transport utilization and create stronger economies of scale in warehousing and consolidation. This may reduce the number of facilities required or make more centralized structures economically feasible (Quintero-Araujo et al., 2017; Sanchez Rodrigues et al., 2015). Analytical research further shows that joint optimization of location and allocation decisions can reduce total logistics cost compared to independently designed networks (Alikhani et al., 2023; Ouhader and El Kyal, 2017). Another relevant mechanism is capacity sharing. Rather than investing in dedicated new facilities, firms may use existing warehouses or transport resources of partner organizations. Such coalition-based structures can improve spatial coverage and reduce transportation distances, but they also introduce capacity constraints and dependencies between the participating actors (Ben Jouida et al., 2021). As a result, collaboration expands the feasible design space of network planning while simultaneously increasing coordination complexity.

The literature also highlights important organizational challenges. Stable collaboration requires governance structures, information sharing, and benefit-allocation mechanisms that are perceived as fair by all partners. If gains are distributed unequally or coordination costs become excessive, collaborative structures may not be sustainable in the long run (Ben Jouida et al., 2021; Ouhader and El Kyal, 2017). This distinguishes collaboration from purely technical network optimization and underlines that inter-organizational feasibility is itself a design constraint.

Beyond horizontal collaboration, outsourcing to logistics service providers represents another important form of structural reconfiguration. Shared logistics infrastructures operated by third-party providers may allow firms to access economies of scale and established transport networks without owning the corresponding assets (De Vos and Raa, 2016; Hsiao et al., 2010). In addition, neutral intermediaries such as fourth-party logistics providers may facilitate collaboration by coordinating information exchange and reducing organizational frictions between participating firms (Guha et al., 2025; Hingley et al., 2011).

From a strategic network design perspective, collaboration therefore acts as a cross-cutting dimension because it changes who designs, owns, and operates the network. It modifies sourcing and facility decisions, affects the viability of centralized versus decentralized structures, and introduces governance considerations into the evaluation of alternative network configurations.

2.6.3 Green and Sustainable Network Design

Sustainability increasingly shapes strategic supply chain network design by extending the evaluation of logistics systems beyond traditional economic criteria. Sustainable supply chain management encompasses environmental, economic, and social dimensions and therefore affects all stages of the distribution system (Govindan et al., 2015; Rajeev et al., 2017; Joshi, 2022). While the economic dimension has always been central to network design, environmental and social considerations have become much more prominent in recent years.

In quantitative SCND research, sustainability is most often operationalized through environmental metrics, such as CO_2 emissions or other transport- and facility-related pollutants (Tai et al., 2023). These arise from transportation activity, facility operations, energy consumption, and infrastructure development (Joshi, 2022; Figueiredo et al., 2025). As a result, the environmental implications of network design depend not only on distances and transport modes, but also on the number, type, and utilization of facilities. A key insight from the literature is that economic and environmental objectives are not necessarily aligned. In some cases, cost-efficient network configurations also reduce emissions by lowering transport effort or improving load factors. In other cases, however, environmentally preferable designs may imply higher logistics cost. For example, a lower number of distribution centers may increase transport distances while reducing emissions from facility operations due to stronger scale effects (Colicchia et al., 2015). The environmental performance of a network therefore depends on how transport, consolidation, and facility-related effects interact.

These trade-offs are commonly modeled using multi-objective optimization approaches, either by weighting economic and environmental objectives or by identifying Pareto-efficient solutions (Govindan et al., 2015; Colicchia et al., 2015; A. Kumar and K. Kumar, 2024; Tai et al., 2023). Alternatively, environmental constraints can be integrated into cost-based models through emission caps, carbon taxes, or carbon pricing mechanisms. Such approaches reflect the fact that sustainability does not simply add another evaluation metric; it can fundamentally alter the preferred structure of the network.

In addition to environmental concerns, the literature increasingly discusses social sustainability dimensions such as employment effects, regional development, and working conditions, although these remain less frequently embedded in formal network design models (Joshi, 2022; Figueiredo et al., 2025). This suggests that the sustainability perspective in SCND is still evolving from a predominantly environmental focus toward a broader multi-dimensional understanding.

In retail logistics, sustainability modifies network design by changing how centralization, transport intensity, and facility specialization are evaluated. It thus acts as a cross-cutting dimension that broadens the objective function of retail SCND and reinforces the need for trade-off-oriented rather than purely cost-driven network design.

2.6.4 Online and Omni-channel Retailing

The rise of e-commerce and omni-channel retailing has fundamentally transformed the structure and requirements of retail distribution systems. Unlike traditional store-based supply chains, omni-channel networks must simultaneously support store replenishment and direct-to-customer fulfillment, thereby increasing both the heterogeneity of demand and the complexity of fulfillment structures (Titiyal et al., 2019; S. F. W. Lim and Srai, 2018; J. Liu et al., 2022; Risberg, 2022). In this sense, omni-channel retailing changes not only the scale of retail logistics, but also the functional role of nodes and flows within the network. A major implication is the emergence of multiple fulfillment node types. In addition to conventional distribution centers, retailers may operate dedicated e-commerce fulfillment centers, micro-fulfillment centers, store-based picking operations, or supplier-based drop-shipping arrangements (Titiyal et al., 2019; Ievgenii Pavlovich, 2025; Risberg, 2022). Each of these options implies different trade-offs between inventory pooling, transport cost, picking efficiency, and service responsiveness. Centralized e-fulfillment systems benefit from scale and inventory consolidation, whereas decentralized store-based or urban fulfillment concepts allow shorter delivery times and closer proximity to customers (Malik and Vidyarthi, 2022; Snoeck et al., 2023; Bilir, 2023).

At the same time, the role of physical stores is changing. Stores increasingly serve not only as sales outlets but also as operational nodes within the logistics system, for example through ship-from-store or click-and-collect concepts (Baron et al., 2024; Lin et al., 2022; S. Yang and Zhang, 2025; Tahirov et al., 2024). More broadly, the growth of direct channels has blurred the traditional separation between upstream manufacturers, downstream retailers, and final customers, increasing the need to coordinate direct and indirect channels within a single fulfillment system (Tahirov and Glock, 2022). This creates additional complexity because stores may simultaneously act as demand nodes, inventory locations, and fulfillment points. The literature further emphasizes that omni-channel retailing intensifies the need for integrated inventory and network decisions. When online and offline demand draw on shared inventories and facilities, capacity constraints and stock allocation rules become more important (Wollenburg et al., 2018; S. Yang and Zhang, 2025). Moreover, omni-channel systems require closer coordination between forward and reverse flows, as returns and cross-channel inventory movements become a central feature of the network (Borba et al., 2020; Nel and Badenhorst, 2020). From a strategic network design perspective, omni-channel retailing therefore acts as a powerful cross-cutting dimension because it changes the definition of demand nodes, introduces additional facility types, and modifies the logic of flow architecture. It increases the value of flexibility and network adaptability, while also reinforcing the need to jointly consider facility location, inventory deployment, and fulfillment strategy.

2.7 Conclusion

This paper develops a conceptual framework for strategic supply chain network design in retail logistics and uses it to synthesize a fragmented literature. The central argument is that retail SCND should not be understood as a set of isolated problems such as supplier selection, store location, warehouse planning, or cross-docking design. Rather, it constitutes an integrated strategic decision system in which sourcing structures, demand-node configurations, intermediate facilities, and flow architectures jointly shape network performance.

The review further shows that a retail perspective adds important insights beyond generic or manufacturing-oriented SCND models. Retail networks are characterized by broad assortments, heterogeneous product requirements, geographically dispersed suppliers, multiple demand sinks, and increasing channel complexity. These characteristics make the interaction of structural decisions particularly important and help explain why resilience, sustainability, collaboration, and omni-channel retailing are not peripheral considerations, but cross-cutting design dimensions that reshape the underlying trade-offs of network design.

The framework contributes by organizing these interdependencies into a coherent structure and by linking fragmented research streams within a common retail-specific perspective. This also points to several directions for future research. In particular, more work is needed on integrated retail SCND models that jointly capture sourcing, facility, inventory, and transport-flow decisions; on empirical research examining how retailers configure hybrid networks across products, channels, and market environments; and on models that incorporate resilience, sustainability, and omni-channel requirements as endogenous design dimensions rather than as ex-post extensions.

Overall, the paper positions retail SCND as a multidimensional and strategically central OM problem. By shifting attention from isolated design choices to the interdependence of structural decisions, it provides a stronger foundation for future research on retail logistics network design.

3 Contribution 2: Design of Distribution Systems in Grocery Retailing

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https://doi.org/10.1007/978-3-030-48439-2_85.

3.1 Introduction

Retailers planning to expand their business to a new geographical area are faced with the question of how to enhance or restructure their current logistics network. A similar problem applies for retailers whose distribution systems have evolved over time and are subject to potential restructuring, for example, because the network is not reasonably aligned with the current supplier/product portfolio anymore, or because the introduction of new technologies necessitates capacity adaptations.

From a strategic network design perspective, retailers have to decide, among many diverse issues, how many warehouses to use, where to locate them, and which functions they will take on Hübner et al., 2013. Furthermore, the network structure that is established by these long-term decisions inherently frames the subsequent tactical planning problems. For instance, the possible distribution paths and storage locations for individual products obviously depend on the predefined network Holzapfel et al., 2018. It is therefore necessary to anticipate the consequences for mid-term planning when designing the retail network structure.

We examine a scenario where a retailer chooses to operate a set of distinct distribution center (DC) types that directly serve a specific set of demand centers, i.e., a set of stores within a specific delivery area. The distribution path (including storage locations) of a certain product is determined accordingly by a product-to-DC type assignment. Each type of DC is primarily specified by the number of parallel warehouses and thus the extent of delivery area that each warehouse covers. A three-type network (central, regional and local DCs), for example, could feature one central warehouse, two regional warehouses, and several local warehouses, while the DCs of a certain type are usually similar in size and equipment. Figure 3.1 depicts an example of such a distribution system. This concept is a common variant in retail practice and is usually applied to place the various products at an appropriate location that minimizes inventory holding and transportation costs, while reducing operational complexity Holzapfel et al., 2018.

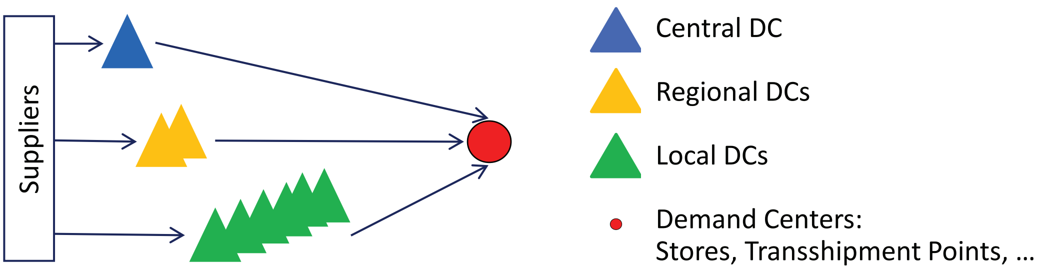

Figure 3.1: Example of a three-type distribution system

Retail-specific network design problems have been examined in multiple contributions. These studies often deal with exact solution approaches applied to simplified models (e.g., disregarding inventory holding and instore operations), with a focus on product flows (e.g. Geoffrion and Graves, 1974, Hindi and Basta, 1994). Other studies focus on specific criteria, such as the selection of plants/suppliers Pirkul and Jayaraman, 1998, resilient network design Sadghiani et al., 2015, or network design with transportation discounts Tsao and Lu, 2012. The novelty of our approach is the detailed design of the distribution network (considering the number of warehouses and their function), taking into account consequences for the subsequent product allocation to different types of DC. Our approach follows a holistic supply chain perspective that considers inbound transportation from suppliers to the warehouses, warehouse operations, inventory holding, outbound transportation from the warehouses to demand centers, and instore operations.

The remainder is organized as follows: In Section 3.2 we present a mathematical formulation and an approach for solving the planning problem described. Section 3.3 then presents the results when applying the approach suggested to the real-life case of a major European retailer. Section 3.4 summarizes our contribution.

3.2 Modeling Approach

We introduce a binary program for the network design problem that we denote as Network Design with Product Allocation (NDPA) model. Building on a predefined set of possible warehouse locations, the NDPA model determines the selection of specific DC types while minimizing total supply chain costs, anticipating the tactical product allocation decision. The locations of possible warehouses per DC type are a relevant input as they impact transportation costs in the distribution network to be designed. If the locations are not predetermined by existing structures or given preferences of the retailer, we suggest using a p-median approach in a preprocessing step to determine the warehouse locations, minimizing the sum of inbound and outbound transportation costs for each DC type considered. The p-median model is NP-hard, but, efficient algorithms exist that can solve instances of real dimensions in reasonable times Kariv and Hakimi, 1979. The resulting warehouse locations are then used to specify the inbound and outbound distances in the NDPA model, for which we propose the following mathematical formulation:

$$\begin{aligned} \text{Minimize } \mathrm{Z} = &\sum_{d \in D} c_d^{\text{DCfix}} \cdot z_d + \sum_{p \in P} \sum_{d \in D} c_d^{\text{DCvar}} \cdot x_{p,d} \\ &+ \sum_{p \in P} \sum_{d \in D} c_{p,d}^{\text{InOutInv}} \cdot x_{p,d} \\ &+ \sum_{d \in D} \sum_{l \in L} c^{\text{Instore}} \cdot y_{d,l}^{\text{Instore}} \end{aligned} \tag{3.1}$$

s.t.

$$\sum_{d \in D} x_{p,d} = 1 \qquad \forall p \in P \tag{3.2}$$

$$\sum_{p \in P} x_{p,d} - z_d \cdot M_1 \leq 0 \qquad \forall d \in D \tag{3.3}$$

$$\sum_{p \in P_l} x_{p,d} - y_{d,l}^{\text{Instore}} \cdot M_2 \leq 0 \qquad \forall d \in D, l \in L \tag{3.4}$$

$$x_{p,d} \in \{0,1\} \qquad \forall p \in P, d \in D \tag{3.5}$$

$$y_{d,l}^{\text{Instore}} \in \{0,1\} \qquad \forall n \in D, l \in L \tag{3.6}$$

$$z_d \in \{0,1\} \qquad \forall d \in D \tag{3.7}$$

The objective function (3.1) minimizes the total supply chain costs considering warehouse (setup and operating), inbound transportation, inventory holding, outbound transportation and instore operations costs.

We split warehouse-related costs into a fixed block for every DC type d to be established (decision variable z_d, which indicates if a DC type d is used or not, and cost factor c_d^{DCfix}), and a size-dependent component (cost factor c_d^{DCvar} and decision variable $x_{p,d}$, which defines if a product p is assigned to type d). Investment costs are thus assumed to be dependent on the number of different SKUs, i.e., picking locations, assigned to a DC.

Inbound and outbound transportation as well as inventory holding costs are summarized in cost factor $c_{p,d}^{\text{InOutInv}}$. They are assumed to be product- and DC-type-specific and therefore also dependent on the assignment of products to a specific DC type (decision variable $x_{p,d}$). The transportation cost components reflect the distances and volumes from the DC locations to the suppliers and demand centers. Inventory holding costs especially account for the different degrees of demand pooling options that come along with the specific number of parallel warehouses that are established using a certain type of DC. One possibility for quantifying the inventory pooling effect is the so-called square root law Fleischmann, 2016, Oeser, 2019.

Costs arising from instore operations are considered by setting a penalty c^{Instore} for each additional DC type d to which products from a certain store layout category l are allocated (decision variable $y_{d,l}^{\text{Instore}}$). For details on the product allocation decision and the costs considered, we refer to Holzapfel et al., 2018.

