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Modelling and optimising a multi-depot vehicle routing problem for freight distribution in a retail logistics network

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ABSTRACT

An efficient freight distribution network is critical for enhancing competitiveness by lowering transportation costs and increasing profitability. This study adopts a case-based modelling approach to tackle a real-world Multi-Depot Vehicle Routing Problem (MDVRP) faced by a UK-based retailer aiming to expand its operations in northern UK. Due to high fixed costs and a limited branch network, the retailer seeks to improve operational efficiency by reducing transportation costs without establishing additional facilities. A novel mixed-integer programming model is developed to optimise the existing distribution network by incorporating realistic operational constraints. The model addresses key complexities such as driver costs, inter-depot routing, transportation hubs, multiple depots, dynamic demand, a heterogeneous fleet, cross-docking, multiple product types, vehicle capacity and travel time restrictions. Using an exact solution method, the model yields optimal results demonstrating significant reductions in transportation costs while maintaining service constraints. The findings provide valuable research insights and practical recommendations for optimising freight distribution networks under realistic and resource-constrained conditions.

1. Introduction

Since the Covid-19 pandemic, companies across various sectors have faced significant financial and operational disruptions (Ivanov, 2025). Global events such as Brexit, the US-China trade war, the Russia-Ukraine conflict, and ongoing crises in the Middle East and Asia have further intensified these challenges (Bednarski et al., 2025). In response, several organisations have adopted strategies such as operational cost reductions, workforce downsizing, facility closures, relocation of manufacturing and storage sites, and reassessment of existing distribution networks. Freight distribution has been particularly impacted due to city and border closures worldwide, causing widespread disruptions in supply chains (Archetti et al., 2022). Concurrently, transportation costs have risen steadily, driven by these global disruptions and increasingly complex supply chain structures. Given that transportation represents a significant share of total logistics and supply chain expenses (Abdi et al., 2020; Wang et al., 2017), many companies have begun redesigning their distribution networks with a focus on optimising resource utilisation and capacity allocation (Farias et al., 2020; Vincent et al., 2021).

Recent global events have exposed significant vulnerabilities in distribution networks, resulting in supply shortages, surges in product demand and delivery delays (Nagurney, 2021). Retail businesses were overwhelmed and struggled to fulfil orders on time due to these disruptions, leading to substantial implications for distribution activities (Tiwari & Sharma, 2023). Efficient and timely transportation remains critical to optimise freight distribution networks (Steadieseifi et al., 2014). The Vehicle Routing Problem (VRP) has emerged as a primary area of research within freight logistics, aiming to optimise vehicle routes to efficiently serve diverse customer locations (Baradaran et al., 2019; Sadati & Çatay, 2021). To adapt to the evolving landscape, businesses need to reassess their distribution networks not only to enhance profitability, but also to address increasing sustainability concerns (Li et al., 2019; Mrabti et al., 2022).

In response to the growing challenges in freight distribution networks, this study addresses the vehicle routing optimisation problem faced by a leading UK-based retailer. To maintain confidentiality, we refer to the company under the hypothetical name *Alpha Partnership Network (APN)*. APN serves as the parent company of two major retail brands, referred to here as *Alpha & Partners* and *Beta & Partners.*

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Currently, APN operates 51 *Alpha & Partners* shops and 349 *Beta & Partners* shops across the UK. Additionally, APN manages 21 Customer Delivery Hubs (CDHs), with 20 operated directly by APN and one by *Beta & Partners.* Its distribution infrastructure includes 11 Distribution Centres (DCs) located predominantly in the southern part of the UK, with six managed by APN and five by *Beta & Partners.*

APN primarily operates through an online business model, supplemented by a limited number of high-street stores. Customers can either request home deliveries through online orders or utilise a Click & Collect (C&C) service, allowing product pickups at APN or selected *Beta & Partners* locations. To provide high-quality customer service, APN employs multiple delivery approaches, including direct APN replenishment, APN customer deliveries, APN C&C services, Beta replenishment and Beta C&C services. Despite this diverse distribution framework, APN has identified operational inefficiencies due to the complexity of its distribution activities. Therefore, the objective of this study is to optimise the APN freight distribution network for operations in the northern part of the UK.

As previously established, APN utilises multiple transportation routes for the distribution of its products. The facilities supporting this complex network in the northern part of the UK are outlined below. APN Branches (AB1-AB3): Three APN branches located in the northern part of the UK are used for APN replenishment and C&C services. Beta Branches (BB1-BB6): Six Beta branches operate in the northern part of the UK, supporting Beta replenishment and C&C services. APN Customer Delivery Hubs (ACDH1 and ACDH2): Two APN CDHs in the northern region primarily handle APN customer home deliveries. APN Distribution Centres (ADC1-ADC7): Several APN distribution centres supply products to APN branches, Beta branches (for C&C services) and APN CDHs. Beta Distribution Centres (BDC1 and BDC2): Two Beta distribution centres serve Beta branches by supporting Beta replenishment operations. APN Changeover Locations (ACO1-ACO3): Three changeover locations in the southern part of the UK facilitate product transfers during long-distance deliveries from the south to the north. APN Transportation Hub (ATH): The APN transportation hub supplies vehicles that depart towards changeover locations. Third-Party Transportation and Sortation Hubs (3PL): A third-party logistics provider supports Beta C&C operations by transporting products to Beta branches. Beta Cross-Dock (BCD): The Beta cross-dock receives products destined for Beta branches, sorts them and despatches them accordingly.