The model is complemented by several restrictions. Constraint (3.2) ensures that each product is allocated to exactly one type of DC. Constraint (3.3) activates DC type d if any product p is allocated to this specific type. In Constraint (3.4), variable $y_{d,l}^{\text{Instore}}$ is set to 1 if at least one product of a certain store layout segment l is allocated to DC type d. The binary decision variables are defined in Constraints (3.5), (3.6) and (3.7).

The NDPA model is implemented in IBM ILOG Studio and solved using CPLEX v12.5. An optional post-processing stage reruns the p-median model using the solution of the DC-type selection and product allocation decision to improve the warehouse locations of the DC types selected.

3.3 Illustration

We implement the modeling approach with data from a major European retail chain located in Germany. The company's main assortment consists of approximately 9,000 products that are sourced from about 300 suppliers. There are 36 transshipment points, which serve as local hubs for distinct subsets of stores. The transshipment points represent the demand centers in this case. Currently the company uses a three-type network design with one central warehouse, two parallel regional warehouses and six parallel local warehouses. Since the company is growing steadily, the question arises as to whether the current network still reflects the optimal configuration.

In order to evaluate the cost savings potential we investigate whether the current warehouse locations can be restructured such that total supply chain costs are minimized. For this brownfield approach new warehouse sites are disregarded. Since there are nine warehouse sites currently being used, the possible DC types to be chosen range from one central warehouse up to nine parallel (local) warehouses.

Our results show that 4% of total supply chain costs can be reduced if a two-type network is used instead of the current three-type network. More precisely, the configuration suggested comprises one central warehouse and five parallel regional warehouses. Figure 3.2 shows the cost components and the savings potential.

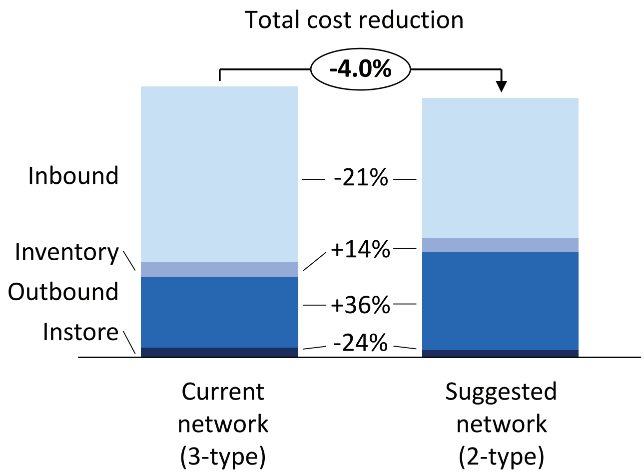

Figure 3.2: Cost structure and potential savings in the case study applying NDPA

Besides the cost reductions that are achieved by limiting the number of DCs in use, major cost reductions can be achieved in inbound transportation by increased bundling potential if DC types are reduced. A positive effect can also be generated for instore logistics, while the more central structure means additional outbound transportation costs. Inventory costs play a minor role and increase slightly as the product allocation that is induced by the new network structure is more focused on transportation and bundling issues than on inventory pooling.

3.4 Summary and Outlook

In this paper we present a modeling approach for the retail network design problem with consideration of product allocations to different types of DC. We include costs arising from operating warehouses, inbound transportation, inventory holding, outbound transportation and instore operations.

The results from a case study indicate that considerable cost savings are possible when restructuring existing retail networks according to the modeling approach proposed. Additionally, the approach can be used when companies set up a distribution network in countries in which they already have a store network but no DCs.

Future research possibilities include the development of a heuristic that directly solves the integrated problem of network design and product allocation, taking into account the potential warehouse location decisions. The latter are assumed to be predefined in the model proposed. Other assumptions can be refined, such as including delivery frequencies based on truck loads instead of linearized transportation costs. The distinction of DC types can also be extended by including more criteria, e.g., the degree of warehouse automation and the respective costs.

4 Contribution 3: Designing the breadth and depth of distribution networks in the retail trade

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4.1 Introduction

Pivotal decisions regarding the design of a distribution network are the number of warehouses, their locations, hierarchical structure (i.e., number of distribution stages), and functions (Chopra, 2003; Melo et al., 2009; Hübner et al., 2013). Considering a two-stage distribution structure, network design mainly specifies both the breadth and depth of the warehouses operated within the network. The products offered by a retailer can have different storage and distribution requirements, so potentially there are several types of warehouses, each storing a specific set of products (Shen, 2005; Holzapfel et al., 2018; Benrqya et al., 2020). The number of different types of distribution center (DC) established in a distribution network defines the breadth or degree of *differentiation* of a retail network. In addition, the number of warehouses operating in parallel to supply identical products to their respectively assigned demand centers defines the depth or degree of *centralization* of the network. This paper analyzes both questions simultaneously, answering what degree of differentiation and centralization retailers should aim for within their distribution network. In doing so we develop a decision support model that decides on the number of DC types, where each DC type consists of a certain number of parallel warehouses and stores a distinct set of products. Each of the products offered by the retailer is located in exactly one of the DC types established in the network.

For instance, a retail network can consist of three DC types. A single warehouse (denoted as DC type "central") that stores products with a high value density and low demand volume, another set of two parallel warehouses that stores products with a moderate value density and a moderate demand volume (denoted as DC type “regional”), and finally, a series of several, e.g., six, parallel warehouses (denoted as DC type “local”) that store products with a low value density and high demand volume. Greater heterogeneity in the retailer’s product mix might require an even higher level of segmentation, e.g., four, five or even more DC types.

The segmentation concept described is a common variant in retail practice and is usually applied to place the various products at an appropriate location minimizing inventory holding and transportation costs while reducing operational complexity and standardizing planning efforts for warehouses within one type (Geoffrion and Graves, 1974; Holzapfel et al., 2018). Operating different DC types can be beneficial for any retail sector that exhibits a heterogeneous mix of products (in terms of demand volume, value density, etc.), which is especially typical in grocery retailing.

Our approach follows a holistic supply chain perspective that considers inbound transportation from suppliers to the warehouses, costs related to setting up and operating warehouses, inventory holding, outbound transportation from the warehouses to demand centers and instore operations. The focus in this paper is on the decisions regarding the network’s degree of differentiation, i.e., the number of different DC types and the associated assignment of products to these DC types, the degree of centralization, i.e., the number of parallel warehouses per DC type, and the respective location of each warehouse. Even though there is abundant literature on facility location and network design problems in the supply chain context (Beamon, 1998; Melo et al., 2009), the problem presented in this paper is novel due to the integration of the particular supply chain components and the decision on determining the optimal combination of DC types. Our approach is suitable for both bricks-and-mortar, online and omnichannel retail and is able to cover several aspects that are highlighted in the current discussion of supply chain network resilience (Aldrighetti et al., 2021; Maharjan and Kato, 2022).

The remainder of this paper is organized as follows: In Section 4.2 we describe the general problem context and special characteristics of the distribution system under investigation. In Section 4.3 we review relevant literature that relates to the problem investigated in this paper. Section 4.4 introduces a modeling approach for the planning problem. In Section 4.5 we present a hierarchical decomposition approach and an iterated local search procedure. To illustrate practical implications we show results from a case study conducted with data from a major European grocery chain and examine the dynamics of the model and solution approach by applying sensitivity analyses in Section 4.6. Lastly, we summarize our contribution and outline possible future research in Section 4.7.

4.2 Research setting and problem description

The following section describes the general problem setting. Section 4.2.1 introduces the typical network structure of a retailing company on which our modeling approach is based. It also clarifies how warehouses are segmented into DC types. Section 4.2.2 then identifies relevant cost factors for determining an optimal network structure when considering different types of DC.

4.2.1 Network structure: degree of centralization, differentiation, and automation

The prevailing distribution system of large-scale retail companies comprises product flows from suppliers via DCs to locations of demand (Kuhn and Sternbeck, 2013). In the DCs the products are consolidated, stored, and picked for store and customer deliveries. This general structure resembles a two-stage distribution network (Klose and Drexl, 2005), with two layers of shipments: inbound transportation from suppliers to warehouses and outbound transportation from warehouses to demand centers. Regarding outbound transportation, two flow types can be distinguished: delivering directly from storage warehouses to points of sale or interposing transshipment hubs in between for consolidating loads from different DCs (Hübner et al., 2013). These structures are particularly visible in bricks-and-mortar retail and for many online and omnichannel retailers. Especially in grocery retail, the same general structures can be assumed, when online fulfillment centers (dark stores) or regular stores are used to fulfill online customer orders (Wollenburg et al., 2018). These locations can also represent Click & Collect points of the retailer where customers can pick up their goods ordered online. In the remainder of the paper we use the generic term "demand center" to refer to each kind of possible fulfillment center, e.g., stationary retail stores or dark stores in the online business. However, we exclude direct deliveries from the DCs to end customers in our study and instead focus on the delivery to demand centers as described above, since this setting reflects a typical situation in retail practice.

Degree of centralization One major decision when designing a distribution network is about the number of parallel warehouses. This number defines the degree of centralization or regionalization. A large variety of solutions to this exist both in theory and practice. One possible configuration can be for instance a central solution where one warehouse acts as a single DC for the retailer's entire distribution network. In that case the entire demand volume is shipped from the product's supplier to this specific warehouse and from there to each store. Alternatively, parallel warehouses can be operated, i.e., the demand area is split into several subareas where each region is supplied by a dedicated regional warehouse. In this scenario the product's supplier has to ship certain proportions to each of the regional warehouses, which in turn provide the items for their assigned stores.

The decision on the degree of centralization of a distribution network is highly dependent on the products offered and the business model operated by the retailer. The demand volume of a product, its value, variance of demand, freshness requirements or the location of the product's supplier in relation to the demand points are main drivers for this decision (Kuhn and Sternbeck, 2013). The product portfolio offered by the retailer is one of the main drivers for the design of the distribution network and its degree of centralization, along with the resilience strategy (Obermair et al., 2022).

Degree of differentiation Retailers offering a wide variety of products, especially grocery retailers, operate both centralized and regionalized networks. This results in a distribution network consisting of different types of DCs, e.g., central, regional, and local DCs (see Figure 4.1 for an example of such a three-type system). In this context, each DC type is defined by a set of parallel warehouses, where each of the parallel warehouses affiliated with the same DC type essentially stores the identical mix of products. The number of different DC types within a distribution network defines the "degree of network differentiation". This degree can very greatly.

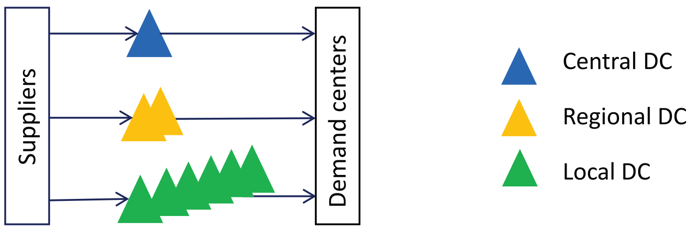

Figure 4.1: Product flow of an three-type distribution system (example)

The optimal degree of network differentiation, i.e., the degree that results in the lowest cost, is significantly influenced by the extent of the products' heterogeneity offered by the retailer. We assume that there is no lateral flow of products between the DC types. The distribution of products strictly follows the principle of a two-stage system, as shown in Figure 4.1, and there is no hierarchical flow between the DC types. This situation is very common in retail practice.

Figure 4.2 illustrates examples of cost functions dependent on the degree of the distribution system's differentiation for four different scenarios. The respective scenarios reflect an increasing degree of heterogeneity in the corresponding product portfolios, starting with Scenario 1, which reflects a largely homogeneous product structure, and ending with

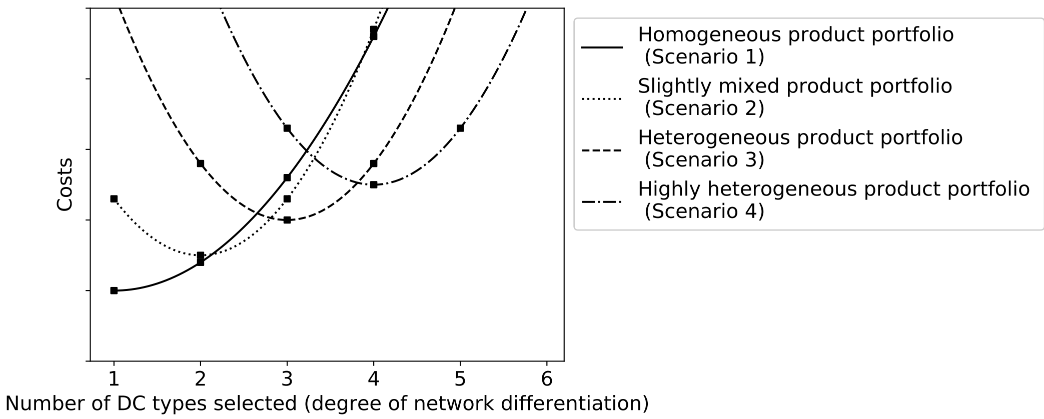

Figure 4.2: Cost functions depending on the degree of network differentiation (examples)

Scenario 4, which represents a high degree of product heterogeneity. In a setting with predominantly homogeneous products (i.e., similar product characteristics, Scenario 1) it is largely beneficial to operate only a single type of DC. This one DC type can consist of either a single warehouse or multiple parallel warehouses. Increasing the number of DC types would usually result in higher costs since the increased network complexity renders no benefits in a setting with homogeneous products. In contrast, when product characteristics vary considerably (e.g., Scenario 4), it might be cost-efficient to establish a higher degree of network differentiation. Offering only a central DC or only multiple parallel warehouses would not be cost-efficient for certain product groups, respectively. Thus, by considering multiple DC types, different product features can be better leveraged.

Degree of automation DC types can have different degrees of automation. Warehouse automation is an essential element within strategic network planning and typically needs to be defined for a long-term planning period (Rouwenhorst et al., 2000; Koster, 2018). Automation potentially decreases operational costs and increases responsiveness, thus creating a competitive advantage (Baker and Halim, 2007). Depending on the products' suitability for automated processes and on how much volume is shipped through a specific type of DC it might be cost efficient to equip the warehouses belonging to that DC type with a higher degree of automation (Dubey and Veeramani, 2017; Boysen et al., 2021).

Resilient network planning The distribution system's resilience is another important aspect to consider on a strategic level (Ribeiro and Barbosa-Povoa, 2018; S. Hosseini et al., 2019; Aldrighetti et al., 2021). Parallel warehouses offer the benefit of facility redundancy, which is a common concept in supply chain resilience planning (Maharjan and Kato, 2022). Thereby, an inoperative warehouse that is affected by a naturally or politically induced disruption might be partially or completely replaced by other warehouses that are not affected by the disruption. Moreover, stores can be flexibly supplied by the parallel warehouses (Obermair et al., 2022). Further aspects that are required with regard to resilience issues are adjustable inventory levels, especially safety stocks that reflect a certain service level (Schmitt et al., 2015), and multiple sourcing (Yildiz et al., 2015).

Summary In addition to the classical decisions on the number of warehouses and their location, the number of parallel DC types to be established is an important decision in retail industry. The larger the variety of DC types in a distribution network, the more the company can exploit product- and segment-specific cost saving potentials. In addition to the cost perspective, differentiated distribution systems also make it possible to consider satisfying requirements of products with more critical supply and/or service specifications (e.g., lead time constraints) without affecting products where supply and service requirements are secondary. The result would be a "combination of delivery networks" (Chopra, 2003). However, the larger the number of DC types applied, the higher the complexity that has to be faced. This constitutes one of the tradeoffs strategic network planning has to resolve.

The objective of this study is therefore to develop a decision support model that determines the different types of DCs, the number of parallel warehouses associated with each DC type, and the specific location of each warehouse defined. It also assigns the different products offered by the retailer to the DC types selected and thus quantifies the capacity required for the warehouses.

4.2.2 Relevant cost factors and tradeoffs

There are several associated cost factors when deciding on the number of different DC types, the number of warehouses and their locations for each DC type chosen, and the allocation of products to each of these DC types. These cost factors include fixed setup costs for the warehouses of the DC types selected, variable warehouse costs dependent on size and throughput, inbound and outbound transportation costs, inventory holding costs, product category related costs, and instore operations costs.

Setup and operating costs of warehouses The costs associated with the setup and operation of a warehouse can be divided into fixed and variable costs (Geoffrion and Graves, 1974; Verter, 2011; Shu et al., 2014). Opening a warehouse incurs fixed costs, which in our case are assumed to be independent of the size of a warehouse. These costs include, for example, size independent components of construction expenses, land price, taxes, general equipment and resources. These costs may depend on the specific location chosen. Variable costs are costs associated with assigning a product to a warehouse. This allocation determines the size of the warehouse, the number of storage locations, the personnel capacity of the warehouse and the operating costs. The ratio between fixed and variable costs is one of the key factors that determines the degree of centralization of the distribution network. A more centralized network with few but large warehouses is for example more likely when fixed costs are the major part of all costs.

Transportation costs Transportation costs can be divided into inbound and outbound costs. Inbound and outbound transportation costs conflict with each other when quantifying the number of parallel warehouses in a distribution network (Holzapfel et al., 2018). A centralized solution with, for example, only one or a few DCs favors inbound shipments over a limited number of transport connections. In contrast, outgoing consignments in this case are disadvantaged by the large number of transport connections and generally long distances to the demand centers. However, a regionalized solution with multiple parallel DCs favors outbound transportation since the warehouses are closer to the demand centers, and disadvantages inbound transportation since one supplier needs to serve all parallel warehouses. Generally, outbound deliveries are usually more costly per unit of product shipped, e.g., per pallet, than inbound deliveries, because the lot sizes of outbound deliveries are usually smaller than those of inbound deliveries. Furthermore, compared to the inbound process, the packing density in the outbound process is reduced due to a more heterogeneous product mix on the pallets (Chopra and Meindl, 2013; Holzapfel et al., 2018).

This leads to a general tendency to set up multiple warehouses that are located relatively close to demand centers.

Inventory costs The number of parallel warehouses established influences system-wide inventories, i.e., safety stock and cycle stock levels, via the portfolio effect (Zinn et al., 1989). A more centralized distribution network is often justified by the consolidation of inventories (Fleischmann, 2016; Oeser, 2019). The total safety stock level, for example, increases with the number of parallel warehouses given a certain service level if the demands at the respective locations are not perfectly correlated. In the special case of independent and identical distributed demands at all warehouses the system-wide inventory decreases by $\frac{1}{\sqrt{n}}$ when reducing n parallel warehouses to a single warehouse. This relation is also known as “square root law” (Maister, 1976). However, Oeser, 2019 shows empirically that the square root law does not always hold in real-life applications. He finds that especially in a multi-commodity setting it is important to consider product-individual impacts of centralization on total stock levels. Nevertheless, the square root law is still a suitable proxy when calculating strategic inventory effects.

Product requirements and instore operations Allocating products of one category to different types of DC may lead to additional setup costs and inefficiencies regarding instore operations. Additional setup costs are for example caused if certain product categories require specialized facilities or equipment, e.g., cooling or sorting systems. The more warehouses that need to be equipped with these systems, the higher the total cost. Nevertheless, a regionalized network structure with a higher number of warehouses might be for example necessary if lead time constraints have to be met, e.g., for fresh or frozen products.

In addition to these mostly technical aspects, the assignment of product categories to DC types also affects instore logistics (Kuhn and Sternbeck, 2013; Holzapfel et al., 2018). Instore logistics is known to be responsible for a substantial share of overall supply chain costs of a retailer, especially in grocery retailing (Zelst et al., 2009). Scattering products of the same category that are typically located closely together in the stores to disjunct sets of warehouses may lead to mixed-category pallets when picking the store deliveries in warehouses of different types. This in turn leads to longer travel distances during shelf replenishment in comparison to homogeneous pallets. From an instore logistics perspective it is thus beneficial to have products from the same category allocated to a common DC type, regardless of whether the DC type is rather centralized or regionalized (Holzapfel et al., 2018). However, a smaller number of different DC types increases the likelihood that items can be packed together in a manner more suitable for store operations.

Summary There are conflicting tendencies on how differentiated a network should be designed and which DC types should ultimately be considered. Figure 4.3 visualizes an example of the tradeoffs between setup and category costs, transportation (inbound and outbound) costs, and inventory holding costs dependent on the number of parallel warehouses of one DC type (Chopra, 2003). Note that instore operations costs depend on the number of different DC types established and are therefore not shown in Figure 4.3. Overall, these cost considerations are very helpful to management when deciding on the minimum number of parallel warehouses to be established in order to be better prepared for possible disruptions.

4.3 Literature review

Given the problem characteristics described in Section 4.2, our network design problem can be described as a multi-stage, multi-commodity setting that considers different DC types. It considers product characteristics and allocation effects including a broad set of influencing cost factors along the retail supply chain. Within the following paragraphs we

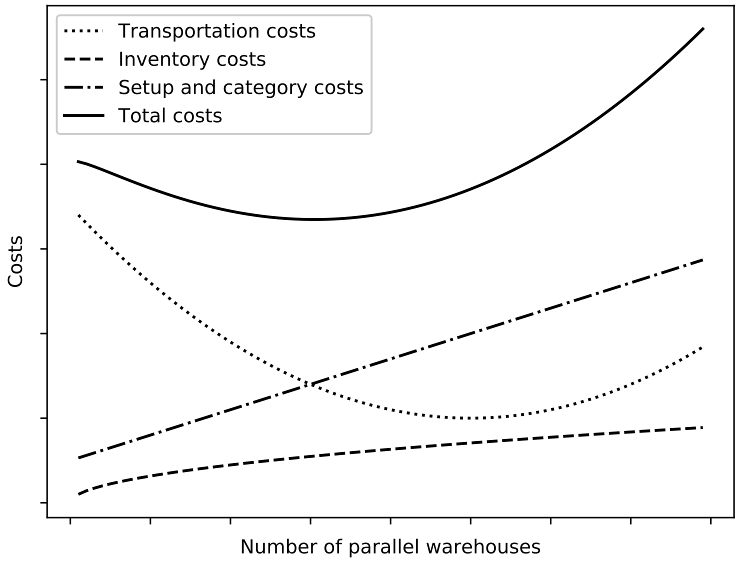

Figure 4.3: Tradeoffs between supply chain costs dependent on the number of parallel warehouses (example)

refer to contributions in literature that are especially relevant for one or several of these characteristics.

Network design Network design has received considerable attention in literature due to its strategic nature. The location problem's elementary form can be represented by a multi-source Weber problem where a certain number of warehouses are to be located on the plane and each demand point is to be assigned to a specific warehouse (Klose and Drexl, 2005). The discrete equivalent to the multi-source Weber problem was originally introduced by Hakimi, 1964 and is generally known as the p-median problem, where a fixed number of warehouses from a given set of candidate sites is to be selected. This basic form has been repeatedly extended (e.g., by Boffey and Karkazis, 1984 and Mirchandani et al., 1985, who transformed the problem into a multidimensional m-median model) and is used not only in the public or service sector where it has its greatest significance, but also in the manufacturing and retail industry (e.g., Camm et al., 1997, Keskin and Üster, 2007). Most relevant in our context is the uncapacitated facility location problem (UFLP) in which capacity at warehouse locations is not scarce and locations are not limited to a predefined number of warehouses (Melo et al., 2009). Compared to the p-median problem, the UFLP includes fixed setup costs for warehouses in addition to transportation costs.

Multi-stage setting Network design research in the field of supply chain management usually considers more than one stage of transportation (Beamon, 1998). The corresponding repercussions are considered in hierarchical layered multi-stage models. Aside from the incorporation of several layers of the supply chain, which are affected by the location decision, research papers can be further distinguished by the number of levels for which location decisions have to be made (Tcha and B.-I. Lee, 1984; Şahin and Süral, 2007). Additionally, several studies also integrate the decision of selecting suppliers (Cakravastia et al., 2002; Cordeau et al., 2008). Within this taxonomy our setting can be classified as a single-level (or single-echelon) location, two-stage network design problem, since we determine the number and locations of distribution centers with given supplier and customer (store) locations and consider both the impacts on inbound and outbound direction. Furthermore, research has been dealing with dynamic (Ballou, 1968; Canel et al., 2001) and probabilistic aspects (Mirchandani et al., 1985) of designing a distribution network. This is especially relevant when model parameters (in particular demand volume) are variable over time, or if the parameters exhibit a particular stochastic dimension that is crucial for incorporation into the model. Closely related is the topic of supply chain resilience which has found a lot of research attention in recent years due to diverse disruptions and crises (e.g. Sadghiani et al., 2015; Yildiz et al., 2015; Alikhani et al., 2021). However, the approaches discussed and proposed so far fail to consider simultaneously the degree of centralization (number of parallel warehouses) and the degree of differentiation (number of different DC types), which is particularly relevant in the retail context where typically very heterogeneous assortments are offered.

Multi-commodity setting Another aspect in our modeling approach is the multi-product feature. Warszawski and Peer, 1973 and Geoffrion and Graves, 1974 have originally introduced distribution system designs that consider multiple products or services. Those models, which are also known as multi-commodity or multi-activity models, and appendant solution approaches have been enhanced by Karkazis and Boffey, 1981, Boffey and Karkazis, 1984 and Mirchandani et al., 1985, for instance. Those contributions mostly differ from our paper in that they consider only a single-stage and/or are based on a p-median problem with a predefined number of warehouses to be set up. As in our case, Hindi and Basta, 1994 examine a two-stage multi-product case. They consider inbound and outbound transportation, fixed and variable warehouse costs and decide upon the number and location of warehouses and transportation flows. In contrast to our setting, they assume that each commodity can be sourced from each supplier, and they do not distinguish between DC types. Jayaraman and A. Ross, 2003 extend the problem by adding a DC level between warehouses and stores for cross-docking operations. They implement a hierarchical modeling approach by introducing a strategic and an operational layer. Similarly, Pirkul and Jayaraman, 1998 examine a two-echelon location problem within a multi-commodity context. In their study the supplier locations are also subject to optimization. Camm et al., 1997 present a case-driven two-stage, multi-product problem and primarily focus on organizational issues in their paper rather than on modeling and solution approaches. They use a simplified hierarchical p-median procedure. Keskin and Üster, 2007 start from the same baseline and present meta-heuristic solution techniques for this p-median model. Shen, 2005 deals with a multi-commodity model that integrates economies of scale, i.e., nonlinear effects. In their model the setup per candidate site and assignment of warehouses to demand centers is decided on.

Distinction of DC types One main contribution of our paper is the introduction of DC types in a two-stage, multi-commodity network design problem where each warehouse is assigned to a specific DC type and the product allocation is not executed on a warehouse level but on a DC type level. Literature in which warehouses are affiliated to a certain type usually examine a setting where the differentiation between types is solely performed by capacity, equipment and setup-related cost aspects. The allocation of products in those studies is still based on a warehouse level. This means the facilities are standardized for each DC type, but the logistics processes that accompany the product portfolio distributed via a specific DC can vary significantly within one type. C. Y. Lee, 1996 describes a two-stage network structure with the distinction of DC types. He assumes that costs can be saved for constructing and operating the facilities by standardizing building design and planning. In his study he considers, however, one central supplier with one product only. Mazzola and Neebe, 1999 investigate a multi-commodity scenario where decisions have to be made based on the number of facilities, the type of each facility and the allocation of products to facilities. They consider type-related as well as product-specific setup costs per facility and costs for outbound transportation. Inbound transportation is neglected rendering this network a single-stage distribution system. The product allocation decision basically depends on warehouse-to-demand-point distances and capacity restrictions at the warehouse level. A similar perspective on type-related warehouses can be found in Karkazis and Boffey, 1981, Boffey and Karkazis, 1984 and Mirchandani et al., 1985.

Product characteristics and allocation Regarding the SKU-based product allocation effects to DC types that are induced by network design, this paper mainly draws on Holzapfel et al., 2018. In their study they identify and model essential implications of assigning a product with certain characteristics (such as demand volume, variance of demand and product value) to a specific DC type. They assume a given network with predefined warehouse to DC type affiliations and optimize the decision process of allocating products to DC types (which are as in this paper distinguished by their degree of centralization). An integration of product portfolio effects on network design is, however, lacking in the pertinent literature so far. There are several studies in the manufacturing domain that deal with supply chain network design and optimal product allocations (e.g. Karkazis and Boffey, 1981, Keskin and Üster, 2007, Tsiakis and Papageorgiou, 2008, Baud-Lavigne et al., 2016. The cost modeling in those papers is however more focused on production and the allocation decisions of products are usually not interdependent (except for shared setup costs of a facility). Furthermore, the number of products is typically assumed to be very limited. For instance, Tsiakis and Papageorgiou, 2008 consider only six products in their numerical analysis.

Cost modeling Most papers dealing with network designs usually minimize setup costs for opening warehouses and transportation costs from warehouses to demand points (and from suppliers to warehouses if applicable). However, the amount of literature also taking inventory aspects into account is increasing. Erlebacher and Meller, 2000 incorporate the effect of inventory consolidation in their facility location model. They assume an economic order quantity (EOQ) replenishment policy and include the system-wide inventory holding costs (dependent on the decision of how many parallel warehouses are to be built) in their objective function. Their cost assessment is based on the square root law (Maister, 1976), but considers quantity-dependent effects on a warehouse level. One important difference between the study of Erlebacher and Meller, 2000 and ours is, however, their focus on a single-product case. Teo and Shu, 2004 consider a network design problem where they decide on the number of warehouses, the assignment of customer zones (set of retailers) and replenishment policies. Specifically, a reorder interval needs to be determined for each warehouse that is set up as well as for each store to assess system-wide inventory costs. Their problem's objective function accordingly minimizes fixed costs for setting up warehouses as well as for inbound and outbound transportation costs and inventory costs resulting from replenishment and inventory holding. Other features considered in the related literature are, for instance, transportation discounts (Tsao and Lu, 2012) and the incorporation of routing costs into strategic location planning (Shen and Qi, 2007). To the best of our knowledge, however, the cost consequences of network design on instore operations and following tactical product allocation have not been considered in any contribution so far.

Summary To summarize, our approach is unique in that it comprehensively designs two-stage retail networks integrating the effects of product flow segmentation. The distinction of DC types in network planning has been implemented in previous research. Table 4.1 illustrates the key differences between our approach and similar works that deal with network design in a setting with multiple products and/or type distinction of DCs. Existing models are not applicable in the context of retail logistics because of assumptions such as for instance a single-commodity setting. Furthermore, the consideration of cost effects along the retail supply chain is more comprehensive compared to previous studies, including fixed and variable warehouse costs, inbound and outbound transportation costs, inventory holding costs, and instore operations costs.