The case company opted against establishing new facilities due to high fixed costs and a limited number of branches to serve in the targeted region. Instead, it prioritised improving operational efficiency and reducing transportation costs to meet nationwide demand. Given the current complexity and interconnectivity of APN's distribution network, vehicle capacity appears to be underutilised, leading to inefficiencies in the existing distribution system. To remain competitive, the company needs to reduce distribution-related costs and enhance supply chain performance. Accordingly, the aim of this research study is to develop a decision support model to optimise deliveries across the regional branch network. This case study formulates and solves a distribution network optimisation problem and offers practical recommendations to support strategic and operational decision making.

The remainder of this paper is organised as follows. Section 2 reviews the relevant literature focusing on multi-depot and multi-constraint VRPs. Section 3 describes the problem context and the case study. Section 4 discusses the research methodology adopted in this study. Section 5 introduces the mathematical model developed to optimise the distribution network. Section 6 presents the results and evaluates the feasibility of the proposed recommendations. Section 7 concludes the study by summarising key findings, outlining theoretical and managerial implications. Finally, Section 8 discusses limitations and suggests directions for future research.

2. Literature review

2.1. Vehicle routing problem

The Vehicle Routing Problem (VRP) is a well-known combinatorial optimisation problem in the fields of operations research and logistics. First introduced by Dantzig and Ramser (1959), the VRP has been widely studied over the past six decades, leading to the development of numerous variants that incorporate increasingly complex and realistic logistics constraints (Chen et al., 2016). These include the Capacitated VRP (CVRP; Ling, 2003), VRP with Time Windows (VRPTW; Cheng & Gen, 1997), Distance Constrained VRP (DCVRP; Ravi, 2012), Multi-Depot VRP (MDVRP; Ho et al., 2008), VRP with Backhauls (VRPB; Handling, 1989), and VRP with Pick-up and Delivery (VRPPD; Clarke & Wright, 1964). This study focuses on the multi-depot VRP and therefore, the literature review is centred on research that addresses this specific variant and its practical characteristics.

The MDVRP considers more than one depot within the distribution network from which vehicles start their journey to serve customers (Li et al., 2019; Soeanu et al., 2020). In the fixed MDVRP, vehicles return to their origin depot, whereas in the non-fixed version, such a restriction does not apply. Comprehensive and critical literature reviews on MDVRPs have been provided by Montoya-Torres et al. (2015) and Karakatič and Podgorelec (2015). A recent survey on VRP-related studies by Elshaer and Awad (2020) revealed that only 9.42 % of the studies published between 2009 and 2017 considered multiple depots, highlighting a clear gap in the literature. Recently, MDVRPs with several interrelations and realistic constraints have been receiving more attention from the research community to develop practical and real-world optimisation models. (Baradaran et al., 2019; Braekers et al., 2016).

2.2. Multi-constraint application of VRPs

Recent research on VRPs has increasingly focused on incorporating multiple dependencies and constraints to capture real-life complexities in mathematical formulations. Allahyari et al. (2015) relaxed the traditional assumption of visiting every customer by integrating the MDVRP with the Travelling Salesman Problem. Zhou et al. (2018) explored a two-echelon MDVRP with home delivery and customer pickup in the context of city logistics, while Huang et al. (2019) examined a covering location and routing problem involving multi-type stations. In addition to pickup, Wang et al. (2025) considered delivery activities while solving an MDVRP with dynamic demand and time windows constraints using CPLEX and various metaheuristic algorithms. In another study, Mo et al. (2024) investigated self-pickup point selection in urban and rural areas under a multi-period heterogeneous VRP. Schmidt et al. (2023) tackled the time-dependent fleet size and mix problem within the MDVRP framework. Models incorporating multiple time periods, heterogeneous fleets, and maximum route constraints were proposed by Mancini (2016) and Ramos et al. (2020). Similarly, Li et al. (2019) worked on multi-depot green VRP for maximising revenue and minimising cost, time and emissions. Wang et al. (2019) highlighted that minimising travel distance does not always lead lower costs or reduced emissions in the MDVRP.

The role of satellite facilities such as cross-docking, temporary storage and transhipment has also been recognised as crucial for VRP optimisation (Soto-Concha et al., 2025). Therefore, Avolio et al. (2025) and Crevier et al. (2007) extended the MDVRP by allowing vehicle replenishment at intermediate depots. Risk-aware models such as the one proposed by Soeanu et al. (2020) considered potential vehicle breakdowns and delivery failures. Alinaghian and Shokouhi (2018) modelled the use of multi- compartment vehicles with no split deliveries for individual product types.