	Type distinction	Quantifying number of warehouses	Multi-product	Multi-supplier	Inventory consideration	Solution approach
Karkazis and Boffey, 1981	✓	✓	✓			mat/meta
Boffey and Karkazis, 1984	✓		✓			exact
Mirchandani et al., 1985	✓		✓			exact
C. Y. Lee, 1996	✓	✓				mat
Mazzola and Neebe, 1999	✓	✓	✓			mat
Warszawski and Peer, 1973		✓	✓			mat
Geoffrion and Graves, 1974		✓	✓	✓		exact
Hindi and Basta, 1994		✓	✓	✓		exact
Jayaraman and A. Ross, 2003		✓	✓			meta
Pirkul and Jayaraman, 1998			✓	✓		heuristic
Camm et al., 1997			✓			exact
Keskin and Üster, 2007			✓	✓		meta
Shen, 2005		✓	✓		✓	exact
Own approach	✓	✓	✓	✓	✓	mat/meta

Table 4.1: Overview of papers with DC type distinction network design problems and/or multi-product setting. mat=matheuristic, meta=metaheuristic

As such, our work extends the literature on both strategic network design and tactical operational planning in retail distribution. Our research specifically contributes to:

- Identifying decision-relevant costs in warehousing, transportation and instore operations for the retail specific warehouse location problem with a particular focus on the distinction of DC types, considering centralization and differentiation effects,
- formulating a novel model that determines the warehouse network structure by selecting DC types and warehouse locations considering cost-optimal product allocations to DC types,
- developing a tailored heuristic solution approach, in particular an iterated local search that is based on a hierarchical decomposition approach and
- demonstrating the model's applicability by presenting numerical results from a case study with actual data from a retailing company.

4.4 Model

Section 4.4.1 describes relevant modeling assumptions and presents the decision variables, constraints, and cost parameters of the modeling approach chosen. Section 4.4.2 then presents the MIP formulation of the model.

4.4.1 Modeling assumptions, sets, parameters and variables

4.4.1.1 Network structure

The distribution network to be established spans the flow of products $p \in P$ from suppliers $s \in S$ via warehouses $w \in W$ to demand centers $k \in K$. We assume that locations of suppliers and demand centers are predetermined and focus on the problem of determining the number of DC types as well as quantifying the number of parallel warehouses for each DC type selected and the associated assignments of products to the different DC types chosen. Each warehouse belongs to a certain type of DC $d \in D$ that is characterized by the number of its parallel warehouses n_d, i.e., its degree of centralization.

The main decision in our model is to determine whether a certain type of DC is to be established, which is represented by the binary variable z_d. The combination of DC types selected then constitutes the degree of network differentiation and the total number of warehouses to be set up. Aligned decisions are the assignment of warehouses to DC types (binary variable $\gamma_{w,d}$) and the capacity of the warehouses of a certain DC type, determined by the allocation of products to the respective types (binary variable $x_{p,d}$).

For DC types with more than one warehouse, each demand center k is assigned to one of the parallel warehouses w (binary variable $\eta_{k,w,d}$). Figure 4.4 schematically illustrates the structure and the main decisions of the problem considered.

4.4.1.2 Warehouse locations

We treat candidate warehouse sites as discrete points within the relevant distribution area. This modeling approach allows differentiation between different locations regarding location-specific characteristics, for example, spatially dependent land prices that affect setup costs for a candidate warehouse at a specific location (Melo et al., 2009). A useful technique for generating candidate locations in a greenfield setting with no pre-evaluated candidate sites is using grid-like structures, where potential warehouse sites are equally distributed along a grid that spans across the company's trading area. The grid's granularity can be set depending on its impact on solvability in reasonable time.

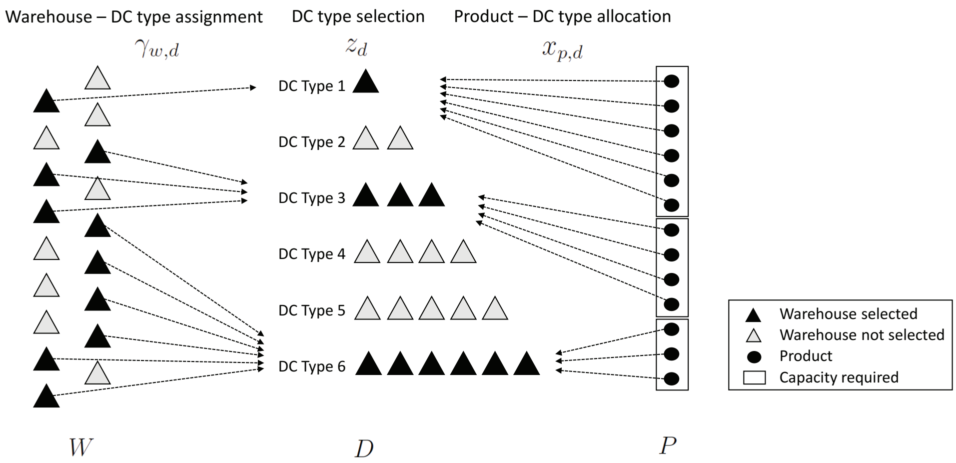

Figure 4.4: Schematic problem structure visualizing decisions and variables

4.4.1.3 Demand

The demand for a product q_p (measured in number of standard transportation units, e.g., pallets) as well as its variance are assumed to be known. Each demand center exhibits a specific total demand a_k. A demand center can be for instance a transshipment point or an outlet. This approach also covers e-commerce settings, where demand centers represent either dark stores or transshipment points from which last-mile deliveries are sent off to end customers. These locations could also represent click & collect points of the retailer where customers can pick up their goods ordered online (Wollenburg et al., 2018; Hübner et al., 2019). The share of demand that is attributed to a specific warehouse $a_{w,d}$ is subject to the decision on the assignment of demand centers to the warehouse and is further restricted by a lower (lb_d) and upper (ub_d) bound for each DC type, to ensure that all warehouses of one DC type are similar in size.

Except for inventory holding where we include stochastic influences for evaluating necessary stocks to be held at the warehouses in order to meet a desired service level, we do not investigate further probabilistic features and treat the model parameters as deterministic. Additionally, demand is assumed to be spatially inelastic, i.e., independent of the location decision, as well as stable, which enables static long-term planning.

4.4.1.4 Cost evaluation

The decisions characterized influence various costs along the retail supply chain (see Section 4.2.2). We make the following modeling choices regarding the different cost terms.

Setup and capacity We consider fixed (c_w^{DCfix}) and variable costs (c_d^{DCvar}) for setting up and operating warehouses that are scaled down to the respective time horizon considered. The fixed cost can be site-specific (Boffey and Karkazis, 1984). As warehouses within one DC type are destined to be standardized (with regard to size, equipment, layout etc.), the variable operational costs can be aggregated on a DC type level. These reflect capacity requirements and operating costs per SKU allocated to the respective DC type.

This cost representation also allows consideration of the fundamental effects of automating all warehouses within a specific DC type d. A higher degree of automation, for example, can be represented by higher investment costs c_w^{DCfix}, and savings on warehouse operations translate into a lower variable cost parameter c_d^{DCvar}. Thus, the selection of highly automated DCs might pay off more if a larger number of products are assigned to the specific DC type, giving more weight to the variable cost component. Note that the automation of warehouses is not modeled as an additional variable. The decision regarding automation is implicitly performed by selecting the corresponding DC types.

Transportation We assume single-modal transport via truck delivery. Our transportation cost assessment is based on unit transportation rates. This is primarily due to complexity reduction in the model and justified by the strategic nature of the problem. Inbound transportation costs from supplier s to warehouse w can be calculated by multiplying the distance-dependent transportation costs $c_{s,w}^{inb}$ by the quantity to be shipped $q_{s,w}^{inb}$, where the latter depends on the assignment of products and the demand share that is attributed to the specific warehouse. Likewise, outbound transportation costs from warehouse w to demand center k are determined by using cost factor $c_{w,k}^{out}$ and transportation quantity $q_{w,k}^{out}$. Note that packing density in outbound transportation is generally lower than in inbound transportation, reflected in factor f^{out} when calculating outbound transportation quantities.

Inventory Considering the effects of the number of parallel warehouses n_d on inventories described in Section 4.2.2, the costs for total capital tied up in safety stock inventory $c_{p,d}^{inv}$ for a specific product p using DC type d can be assessed taking into account the product value, the safety stock factor corresponding to the service level targeted, the product's demand variance and the respective inventory pooling factor. The relation between safety stock levels SS for a distribution system with one central warehouse and total safety stock levels for a distribution system with n parallel warehouses can be generally stated as $SS = pool_n \cdot SS_n$ where the pooling factor $pool_n$ is dependent on the covariance of demand and the variability of demand variances.

We aggregate cost parameters c_d^{DCvar} and $c_{p,d}^{inv}$ into a single parameter since both parameters solely depend on the decision variable $x_{p,d}$. Parameter $c_{p,d}^{assign}$ then represents the decision-relevant costs of assigning product p to DC type d.

Product requirements and instore operations Including the effects of product category allocation within the distribution network on technical setup and instore operations costs, we introduce a cost factor $c_{d,l}^{cat}$ for every DC type d that a product category $l \in L$ is associated with. Binary variable $y_{d,l}^{cat}$ evaluates whether any product within category l is assigned to DC type d.

4.4.1.5 Network resilience

Our modeling approach covers several aspects of resilience planning. Concepts like multiple sourcing and expandable capacities can easily be considered. Furthermore, adjustable service levels can be applied in our model in order to deal with demand uncertainties. The corresponding inventory levels and holding costs affect the network that results from our model. In order to provide an optional degree of facility redundancy, we introduce the parameter $n^{min,total}$ that represents a desired minimum number of warehouses in the overall network across all DC types chosen. Additionally or alternatively, a minimum number of parallel warehouses might be required for individual products. This product-individual number is represented by the parameter $n_p^{min,product}$.

Table 4.2 summarizes all sets, parameters, and variables used.

Index Sets	
$d \in D$	DC types
$k \in K$	Demand centers
$l \in L$	Product categories
$p \in P$	Products
$p_l \in P_l$	Products of category l
$p_s \in P_s$	Products of supplier s
$s \in S$	Suppliers
$w \in W$	Candidate warehouse sites
Parameters	
a_k	Demand at demand center k as s share of total demand
$c_{p,d}^{assign}$	Costs of assigning product p to DC type d
c_w^{DCfix}	Fixed setup costs for warehouse w
$c_{s,w}^{inb}$	Distance-dependent transportation cost rate between supplier s and warehouse w
$c_{w,k}^{out}$	Distance-dependent transportation cost rate between warehouse w and demand center k

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$c^{cat}_{d,l}$	Cost factor for distributing a product category l via DC type d
f^{out}	Additional volume required for outbound relative to inbound transportation
lb_d	Lower bound of demand volume shipped through one warehouse of DC type d
n_d	Number of parallel warehouses for DC type d
$n^{min,product}_p$	Desired minimum number of parallel warehouses for product p
$n^{min,total}$	Desired minimum number of warehouses in total across all DC types
q_p	Demand volume for product p in transportation units
ub_d	Upper bound of demand volume shipped through one warehouse of DC type d
Decision and auxiliary variables	
$\gamma_{w,d}$	Binary variable; 1 if warehouse w is assigned to DC type d; otherwise 0
$\eta_{k,w,d}$	Binary variable; 1 if demand center k is assigned to warehouse w for DC type d; otherwise 0
$a_{w,d}$	Demand at warehouse w of DC type d as a share of total demand
$q^{inb}_{s,w}$	Quantity shipped from supplier s to warehouse w
$q^{out}_{w,k}$	Quantity shipped from warehouse w to demand center k
$x_{p,d}$	Binary variable; 1 if product p is assigned to DC type d; otherwise 0
$y^{cat}_{d,l}$	Binary variable; 1 if at least one product from category l is assigned to DC type d; otherwise 0
z_d	Binary variable; 1 if DC type d is set up; otherwise 0

Table 4.2: Notation for the model NDDCT

4.4.2 Model formulation

The model integrating all network design decisions mentioned (**N**etwork **D**esign with different **DC T**ypes) minimizes total supply chain costs by determining the warehouses' locations, their type affiliations, and capacities.

NDDCT model

$$\begin{aligned}\min\ TC = &\sum_{w\in W}\sum_{d\in D} c^{DCfix}_{w}\cdot\gamma_{w,d} + \sum_{p\in P}\sum_{d\in D} c^{assign}_{p,d}\cdot x_{p,d}\\ &+\sum_{w\in W}\sum_{s\in S}\sum_{d\in D} c^{inb}_{s,w}\cdot q^{inb}_{s,w}\\ &+\sum_{w\in W}\sum_{k\in K}\sum_{d\in D} c^{out}_{w,k}\cdot q^{out}_{w,k}\\ &+\sum_{d\in D}\sum_{l\in L} c^{cat}_{d,l}\cdot y^{cat}_{d,l}\end{aligned} \tag{4.1}$$

s.t.

$$\sum_{d \in D} x_{p,d} = 1 \qquad \forall p \in P \tag{4.2}$$

$$\sum_{p \in P} x_{p,d} - z_d \cdot |P| \leq 0 \qquad \forall d \in D \tag{4.3}$$

$$\sum_{p \in P_l} x_{p,d} - y^{cat}_{d,l} \cdot |P_l| \leq 0 \qquad \forall d \in D, l \in L \tag{4.4}$$

$$\sum_{w \in W} \gamma_{w,d} = n_d \cdot z_d \qquad \forall d \in D \tag{4.5}$$

$$\sum_{w \in W} \eta_{k,w,d} = 1 \qquad \forall k \in K, d \in D \tag{4.6}$$

$$q^{inb}_{s,w} = \sum_{p \in P_s} \sum_{d \in D} q_p \cdot a_{w,d} \cdot x_{p,d} \cdot \gamma_{w,d} \qquad \forall s \in S, w \in W \tag{4.7}$$

$$q^{out}_{w,k} = f^{out} \cdot \sum_{p \in P} \sum_{d \in D} q_p \cdot a_k \cdot x_{p,d} \cdot \eta_{k,w,d} \cdot \gamma_{w,d} \qquad \forall w \in W, k \in K \tag{4.8}$$

$$a_{w,d} \geq \gamma_{w,d} \cdot lb_d \qquad \forall w \in W, d \in D \tag{4.9}$$

$$a_{w,d} \leq \gamma_{w,d} \cdot ub_d \qquad \forall w \in W, d \in D \tag{4.10}$$

$$a_{w,d} = \sum_{k \in K} \eta_{k,w,d} \cdot a_k \qquad \forall w \in W, d \in D \tag{4.11}$$

$$\sum_{d \in D} z_d \cdot n_d \geq n^{min,total} \tag{4.12}$$

$$\sum_{d \in D} x_{p,d} \cdot n_d \geq n^{min,product}_p \qquad \forall p \in P \tag{4.13}$$

$$\gamma_{w,d} \in \{0,1\} \qquad \forall w \in W, d \in D \tag{4.14}$$

$$\eta_{k,w,d} \in \{0,1\} \qquad \forall k \in K, w \in W, d \in D \tag{4.15}$$

$$x_{p,d} \in \{0,1\} \qquad \forall p \in P, d \in D \tag{4.16}$$

$$y^{cat}_{d,l} \in \{0,1\} \qquad \forall d \in D, l \in L \tag{4.17}$$

$$z_d \in \{0,1\} \qquad \forall d \in D \tag{4.18}$$

The first component in the objective function (1) considers the fixed set-up and operating costs per established warehouse. The second component consists of variable warehousing costs (inventory and capacity costs) that depend on the allocation of products to DC types. The third component includes distance- and volume-dependent inbound transportation costs from suppliers to warehouses. Outbound transportation costs are calculated accordingly from the warehouses to the demand centers in the fourth cost term. Lastly, a cost penalty is added for allocating product category l to DC type d. This reflects technical requirements for those products in the warehouses and costs of instore operations that are incurred when at least one product of category l is distributed from a warehouse of type d.

Constraint (4.2) guarantees that each product is allocated to exactly one DC type. In Constraint (4.3) the binary variable for selecting a DC type is set to 1 if any product is allocated to that DC type. Constraint (4.4) determines whether any product of category l is allocated to DC type d. Constraint (4.5) ensures that the number of parallel warehouses selected for a specific DC type matches the number of warehouses required. Each demand center k has to be assigned to a dedicated warehouse per DC type, which is set in Constraint (4.6). Constraints (4.7) and (4.8) determine the quantities of transportation units shipped from supplier s to warehouse w and from there to demand center k, respectively. Constraints (4.9) and (4.10) guarantee warehouses of similar sizes within one DC type with a tolerable degree of variation in size limited by an upper and a lower bound. The quantity shares of each warehouse w for a specific DC type d are determined by Constraint (4.11). Constraints (4.12) and (4.13) optionally guarantee a minimum total number of warehouses across all DC types chosen and that a product is available at a minimum number of parallel warehouses, respectively. Constraints (4.14) - (4.18) define the decision variables as binary.

The problem includes several interdependent variables. Specifically, the assignment of warehouses to a DC type, the affiliation of a demand center to a warehouse and the allocation of products to a DC type exhibit multiplicative connections when all decisions are considered simultaneously. This combinatorial complexity makes it hard to solve the problem optimally and therefore requires a heuristic approach.

4.5 Solution approach

As a solution approach, we propose an iterated local search that is based on a hierarchical decomposition approach and heuristically solves model NDDCT. Within this solution approach we split the original problem into two subproblems. Firstly, a locational problem that determines warehouse locations and demand center assignments per potential DC type (Section 4.5.1), and secondly, a DC type selection problem (Section 4.5.2) that determines the combination of DC types to be operated based on cost-optimal product allocations. This efficiently reduces the problem complexity since the variables of selecting a DC type on the one hand and specifying the warehouse locations per DC type on the other are separated. Consequently, the two submodels can be solved by using standard solvers. In order to deal with the limitations of a purely sequential approach, we present an iterated local search algorithm (Section 4.5.3) that alleviates the risk of obtaining a suboptimal local minimum.

4.5.1 Locational problem

The location problem is divided into several independent but specialized p-median problems, each problem determining the locations of the respective intended number of parallel warehouse for a possible DC type. This approach is suitable since we assume a predefined number of parallel warehouses for each type of DC. Since the locations of warehouses are independent between DC types, a total number of $|D|$ p-median problems are to be solved. The following model formulation (denoted as **W**arehouse **L**ocation and **D**emand **C**enter **A**ssignment model) determines whether a warehouse location w will be established as a DC of type d (decision variable $\gamma_{w,d}$). Extending classic p-median approaches, in our case each demand center k also has to be assigned to a specific warehouse w per type of DC d (decision variable $\eta_{k,w,d}$).

WLDCA model

$$\begin{aligned} Minimize\ Z_d^{\text{WLDCA}} = & \sum_{w \in W} c_w^{DCfix} \cdot \gamma_{w,d} \\ & + \sum_{s \in S} \sum_{w \in W} \sum_{p \in P_s} c_{s,w}^{inb} \cdot q_p \cdot \frac{1}{n_d} \cdot \gamma_{w,d} \\ & + \sum_{k \in K} \sum_{w \in W} c_{w,k}^{out} \cdot q_p \cdot a_k \cdot \eta_{k,w,d} \end{aligned} \tag{4.19}$$

s.t.

$$\sum_{w \in W} \gamma_{w,d} = n_d \tag{4.20}$$

$$\sum_{w \in W} \eta_{k,w,d} = 1 \qquad \forall k \in K \tag{4.21}$$

$$\sum_{k \in K} \eta_{k,w,d} \cdot a_k \geq \gamma_{w,d} \cdot lb_d \qquad \forall w \in W \tag{4.22}$$

$$\sum_{k \in K} \eta_{k,w,d} \cdot a_k \leq \gamma_{w,d} \cdot ub_d \qquad \forall w \in W \tag{4.23}$$

$$\gamma_{w,d} \in \{0,1\} \qquad \forall w \in W \tag{4.24}$$

$$\eta_{k,w,d} \in \{0,1\} \qquad \forall k \in K, w \in W \tag{4.25}$$

The objective function (4.19) minimizes location-related setup costs as well as transportation costs. The cost terms are formulated equivalent to model NDDCT except for the fact that in the p-median model product assignments to DCs are not considered. Variable setup costs are therefore not included and transportation volume from suppliers to warehouses and from there to demand centers have to be based on assumptions regarding their distribution. We therefore assume that all warehouses may provide the full assortment and additionally suppose that quantities shipped from a supplier s are equally split across the parallel warehouses w of a certain type d.

The first constraint (4.20) sets the selected number of warehouses for DC type d equal to the required number of parallel warehouses n_d which is designated for this DC type. The second constraint (4.21) ensures that each demand center k is supplied by exactly one warehouse w per DC type d. The following two constraints (4.22 and 4.23) specify that the warehouses for each DC type are of similar size regarding their share of distributed quantities equivalent to Constraints (4.9) and (4.10) in model NDDCT. The binary decision variables are defined in Constraints (4.24) and (4.25).

The p-median problem that underlies our **WLDCA** model is known to be NP-hard, however, exact and efficient algorithms exist for solving realistically dimensioned instances (Kariv and Hakimi, 1979). Standard solvers can thus be used to solve the WLDCA problems within a reasonable time.

4.5.2 Selection and dimensioning of DC types

Based on the results of the WLDCA model, the subsequent **DC Type Selection** model determines the cost-optimal combination of DC types. In order to assess the costs of selecting DC types, the product allocations to DC types - more specifically the allocations' cost implications for transportation, warehousing and instore logistics - are a key factor. Since warehouse locations per DC type have already been specified in the WLDCA model through the variable $\gamma_{w,d}$, we can define the set of warehouses per DC type with W_d accordingly ($W = \bigcup\limits_{d \in D} W_d$). The same applies to the assignment of demand centers to warehouses, resulting in the sets K_w ($K = \bigcup\limits_{w \in W} K_w$). Since the assignment of demand centers to warehouses per DC type has been determined in model WLDCA through the variable $\eta_{k,w,d}$, the result is now used as a parameter $\eta^*_{k,w,d}$ in model DCTS.

DCTS model

$$\begin{aligned} Minimize\ \ Z^{\text{DCTS}} = & \sum_{d \in D} \sum_{w \in W_d} c_w^{DCfix} \cdot z_d + \sum_{p \in P} \sum_{d \in D} c_{p,d}^{assign} \cdot x_{p,d} \\ & + \sum_{d \in D} \sum_{w \in W_d} \sum_{s \in S} c_{s,w}^{inb} \cdot q_{s,w}^{inb} \\ & + \sum_{d \in D} \sum_{w \in W_d} \sum_{k \in K_w} c_{w,k}^{out} \cdot q_{w,k}^{out} \\ & + \sum_{d \in D} \sum_{l \in L} c_{d,l}^{cat} \cdot y_{d,l}^{cat} \end{aligned} \tag{4.26}$$

s.t.

$$\sum_{d \in D} x_{p,d} = 1 \qquad \forall p \in P \qquad (4.27)$$

$$\sum_{p \in P} x_{p,d} - z_d \cdot |P| \leq 0 \qquad \forall d \in D \qquad (4.28)$$

$$\sum_{p \in P^l} x_{p,d} - y^{cat}_{d,l} \cdot |P_l| \leq 0 \qquad \forall d \in D, l \in L \qquad (4.29)$$

$$q^{inb}_{s,w} = \sum_{p \in P_s} \sum_{d \in D} q_p \cdot a_{w,d} \cdot x_{p,d} \qquad \forall s \in S, w \in W \qquad (4.30)$$

$$q^{out}_{w,k} = f^{out} \cdot \sum_{p \in P} \sum_{d \in D} q_p \cdot a_k \cdot \eta^{*}_{k,w,d} \cdot x_{p,d} \qquad \forall w \in W, k \in K \qquad (4.31)$$

$$\sum_{d \in D} z_d \cdot n_d \geq n^{min,total} \qquad (4.32)$$

$$\sum_{d \in D} x_{p,d} \cdot n_d \geq n^{min,product}_p \qquad \forall p \in P \qquad (4.33)$$

$$x_{p,d} \in \{0,1\} \qquad \forall p \in P, d \in D \qquad (4.34)$$

$$y^{cat}_{d,l} \in \{0,1\} \qquad \forall n \in D, l \in L \qquad (4.35)$$

$$z_d \in \{0,1\} \qquad \forall d \in D \qquad (4.36)$$

The model formulation of DCTS is similar to that of the integrated model NDDCT with the following adaptations. The results of the variables $\gamma_{w,d}$ and $\eta_{k,w,d}$ are represented by the sets W_d and K_w. The result for $a_{w,d}$ as determined in the WLDCA model is now considered as a parameter. This causes an extension of the first term of the objective function where the fixed location costs are now multiplied by decision variable z_d. Former constraints (4.5) - (4.6), (4.9) - (4.11) and (4.14) - (4.15) are not necessary anymore and therefore excluded.

This reduced model represents a special case of the generalized assignment problem, where a task (in our case an SKU) is assigned to an agent (DC type), allowing multiple assignments to agents (G. T. Ross and Soland, 1975). This type of problem is known to be NP-hard and is usually solved by branch and bound techniques using, e.g., Lagrangian or surrogate relaxation (Jörnsten and Näsberg, 1986; Cattrysse and Wassenhove, 1992).

4.5.3 Solution algorithm

Sequentially solving the two submodels bears the risk of quickly steering into a local minimum, since model WLDCA assumes that each product is distributed via each DC type to get an initial solution for the warehouse locations. This might result in a suboptimal network structure selected by model DCTS. A post-optimization of the warehouse locations based on the product allocations of model DCTS can lead to a better solution but usually reinforces the DC types that were selected by the DCTS model. Thus, we propose an iterated local search (ILS), as depicted in Figure 4.5, to alleviate this problem.

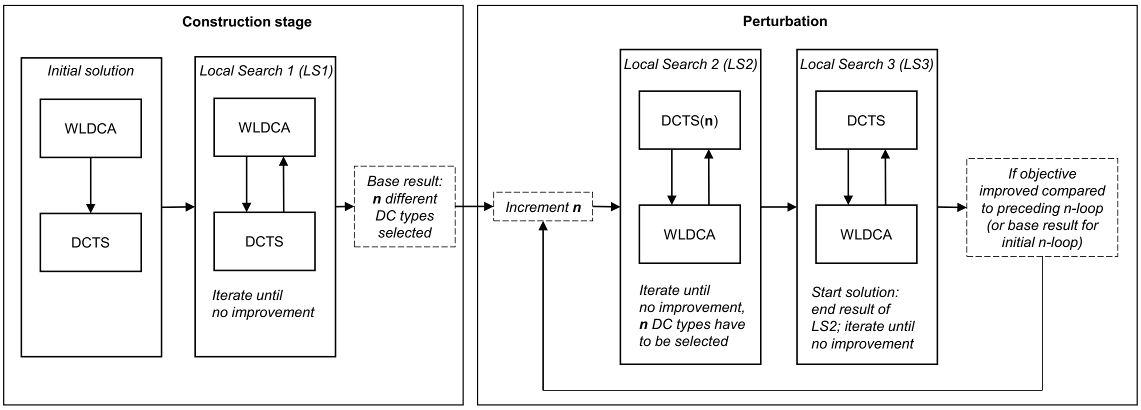


Figure 4.5: Outline of the solution approach

As opposed to multi-start descent search approaches that randomly generate a population of initial solutions, the ILS metaheuristic builds on an opening local search from where neighboring solutions are systematically analyzed in an iterative manner (Rothlauf, 2011; Lourenço et al., 2018). The ILS has been successfully applied in a variety of combinatorial problems (Stützle, 2006; Juan et al., 2013; Fernandez et al., 2018; Muritiba et al., 2021), including network design problems (Cordeau et al., 2008). After a construction stage where an initial solution is generated and a local search is performed, a perturbation is introduced to diversify the search space. Another local search is performed based on the perturbed solution. The perturbation and subsequent local search is then iteratively repeated until no further improvement is found. In the following we present the single stages of the ILS adapted to our problem.

Construction stage The models WLDCA and DCTS are solved sequentially to gain an initial solution. Model WLDCA generates warehouse locations for each potential DC type, model DCTS then selects the optimal combination of DC types based on the warehouse locations found by model WLDCA. In a local search (LS1), the two models are solved iteratively. The resulting allocations of products to DC types are used to refine the warehouse locations considering only those products per DC type that have been assigned to the respective type in the previous DCTS model. The updated warehouse locations are then again passed to the DCTS model. The process of iteratively solving model WLDCA and model DCTS might undergo some loops until no further improvement is achieved. However, it naturally converges to stable decisions within a few iterations since warehouse locations and product allocations reciprocally reinforce their solutions. The local search finally leads to a solution with n different DC types.

Perturbation As different product clustering might lead to an alternative, more cost-efficient network structure, we add the following perturbation step: we set the number of DC types that have to be selected in model DCTS as a hard constraint in order to isolate the most promising alternative product cluster that has not yet been considered. This number is set to an increment of 1 compared to the LS1 solution, such that $n = n + 1$. All other decisions are reset after LS1. While keeping the constraint of fixating the number of DC types to be selected, a second local search (LS2) of model WLDCA and model DCTS is applied. This local search is required for sufficiently aligning the warehouse locations to the perturbed solution. As a result, a certain product group is isolated for the additional DC type, a new set of DC types is generated, and warehouse locations are adapted accordingly. The solutions of LS2 are then passed to a third local search (LS3) where the constraint introduced in LS2 is discarded, i.e., the number of DC types can be freely selected again. If LS3 produces a new best solution, the perturbation step of the ILS is repeated while incrementing the number of DC types that have to be selected in LS2 until no further improvement of the solution is found.

The ILS may lead to various results. Besides producing the same result as LS1, a more differentiated network with additional DC types could be established, the selected DC types could remain the same, but product allocations and warehouse locations might change, and finally, a shift in the selected DC types may occur, even if the number of DC types stays the same. An example of a path when searching for the most cost-efficient solution could be for instance: LS1 leads to the following setting of DC types 1-3-6 (numbers represent the number of parallel warehouses for each DC type) with $n = 3$, LS2 with $n = 4$ as a hard constraint leads to 1-3-5-6 and LS3 results in 1-3-5, which reduces overall costs compared to 1-3-6. In a next iteration, LS2 with $n = 5$ as a hard constraint would lead to a 1-3-5-6-7 selection and LS3 finally offers no further improvement when suggesting 1-3-5, such that the search process stops in this example.

4.6 Application

In order to assess the model's aptitude and dynamics as well as potential cost reductions for real-life settings, we implement our network design approach with data from a major European grocery chain. After introducing the case setting and relevant data (Section 4.6.1), we present numerical results for three different network restructuring scenarios (Section 4.6.2). Thereafter we provide sensitivity analyses of results varying the cost parameters to obtain further managerial insights (Section 4.6.3).

4.6.1 Case setting and implementation

This case study focuses on the German market of a major European grocery retailer with a special focus on the ambient food and drugstore segment. The retailer runs around 2,000 stores in Germany. The product mix is diversified, including ambient food, health products, household articles, cosmetics, and baby products. The company's structure is suitable for applying the segmentation-oriented network design approach presented in this paper due to the broad spectrum of categories offered and the resulting variety of product characteristics.

For our implementation we consider around 8,000 products (constituting the retailer's main assortment) belonging to 11 different categories, all sourced from around 300 different suppliers. The suppliers are located either in Germany or neighboring countries. Those products are designated to be transported to and stored in one or several parallel DCs. From there they are shipped to 36 transshipment points, which are cross-dock facilities close to the respective stores. These transshipment points act as demand center references in our application. Products that are better suited for means of distribution other than shipment and storage via DC have been excluded from our analysis. Currently the company operates a three-type DC network consisting of one central DC, two parallel regional DCs and another six parallel local DCs. Each product is assigned to exactly one type of DC.

Since the company's network has developed over time with significant organic growth during recent years, the question arises as to whether the current DC network configuration is still appropriate. The aim of this case study is therefore to evaluate the current situation and to demonstrate the effects of restructuring the supply chain according to our proposed model and solution approach.

All cost components, product and location parameters used in this case study are provided by the case company and are subject to confidentiality regulations. We limit our analysis to investigation of the number of parallel warehouses per DC type for the sake of clarity. We therefore assume the costs of setting up a warehouse as well as variable warehousing cost rates to be identical between DC types. Within this scheme, each DC type basically offers a different degree of centralization for distributing a product. Thus, "DC type 1" would refer to a single warehouse, "DC type 2" refers to two parallel warehouses, etc. We analyze DC types with up to 10 parallel warehouse locations if not otherwise stated. Pretests assuming low setup and capacity costs showed that this is a reasonable limit and for reasons of computational runtime a limitation of candidate DC types is favorable, if not indispensable.

Using this data we implemented the solution approach suggested in Section 4.5 in Python applying Gurobi v8 1.1 as solver for the mathematical models. All tests were run on an

Intel Core i5-4300U CPU @ 1.9 GHz with 8 GB RAM.

4.6.2 Restructuring scenario analyses

Three restructuring scenarios are considered in our analysis:

Scenario A Reassigning current warehouses to DC types and reallocating products to the new DC types, i.e., a restructuring without the possibility of opening new locations, i.e., brownfield setting.

Scenario B Extending the set of potential warehouses using transshipment point locations as candidate warehouse sites, resulting in a mixed setting.

Scenario C Redesigning the distribution network with a greenfield approach, i.e., using a multitude of candidate sites, regardless of existing locations belonging to the company.

We apply the same fixed setup costs for all candidate locations irrespective of whether warehouses already exist or have to be set up. Table 4.3 summarizes the DC types selected and capacity requirements for the different scenarios, while Table 4.4 details cost distributions and savings potential.

	DC Types									
	1	2	3	4	5	6	7	8	9	10
Current setting	55	37	0	0	0	8	0	0	0	-
Scenario A	75	25	0	0	0	0	0	0	0	-
Scenario B	86	0	0	0	14	0	0	0	0	0
Scenario C	70	24	6	0	0	0	0	0	0	0

Table 4.3: Capacities used per potential DC type in percent of total SKUs

		Cost components				
	Total	Capacity	Inbound	Inventory	Outbound	Instore
Current setting	100	12	54	2	28	6
Scenario A	-12.7	-41	-36	-19	+50	-40
Scenario B	-12.8	-19	-19	-8	+9	-53
Scenario C	-14.9	-26	-43	-13	+48	-30

Table 4.4: Shares of cost components on overall costs for current setting and relative cost differences in the scenarios compared to the cost components' levels in the current setting (in percent)

Scenario A: Brownfield setting First we examine the results from restructuring the current DC network without the possibility of opening new locations. Applying our solution approach, the results show that costs are minimized when restructuring the network from a three-type to a two-type design. As shown in Table 4.3, 75% of the products are then allocated to a central warehouse and the remaining 25% of the products are distributed via two parallel regional warehouses. Compared to the current situation, this allows a reduction of 12.7% of overall costs to be realized (see Table 4.4). Those cost savings are primarily due to lower inbound and capacity/warehousing costs that are a direct result of reducing the number of warehouses. On the other hand, costs for outbound transportation increase by 50% compared to the original setting since total distances from the warehouses to their corresponding demand center are lengthened. Inventory costs are reduced, but they only play a minor part in our setting as they amount up to merely 1.5% of total costs. Instore costs, which account for 5.6% of total costs in the original setting, are reduced by 40%.

Scenario B: Mixed setting Since the number of candidate warehouse sites is relatively low in Scenario A, the results may have only little indicative value for total cost savings potential and structural issues in a broader network analysis. We thus investigate how an increase in potential warehouse locations might impact the selection of DC types. In Scenario B we expand the candidate sites by the transshipment point locations, which provides us with a total of 45 coordinates where logistics facilities are operated at present and therefore could potentially be used for DC operations with limited financial effort. Like Scenario A, a two-type network is established in Scenario B, but five parallel warehouses are to be set up in addition to the central DC. Due to the increase in the number of parallel warehouses for the regional DC type, compared to scenario A, costs of inbound transportation and warehousing rise, but the savings in outbound transportation compensate for this effect. Regarding total costs, the savings potential is only marginal compared to scenario A, which is a first indicator that restructuring the current DC network using given DC locations is enough for the company to benefit from a major proportion of total cost savings achievable.

Scenario C: Greenfield setting To further verify the overall cost savings potential regarding the DC network for the retailer, we examine a greenfield approach in which 400 potential warehouse sites are uniformly aligned within a rectangle grid covering the retailer's distribution area. Our solution approach results in a three-type setting where 70% of products are distributed via a central DC, 24% of products are distributed via two parallel warehouses, and the remaining 6% of products are distributed via three parallel warehouses. Overall costs can be reduced by 14.9% when applying this greenfield approach compared to the company's original setting. Even though only 6% of products are stored in the third DC type, they make up for 39% of total demand as measured by the number of pallets delivered to the warehouses (compared to 21% for DC type 1 and 40% for DC type 2). The value density, i.e., the value per pallet of a product, is an average of 25 times higher in DC type 1 than in DC type 3.

Cross-scenario analysis The scenario analysis shows that a major share of the products are apparently more suitable to be distributed centrally, while a minor group of products is preferably distributed in a regionalized system. It is apparent that a major cost reduction can already be achieved when restructuring the company's current setting. This can be explained mainly by the cost reductions in inbound, capacity and instore costs. However, the benefit from providing additional 36 potential candidate sites in Scenario B compared to Scenario A is only marginal. For solving the second type there seems to be a balanced tradeoff between outbound costs and capacity costs. The costs when setting up two parallel warehouses in Scenario A are therefore at approximately the same level compared to the five parallel warehouses in Scenario B, where setup costs are increased but counterbalanced by the reduced outbound transportation costs. Finally, when providing a much denser grid of candidate sites for warehousing in Scenario C, the costs of the brownfield settings can be reduced by yet another 2.4% by using a more differentiated network. This indicates the influence of the candidate sites on both the total costs and the solution structure (in terms of network structure and product allocations). The specific coordinates for candidate warehouse sites can hence be pivotal for the resulting network's shape in terms of its total number of warehouses and thus for the financial effort that is attributed to the different cost components of the supply chain. This means that a deeper analysis of the individual cost components, as will be provided in the following Section 4.6.3, can yield additional information for a robust network design.

4.6.3 Analysis of cost components

This section further analyzes the different cost components and their impact on the network decision. Section 4.6.3.1 describes the individual effects of certain cost components on the solution, whereas Section 4.6.3.2 illustrates the dynamics of network configurations when cost parameters are gradually altered in a sensitivity analysis. This section's analysis is based on the greenfield scenario (Scenario C in the previous section), where warehouse locations can be chosen from a grid of 400 candidate sites.

4.6.3.1 Effects of individual cost components

In the first set of analyses we gradually include the different cost terms in our calculation. In order to explore more potential outcomes, we expand the number of possible DC types to its maximum, i.e., the number of available demand centers. In our case, the

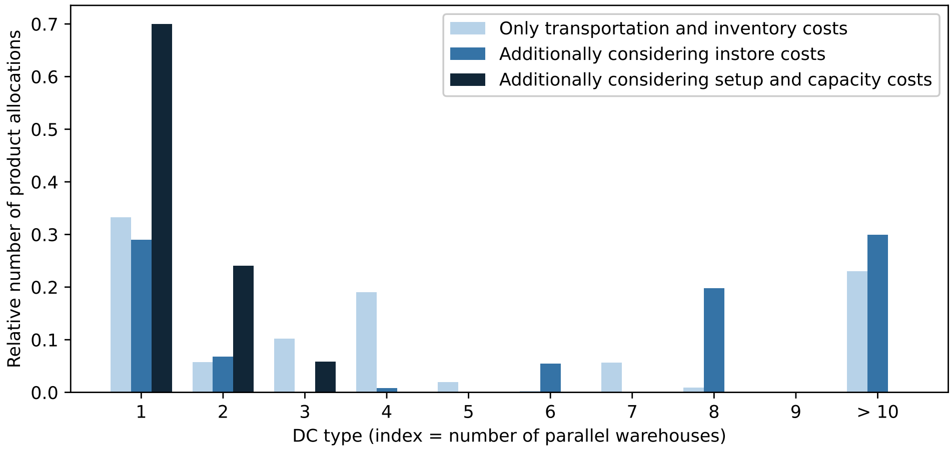


Figure 4.6: DC type selection and capacity requirements considering the individual cost terms

maximum number of different DC types amounts to 36, ranging from a central warehouse ("DC type 1") that supplies all demand centers to 36 parallel warehouses ("DC type 36") that supply one single demand center each. First we examine the results when only product-individual costs are considered, i.e., only transportation and inventory costs per product, but warehouse setup and capacity costs as well as instore costs that mainly result from the interdependence of product allocations are neglected (corresponding cost factors are set to 0). Second, instore operations costs are added, and finally costs for setting up and operating warehouses. The resulting DC type selections and respective capacity requirements are summarized in Figure 4.6.

Transportation and inventory costs Key findings are that omitting warehouse capacity costs and effects on instore operations leads to a highly differentiated network in the case considered. The resulting distribution system then consists of 23 different DC types (selected out of 36 potential types). It appears that a substantial number of products (33%) is obviously prone to be distributed via a central DC. The remaining products are divided into a plurality of different DC types with a maximum number of 34 parallel warehouses in the most regionalized DC type that is selected. This shows that certain products - especially those assigned to 34 parallel warehouses - might be suitable to be shipped directly from suppliers to demand centers. In general, this analysis highlights the heterogeneous characteristics of the product assortment investigated and the differentiated needs of the products regarding centralization and regionalization.

Instore operations costs Introducing effects resulting from instore operations intuitively leads to a reduction of DC types since dividing products from one category on multiple DC types is penalized. The results thus show a concentration on six DC types (featuring

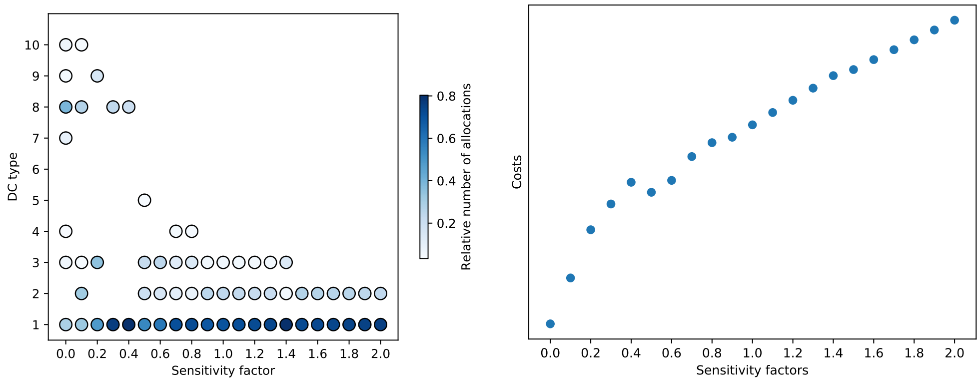
1, 2, 4, 6, 8, and 34 parallel warehouses, respectively). This major reduction in DC types underlines the significant influence of instore operations and product category effects on the network design even though the percentage proportion of this cost component in relation to total relevant costs is comparatively small (compare Table 4.4).

Setup and capacity costs Finally, when considering the remaining cost components, namely fixed and variable costs for setting up and operating warehouses, the results shift towards the solution of Scenario C in Section 4.6.2, i.e., the network complexity reduces to three DC types with one central warehouse, two parallel regional and another three parallel local warehouses.

4.6.3.2 Cost sensitivity analysis

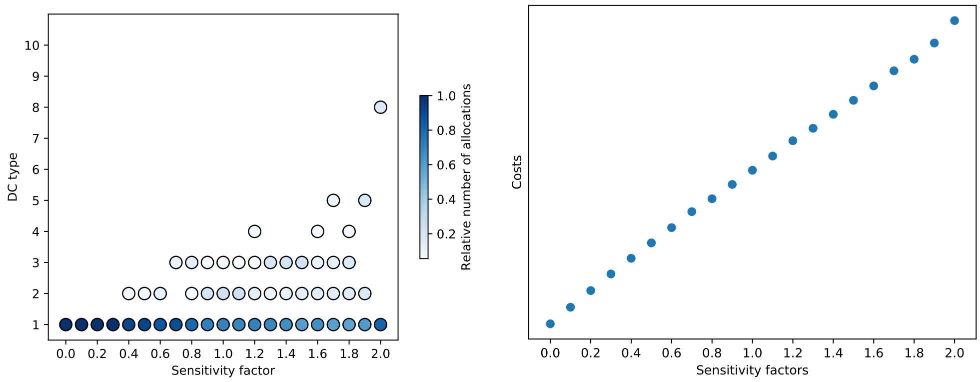
A common method for evaluating the results' robustness during the network design is to conduct sensitivity analyses on critical parameters (Aldrighetti et al., 2022). We focus on capacity cost rates (setup and variable costs for warehousing) as well as transportation rates since these factors show the highest share of total relevant costs (see Table 4.4). Additionally, these cost components may be subject to major changes during the strategic planning horizon. Capacity costs might vary due to fluctuations in land prices and developments in technology, whereas transportation rates are for instance prone to technological advancements or political impacts (e.g., taxes, emission reduction policies). Sensitivity factors for the following analyses are set in 0.1 intervals ranging from 0.0 to 2.0 in relation to the original values used in Section 4.6.2.

Capacity costs The findings depicted in Figure 4.7a show that with increasing costs for setting up and operating a warehouse, the total number of warehouses in the distribution system decreases. For example, while eleven warehouses (types 1, 2, 3 & 5) are used when assuming a halved rate (sensitivity factor 0.5) for setup and capacity costs, the number reduces to six (types 1, 2 & 3) in the base scenario (sensitivity factor 1.0). Starting with a factor of 1.5, the three-type configuration changes to a two-type configuration (type 1 & 2). This tendency is also apparent when analyzing the changes in total costs (see Figure 4.7b). At low rates of setup and capacity costs, the network structure sensitively reacts to changes and thus total costs increase sharply. At the point where the network structure attunes to the same three-type and then two-type system, total costs continue to increase in a relatively linear manner. Especially for very low-capacity cost rates, it is evident that better solutions can be found compared to the results from the iterated local search approach proposed. For example, overall costs can obviously be reduced for the setting with factor 0.4 by applying the configuration of the setting that results with factor 0.5.



(a) Allocations (b) Total costs

Figure 4.7: Sensitivity analysis: Setup and capacity costs



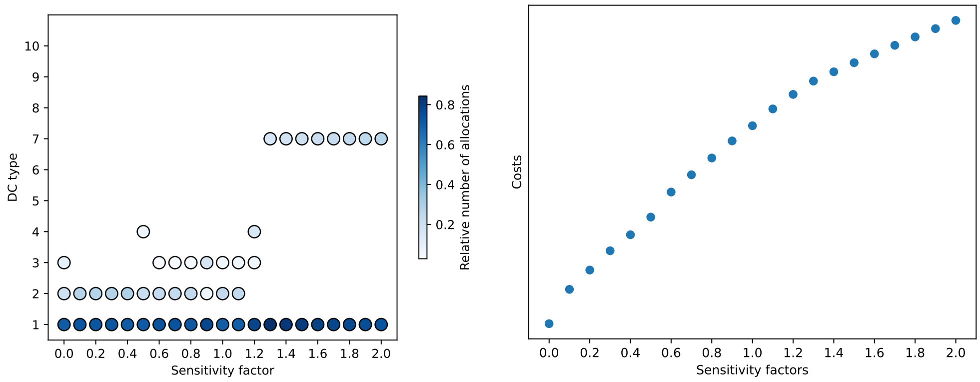
(a) Allocations (b) Total costs

Figure 4.8: Sensitivity analysis: Transportation costs

This is due to the fact that with such low capacity costs the problem becomes much more complex since a large variety of type combinations needs to be considered. In the end, those marginal settings are rather atypical in the retail context. In the range of realistic cost variations (factor 0.8 to 1.2), the heuristic generates relatively robust solutions and thus reliable suggestions for how retailers should ideally structure their network.

Transportation costs The network becomes more regionalized with increasing transportation costs. Only one central warehouse is opened if extremely low transport rates (sensitivity factor 0.0 to 0.3) are assumed, whereas nine warehouses (DC types 1 & 8) are opened when transportation rates are double compared to the original setting (sensitivity factor 2.0). This effect can be attributed to the circumstance that we assume outbound transportation costs to be slightly more expensive than inbound transportation costs due to the less efficient last-mile delivery (e.g., lower packing density for pallets). Thus, more regionalized warehouses decrease the distances from warehouses to demand centers.

We estimate the factor f^{out} that reflects the difference in packing density between inbound



(a) Allocations (b) Total costs

Figure 4.9: Sensitivity analysis: Outbound costs (packing density)

and outbound transportation based on empirical data of the case company. f^{out} thereby measures the additional required number of pallets in outbound compared to inbound transportation. In order to evaluate the result's robustness we provide the solutions of a sensitivity analysis on this factor. Figure 4.9 shows that an increase in outbound costs due to lower packing density (and thus a higher value of factor f^{out}) leads to a more decentralized network. Our solution thereby appears to be robust in a practically realistic range of the parameter f^{out}, i.e., -20% (factor 0.8) and +10% (factor 1.1).

A separate sensitivity analysis on inbound transportation rates has proven to produce the opposite tendency, i.e., regionalized structures for low inbound rates and a centralized solution for high inbound rates. Total costs increase in an almost linear manner, although the network structure and distribution of products among DC types change noticeably.

Summary The results show that the network solutions generated are comparatively robust in terms of changes of the major cost components within realistic ranges. For all cost factors analyzed there is hardly a change in the basic network structure for a cost variation interval between -20% (factor 0.8) and +20% (factor 1.2) compared to the base scenario (factor 1.0). Similar robust results are obtained when the packing density factor f^{out} is varied within practically relevant quantities. This confirms the suitability of the strategic network design approach proposed for retail practice.

4.6.4 Runtime performance

The total runtime of the ILS approach including all pre-process steps varies between 1.4 and 98 minutes in all our numerical experiments, with a mean of 24 minutes, a median of 20 minutes and a standard deviation of 20 minutes. The number of loops within the ILS (which is equivalent to the number of WLDCA optimization runs) varies between 2 and 31, with a mean of 10, a median of 9 and a standard deviation of 7. We found that the overall runtime is highly dependent on the parameter constellation. Thus, slightly increasing or decreasing a parameter (e.g., transportation cost rate) might result in a lot more loops within the ILS depending on the criticality of parameter combinations. Nevertheless, considering the usually quite moderate computation times, the proposed modeling and solution approach seems to be very well suited for an application in retail practice.

4.7 Conclusions and future research

This paper presents a modeling and solution approach for the retail-specific network design problem with different DC types. This allows us to close a corresponding gap in literature by integrating several retail specific issues of practical relevance.

We provide an in-depth discussion on the two basic dimensions when deciding on the arrangement of the warehouse network: the degree of differentiation, i.e., the number of different DC types for storing distinct sets of products, and the degree of centralization, i.e., the number of parallel warehouses per DC type. We identified several factors that are relevant for the planning problem, including capacity costs, transportation, inventory holding, instore logistics, as well as product heterogeneity.

We develop a comprehensive MIP model denoted “Network Design with different DC Types (NDDCT)” to support the decision on the number and structure of DC types, the associated assignments of products to these DC types, and the respective location of each warehouse. Although only implicitly modeled, our modeling approach accommodates basic aspects of several topics related to retail network design, such as warehouse automation decisions, resilience planning and e-commerce settings. For instance in resilience planning, our model covers basic aspects such as multiple sourcing, parallel warehouses, service level considerations and expandable capacities. We hierarchically decompose the entire NDDCT problem to reduce complexity and facilitate solvability. The resulting two sub-models, i.e., the warehouse location and demand center assignment (WLDCA) model and the DC type selection (DCTS) model, sequentially solve the entire NDDCT problem. Both MIP models are then used in an iterated local search procedure to find new feasible and competitive solutions in the immediate neighborhood of solutions already available in reasonable computation time.

In a case study conducted with data from a major European grocery chain we demonstrated the cost savings potential from applying our modeling and solution approach. We found that overall supply chain costs in that company can be reduced with our approach by up to 15% and even 30% to 50% of the decision-relevant instore costs. We demonstrate the suitability and benefits of our approach for greenfield network designs as well as for network restructuring decisions. Detailed cost analyses provide managerial insights on cost influences and support the robustness of the results obtained by our modeling and solution approach.

Although we consider a large set of retail specifics and the main problem characteristics that are of practical relevance for retail distribution network design, our model has several limitations which offer opportunities for future research:

(a) Further research possibilities include for example the extension of this network design problem by considering service-oriented criteria. In markets with large transportation distances or limited transportation infrastructure it may be necessary to include general or product-individual maximum response times. These may affect both the allocation decision and DC type selection, potentially leading to a more regionalized and/or to a more differentiated network (in the event of varying service requirements between products).

(b) Regarding the product mix, we assume a stable portfolio that enables static long-term planning. This assumption holds in the grocery trade for instance, where the core assortment does not significantly change over time. In order to apply the approach to other retail sectors where fluctuations in the product mix occur due to new listings and de-listing as well as parameter changes (e.g., demand, and cost factors), different programming approaches may be necessary to account for dynamic developments (Sadghiani et al., 2015; Mohamed et al., 2020). With regard to resilience planning, the model could be adapted by further concepts, such as facility dispersion, lateral shipments and stochastic programming (see, e.g., Alikhani et al., 2021; Maharjan and Kato, 2022)

(c) Returns play an increasingly important role in certain retail sectors (e.g., fashion, consumer electronics). The integration of forward and reverse logistics processes can be significantly more expedient in such cases than executing detached planning concepts for these two logistics processes, especially when product life cycles require a high pace for processing and recirculation of returns (Bernon et al., 2011). The consideration of reverse logistics flows in network design is therefore an interesting field for future research.

(d) Another aspect of further model development can be the integration of additional distribution paths. In our approach we assume that products that are directly delivered or drop-shipped are excluded upfront in the decision process of determining warehouse locations and selecting DC types. However, for certain products the decision between direct shipping vs. distribution via warehouse(s) may be dependent on the respective selection of DCs.

(e) We investigate the case of a traditional bricks-and-mortar retailer. The level of cross-channel integration is of crucial importance for retailers who operate a multi-channel system when designing the physical network structure (Hübner et al., 2016). Developing a network design model tailored to omnichannel business may thus be a further interesting field for future research. This also includes direct deliveries to final customers from the warehouses.

(f) The basic effects of selecting different degrees of warehouse automation per DC type can be quantified in our model. However, in its present form the effects of automation are only represented by the fixed setup costs that include the amount of investment in automation equipment and the corresponding savings in variable costs for warehouse operations based on product volumes. Further developments of the model could integrate more detailed effects of automation on warehouse operations, representing the impact on processes such as picking more thoroughly.

5 Contribution 4: Integrated cross-dock location and supply mode planning in retail networks

This chapter is based on the following manuscript:
Tobias Potoczki, Andreas Holzapfel, Heinrich Kuhn, Michael Sternbeck. „Integrated cross-dock location and supply mode planning in retail networks“. International Journal of Production Economics, 2024.
https://doi.org/10.1016/j.ijpe.2024.109349.

5.1 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. Practicioners 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 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 F.-T. 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; S. D. 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.

5.2 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.

5.2.1 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; Holzapfel et al., 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.

5.2.2 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.

5.2.3 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 (Abouee-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).

5.3 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 5.3.1 therefore reviews CD location and network design contributions. Section 5.3.2 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 5.3.3 presents the reviewed literature in a comparative table, summarizes the findings obtained from the literature, and highlights the distinctive contribution of our work.

5.3.1 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 and Campbell, 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 W. 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 A. Ross, 2003 and A. 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., 2013a 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., 2013c and Mousavi et al., 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 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.

5.3.2 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 F.-T. 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; Z. Li et al., 2009; S. D. 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 A. 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.

5.3.3 Summary, Research Gap and Contribution

Table 5.1 differentiates the literature analyzed from the problem setting we are considering and illustrates the novelty of our approach.

Table 5.1: 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 neighbourhood 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 W. Yang, 2008	✓	✓	-	-	-	truck	-	-	exact (B&P)
Jayaraman and A. Ross, 2003	✓	-	-	-	-	linear	✓	-	metaheuristic (SA)
Bachlaus et al., 2008	✓	✓	-	-	-	linear	-	-	metaheuristic (PSO)
Mousavi et al., 2013a	✓	✓	-	-	-	truck	-	-	metaheuristic (SA/TS)
Mousavi et al., 2013c	✓	✓	-	-	-	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)

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 5.1). 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, our approach differs significantly from the approaches proposed in the literature, as we assume a limited number of delivery frequencies and delivery patterns that allow 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 5.3.2) 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 5.1 that a wide variety of approaches have 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.

5.4 Model

The given supply network of a retail company consists of a set of suppliers, $S = \{1, 2, \ldots, s, \ldots |S|\}$, a set of (potential) cross-dock points (CDs), $I = \{1, 2, \ldots, i, \ldots |I|\}$, and a set of warehouses, $W = \{1, 2, \ldots, w, \ldots |W|\}$. 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, $D = \{1, 2, \ldots, d, \ldots |D|\}$. 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 $freq_m$, $m \in M = \{1, 2, \ldots, m, \ldots |M|\}$ 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 $J = \{1, 2, \ldots, j, \ldots |J|\}$, which specifies the possible combinations of the exact delivery days for each of the possible frequency modes. Table 5.2 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 5.2 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.

Table 5.2: 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	$freq_m$	$\frac{\|D\|}{freq_m}$	$q_{s,w,j}$
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
⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

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 $I = \{1, 2, \ldots, i, \ldots |I|\}$, (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 (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_i^{setup} 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 $c_{s,i,m}^{\text{assign}}$. Cost parameter $c_{s,i,m}^{\text{assign}}$ 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 $c_{s,i,m}^{\text{assign}}$, which are influenced by the respective shipping option and frequency mode.

The cost rate per truck travelling from CD i to warehouse w is denoted by $c_{i,w}^{\text{outb}}$. 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., $q_i^{\min}$ and $q_i^{\max}$. 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 5.3 summarizes the notation used.

Table 5.3: Notation for model SNDP-FT

Index sets	
D	Days of the planning cycle, $D = \{1, 2, \ldots, d, \ldots \lvert D\rvert\}$
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, $I = \{1, 2, \ldots, i, \ldots \lvert I\rvert\}$
J	Delivery patterns, $J = \{1, 2, \ldots, j, \ldots \lvert J\rvert\}$
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, $M = \{1, 2, \ldots, m, \ldots \lvert M\rvert\}$
S	Suppliers, $S = \{1, 2, \ldots, s, \ldots \lvert S\rvert\}$
W	Warehouses, $W = \{1, 2, \ldots, w, \ldots \lvert W\rvert\}$
Parameters	
$c_{s,i,m}^{\text{assign}}$	Costs for assigning supplier s to delivery path i and frequency mode m
c_i^{setup}	Fixed costs for setting up and operating a CD at candidate site i
$c_{i,w}^{\text{outb}}$	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
$q_i^{\min}$	Minimum quantity to be processed through CD i within the entire planning cycle
$q_i^{\max}$	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

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Decision and auxiliary variables	
$f_{i,w,d}$	Integer variable quantifying the number of truck shipments required to fulfil the transport volume between CD i and warehouse w on day d
$y_{i,w}^{\text{out}}$	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

Model SNDP-FT

$$\min \ Z = \sum_{i \in I} c_i^{\text{setup}} \cdot z_i + \sum_{s \in S} \sum_{i \in I_0} \sum_{m \in M} c_{s,i,m}^{\text{assign}} \cdot \sum_{j \in J_m} y_{s,i,j} + \sum_{i \in I} \sum_{w \in W} \sum_{d \in D} c_{i,w}^{\text{outb}} \cdot f_{i,w,d} \tag{5.1}$$

s.t.

$$\sum_{i \in I_0} \sum_{j \in J} y_{s,i,j} = 1 \qquad \forall \ s \in S \tag{5.2}$$

$$\sum_{s \in S} \sum_{i \in I_0} \sum_{j \in J} y_{s,i,j} \cdot q_{s,w,j} \leq cap_w \qquad \forall \ w \in W \tag{5.3}$$

$$\sum_{s \in S} \sum_{j \in J_d} y_{s,i,j} \cdot q_{s,w,j} \leq cap^{truck,out} \cdot f_{i,w,d} \qquad \forall \ i \in I, w \in W, d \in D \tag{5.4}$$

$$q_i^{\min} \cdot z_i \leq \sum_{s \in S} \sum_{j \in J} y_{s,i,j} \cdot q_s \leq q_i^{\max} \cdot z_i \qquad \forall \ i \in I \tag{5.5}$$

$$lb_i \cdot \sum_{s \in S} \sum_{j \in J} q_s \cdot y_{s,i,j} \leq \sum_{s \in S} \sum_{j \in J_d} \sum_{w \in W} q_{s,w,j} \cdot y_{s,i,j} \leq ub_i \cdot \sum_{s \in S} \sum_{j \in J} q_s \cdot y_{s,i,j} \qquad \forall \ i \in I, d \in D \tag{5.6}$$

$$\sum_{j \in J} y_{s,i,j} \leq z_i \qquad \forall \ s \in S, i \in I \tag{5.7}$$

$$y_{s,i,j} \in \{0,1\} \qquad \forall \ s \in S, i \in I_0, j \in J \tag{5.8}$$

$$z_i \in \{0,1\} \qquad \forall \ i \in I \tag{5.9}$$

$$f_{i,w,d} \in \mathbb{Z}_0^+ \qquad \forall \ i \in I, w \in W, d \in D \tag{5.10}$$

The model's objective function (5.1) 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 (5.2) ensure that exactly one delivery path and pattern is assigned to each supplier. Constraints (5.3) ensure that the capacity per warehouse is not exceeded. Constraints (5.4) determine the daily number of trucks needed per CD-to-warehouse connection. Constraints (5.5) 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 (5.6) balance the daily workload per CD. Constraints (5.7) 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 (5.8) to (5.10) define the model's variables.

In retail practice it is often the case that 3PL service providers are responsible for the fulfilment 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 (5.11) and (5.12)).

$$\sum_{s \in S} \sum_{j \in J} q_{s,w,j} \cdot y_{s,i,j} \geq q^{\text{min,out}} \cdot y^{\text{out}}_{i,w} \qquad \forall\, i \in I, w \in W \tag{5.11}$$

$$\sum_{j \in J} y_{s,i,j} \leq y^{\text{out}}_{i,w} \qquad \forall\, i \in I,\ (s,w) \in S \times W,\ \text{where } q_{s,w} > 0 \tag{5.12}$$

Constraints (5.11) and (5.12) 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 5.5.2). Note that in case these constraints are added to model SNDP-FT, the formulation can be further strengthened, if Constraints (5.7) are replaced by $y^{\text{out}}_{i,w} \leq z_i$, $\forall\, i \in I, w \in W$.

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.

5.5 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 5.3, 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 5.6). We outline the general approach in Section 5.5.1, while addressing the master and sub-models in sections 5.5.2 and 5.5.3, respectively.

5.5.1 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 5.5.2, and a CD-individual Operational Problem (CDOP$^{(i)}$), see Section 5.5.3, that can each be optimally solved by standard MIP solvers for real-life instances.

5.5.2 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 $M = \{1, 2, \ldots, m, \ldots |M|\}$ replaces the delivery patterns $J = \{1, 2, \ldots, j, \ldots |J|\}$ used in model SNDP-FT, see Section 5.4. 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 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.

$$x_{s,i,m} = \sum_{j \in J_m} y_{s,i,j} \qquad \forall\, s \in S,\ i \in I_0,\ m \in M \tag{5.13}$$

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

$$\hat{c}^{\text{assign}}_{s,i,m} = c^{\text{assign}}_{s,i,m} + \sum_{w \in W} q_{s,w} \cdot c^{\text{outb-lin}}_{i,w} \qquad \forall\, s \in S, i \in I, m \in M \tag{5.14}$$

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, $c_{i,w}^{\text{outb-lin}} = \frac{c_{i,w}^{\text{outb}}}{cap^{\text{truck,out}}}$.

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).

$$\hat{c}_{s,i=0,m}^{\text{assign}} = c_{s,i=0,m}^{\text{assign}} \qquad \forall\, s \in S,\ m \in M \tag{5.15}$$

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 5.5.3), 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 (5.11) and (5.12) of the original model SNDP-FT. Binary variable $y_{i,w}^{\text{out}} \in \{0,1\}$ 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_i^{setup}) are equivalent to model SNDP-FT. Table 5.4 summarizes the additional notation used.

Table 5.4: Additional notation used for model CDFTSP

Parameters	
$\hat{c}_{s,i,m}^{\text{assign}}$	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

Model CDFTSP

$$\min\ Z = \sum_{i \in I} c_i^{\text{setup}} \cdot z_i + \sum_{s \in S} \sum_{i \in I_0} \sum_{m \in M} \hat{c}_{s,i,m}^{\text{assign}} \cdot x_{s,i,m} \tag{5.16}$$

s.t.

$$\sum_{i \in I_0} \sum_{m \in M} x_{s,i,m} = 1 \qquad \forall\, s \in S \tag{5.17}$$

$$\sum_{s \in S} \sum_{i \in I_0} \sum_{m \in M} x_{s,i,m} \cdot q_{s,w,m} \leq cap_w \qquad \forall\, w \in W \tag{5.18}$$

$$q_i^{\min} \cdot z_i \leq \sum_{s \in S} \sum_{m \in M} x_{s,i,m} \cdot q_s \ \leq q_i^{\max} \cdot z_i \qquad \forall\, i \in I \tag{5.19}$$

$$\sum_{s \in S} \sum_{m \in M} q_{s,w} \cdot x_{s,i,m} \geq q^{\text{min,out}} \cdot y_{i,w}^{\text{out}} \qquad \forall\, i \in I,\ w \in W \tag{5.20}$$

$$\sum_{m \in M} x_{s,i,m} \ \leq y_{i,w}^{\text{out}} \qquad \forall\, i \in I,\ (s,w) \in S \times W, \text{ where } q_{s,w} > 0 \tag{5.21}$$

$$y_{i,w}^{\text{out}} \ \leq z_i \qquad \forall\, i \in I,\ w \in W \tag{5.22}$$

$$x_{s,i,m} \in \{0,1\} \qquad \forall\, s \in S,\ i \in I_0,\ m \in M \tag{5.23}$$

$$y_{i,w}^{\text{out}} \in \{0,1\} \qquad \forall\, i \in I,\ w \in W \tag{5.24}$$

$$z_i \in \{0,1\} \qquad \forall\, i \in I \tag{5.25}$$

The objective function (5.16) 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 Equation (5.16), the only difference being that it omits discrete consolidation effects. Constraints (5.17) assign exactly one flow type and one mode of delivery frequency to each supplier. Constraints (5.18) ensure that the warehouses' capacities are not exceeded. Constraints (5.19) ensure that total CD throughput is within the specified range. Constraints (5.20) and (5.21) 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 (5.22) strengthen the LP relaxation of the problem. Constraints (5.23), (5.24) and (5.25) 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., $f_{i,w,d} \geq 0,\ f_{i,w,d} \in R_0^+$, and the balancing constraints of the daily workload per CD, i.e., Constraints (5.6), 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 (5.11) and (5.12) of model SNDP-FT as well as Constraints (5.20) and (5.21) of model CDFTSP, respectively.

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

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 $f^{(i)}_{w,d}$ 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 $c^{\text{out},(i)}_w$, $lb^{(i)}$, $ub^{(i)}$ 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 5.5 summarizes the additional and modified notation used within model CDOP$^{(i)}$.

Table 5.5: 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 $(s \in S\|\sum_{m\in M} x_{s,i,m} = 1)$, $S^{(i)} \subseteq S$

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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
$ub^{(\text{i})}$	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 fulfil 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, $S^{(i)}$

Model CDOP$^{(i)}$

$$\min \; Z^{(i)} = \sum_{w \in W} \sum_{d \in D} c_w^{\text{out},(i)} \cdot f_{w,d}^{(i)} \tag{5.26}$$

s.t.

$$\sum_{s \in S^{(i)}} \sum_{j \in J_d} y_{s,j}^{(i)} \cdot q_{s,w}^{(m)} \leq cap^{\text{truck,out}} \cdot f_{w,d}^{(i)} \qquad \forall\, w \in W,\; d \in D \tag{5.27}$$

$$\sum_{j \in J_s} y_{s,j}^{(i)} = 1 \qquad \forall\, s \in S^{(i)} \tag{5.28}$$

$$\sum_{s \in S^{(i)}} \sum_{j \in J_d} \sum_{w \in W} q_{s,w}^{(m)} \cdot y_{s,j}^{(i)} \geq lb^{(i)} \cdot q^{\text{total},(i)} \qquad \forall\, d \in D \tag{5.29}$$

$$\sum_{s \in S^{(i)}} \sum_{j \in J_d} \sum_{w \in W} q_{s,w}^{(m)} \cdot y_{s,j}^{(i)} \leq ub^{(i)} \cdot q^{\text{total},(i)} \qquad \forall\, d \in D \tag{5.30}$$

$$f_{w,d}^{(i)} \in \mathbb{Z}_0^+ \qquad \forall\, w \in W,\; d \in D \tag{5.31}$$

$$y_{s,j}^{(i)} \in \{0,1\} \qquad \forall\, s \in S^{(i)},\; d \in D \tag{5.32}$$

The objective function (5.26) 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 (5.27). Constraints (5.28) ensure that a delivery pattern is selected for each supplier. Constraints (5.29) and (5.30) 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 (5.31) and (5.32) define the decision variables.

5.5.4 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 (5.6) 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 5.6) 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 5.3.1). 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.

5.6 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 5.6.1 we describe the case setting, followed by a scenario analysis in Section 5.6.2.

5.6.1 Case Setting

We gathered data from a major European grocery retail company that sources over 8,000 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 minutes 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.

5.6.2 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.

5.6.2.1 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 25x25 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%. 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 retailers' 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.

5.6.2.2 General Results

Table 5.6 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.

Table 5.6: 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	

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 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.

5.6.2.3 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 5.6). 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 5.6). Third, we solve the original model SNDP-FT using the Gurobi MIP solver (see Table Section “Model SNDP-FT, MIP solver” of Table 5.6). Finally, we provide further benchmark comparisons on a variety of additional instances generated based on Scenario C (see Table 5.7 and 5.8).

Lower bound assessment As stated in Section 5.5.4, 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 5.3. 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 hours (see Table Section "Model SNDP-FT, MIP solver" of Table 5.6). 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 hours 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 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 (5.11) and (5.12)). The results are listed in Table 5.7.

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

Table 5.7: 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	<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	-	-

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 can not 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 hours). 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 5.8).

Table 5.8: 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

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 5.7. 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 (5.6)) 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 5.5.4. 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 5.9. This is due to the fact that LB1 incorporates the balancing constraints (Constraints 5.6) in contrast to LB2. For all instances presented in Table 5.9 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 of the mean (e.g., factor 1.1 allows a 10% deviation per day from the daily mean of throughput).

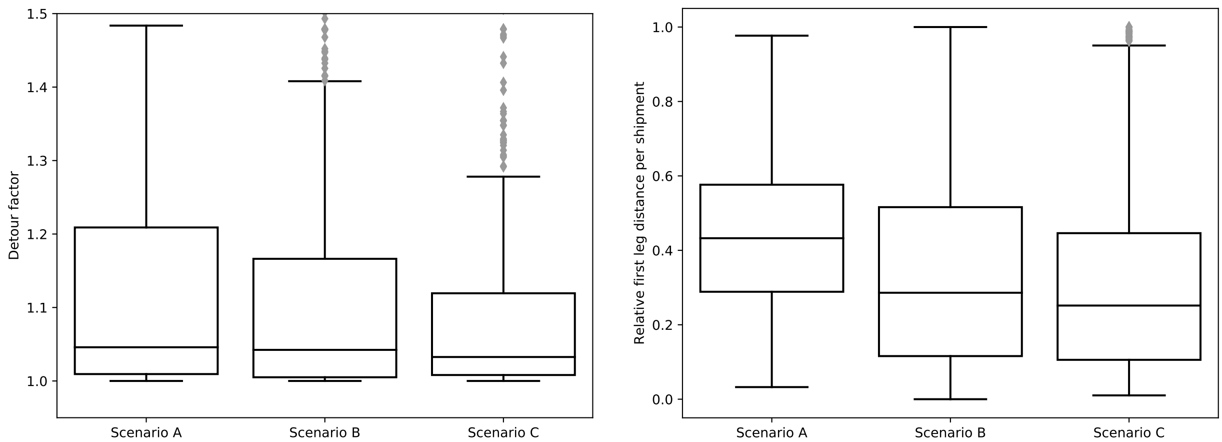
Table 5.9: Comparison of lower bounds with varying balancing constraints. The lower bounds are expressed as cost savings [%] relative to the status quo without CDs. The sensitivity factor is expressed as a factor of the mean daily throughput at the CDs

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

5.6.2.4 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 that 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. Figure 5.1a 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.



(a) Detour factors (truncated)

(b) Relative CD positioning

Figure 5.1: Structural results of scenarios A, B, and C

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 5.2). 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 Figure 5.1b). A higher number of CDs not only reduces the detour per shipment (see Figure 5.1a), but also the distance from the suppliers to CDs.

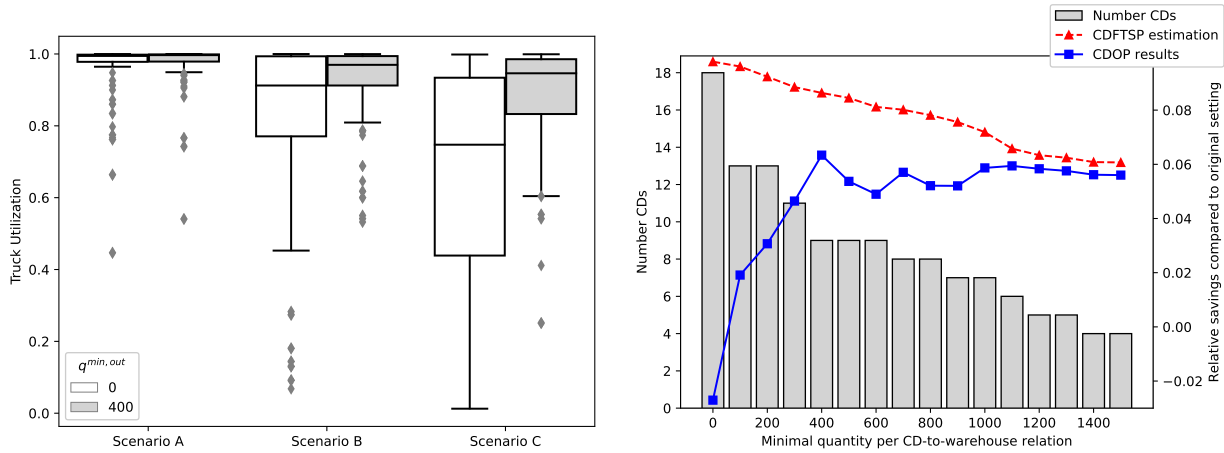
In Scenario C with nine CDs, the supplier-to-CD distance is less than 25% of total travel distance for 50% of CD shipments, i.e., the majority of CDs can be characterized as primarily in close proximity to the suppliers in this case. The median for Scenario A with only two CDs is 45%, which means that 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 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.

5.6.2.5 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 Figure 5.2a 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%.



(a) Box plot: Truck utilization per CD-to-warehouse shipment, scenario comparison

(b) Number of CDs and cost savings (Scenario C)

Figure 5.2: Analysis results for $q^{\text{min,out}}$

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 $q^{\text{min,out}}$.

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 Figure 5.2b. 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 $q^{\text{min,out}} = 0$ leads to a large number of CDs – 18 locations (see Figure 5.2b) – 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 travelling 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, $q^{\text{min,out}} = 400$. At this value, the average utilization of outgoing trucks approaches 90%.

Compared to the setting with $q^{\text{min,out}} = 0$, 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 $q^{\text{min,out}}$. 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.

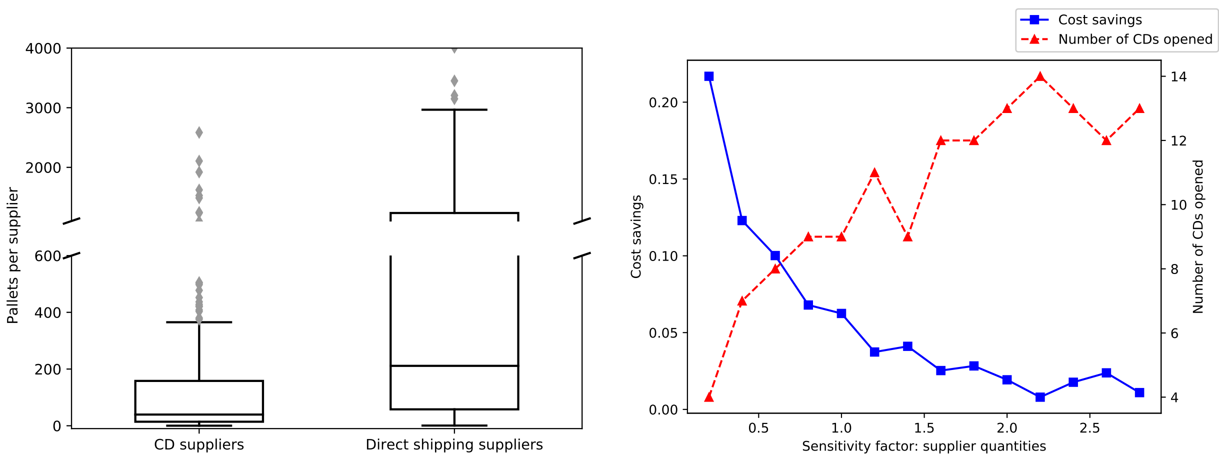
Setting $q^{\text{min,out}}$ between 400 and 1,000 leads to roughly similar results with regard to cost savings, since the remaining CD-to-warehouse links exhibit such a high volume that the minimum quantity restriction does not make a decisive difference anymore. Eventually, with minimum quantities of around 1,000 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 ($q^{\text{min,out}} = 0$) might not be realized on an operational level.

5.6.2.6 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 Figure 5.3a. 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.



(a) Quantity distributions (truncated) (b) Sensitivity analysis on supplier quantities

Figure 5.3: Quantity-related results for Scenario C

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 Figure 5.3b). Granted that the 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 Figure 5.3b.

5.7 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 direct 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.

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