Recent developments have also addressed the complexity of omnichannel logistics. Li and Wang (2025) proposed a model for the omnichannel VRP with multiple products, time windows and split deliveries.

Xiao et al. (2024) investigated the electric VRP with synchronised mobile partial recharging and flexible waiting strategies for mobile charging vehicles. Boroujeni et al. (2025) focused on optimising electric vehicle routes, locker usage and opening costs while maximising profit in parcel locker-based deliveries for premium customers. Bae and Moon (2016) considered depot, transportation, and labour costs under the service level constraint. Recently, Zhen et al. (2020) proposed a mathematical model for the delivery of online shopping packages incorporating multiple depots, multiple trips, time windows and release dates. For sustainable grocery delivery, Tudisco et al. (2025) developed an optimisation model for VRPTW that includes on-demand vehicle hire, aiming to reduce cost and emissions for an Italian e-retailer.

A few researchers have explored cross-docking operations in conjunction with VRPs, significantly increasing the complexity of these models (Chen et al., 2016; Vincent et al., 2023). The Vehicle Routing Problem with Cross-Docking (VRPCD) typically involves three interconnected sub-problems: pickup, cross-docking, and delivery (Nasiri et al., 2018). Cost-efficient routes for distribution systems with capacitated and multiple cross-dock VRP that incorporates pickup, delivery and time windows were established by Ahkamiraad and Wang (2018). Transportation costs were significantly reduced after considering cross-docking operations in pickup and delivery problem, as examined by Chen et al. (2016). Several other studies have extended cross-docking systems to different VRP variants, such as open VRP (Vincent et al.,

Table 1
Summary of the key literature on VRPs.

Study		Problem characteristics										
	Multi-depot	Vehicle capacity	Heterogeneous fleet	Multi-echelon	Travel time	Driver cost	Cross-dock	Multi-Products	Inter-depot routes	Transportation Hubs	Dynamic demand	Real case study
Alinaghian and Shokouhi (2018)	x	x						x				
Allahyari et al. (2015)	x	x										
Avolio et al. (2025)	x	x	x		x							x
Bae and Moon (2016)	x	x	x		x							
Brandão (2020)	x	x										
Boroujeni et al. (2025)		x			x							
Crevier et al. (2007)	x	x			x				x			
Huang et al. (2019)		x	x									
Li et al. (2019)	x	x			x					x		
Wang et al. (2025)	x	x	x		x						x	x
Mancini (2016)	x	x	x		x							x
Vincent et al. (2021)	x	x	x		x	x						
Ramos et al. (2020)	x	x	x		x							
Li and Wang (2025)		x			x			x				
Wang et al. (2019)	x	x			x							x
Zhen et al. (2020)	x	x			x							
Zhou et al. (2018)	x	x			x							
Soeanu et al. (2020)	x	x										x
Chen et al. (2016)		x			x		x	x				
Wang et al. (2017)		x	x		x		x	x				
Abad et al. (2018)		x				x	x	x				
Ahkamiraad and Wang (2018)		x			x		x					
Tudisco et al. (2025)		x	x		x					x	x	x
Vincent et al. (2023)		x		x			x	x			x	
Sadati and Çatay (2021)	x	x			x				x			
Present study	x	x	x	x	x	x	x	x	x	x	x	x

2016), multi-echelon VRP (Ahmadizar et al., 2015), VRP with scheduling constraints (Lee et al., 2006), and split delivery VRP (Wang et al., 2017). These extensions highlight the importance of cross-docking as a strategic tool to improve distribution efficiency while addressing complex logistical requirements.

2.3. Research gaps and contributions.

A summary of key prior studies and the main features of the current study are presented in Table 1. This table clearly displays evident research gaps in the academic literature from various perspectives and highlights the imperative need for a new mathematical model to solve the defined VRP. While many studies have addressed multiple depots, vehicle capacity and travel time constraints (Ramos et al., 2020; Wang et al., 2019), only a few have incorporated heterogeneous fleets (Bae & Moon, 2016; Huang et al., 2019; Wang et al., 2017), cross-docking operations and multiple product types (Abad et al., 2018; Chen et al., 2016; Wang et al., 2017). Moreover, limited attention has been paid to the simultaneous integration of drivers' costs, multi-echelon distribution, inter-depot routing, transportation hubs and dynamic demand (Abad et al., 2018; Konstantakopoulos et al., 2022; Li et al., 2019).

Furthermore, most prior research has focused on the development of heuristic or metaheuristic algorithms to manage model complexity (Boroujeni et al., 2025; Brandão, 2020; Elshaer & Awad, 2020; Wang et al., 2017), often at the expense of real-world applicability and case-specific validation (Mancini, 2016; Soeanu et al., 2020; Wang et al., 2019). The simultaneous consideration of several key factors like driver costs, inter-depot routing, transportation hubs, dynamic demand, heterogeneous fleets, cross-docking operations, multiple products, vehicle capacities and travel time restrictions act as a strong motivation for the development of a novel and practically relevant mathematical model. To the best of our knowledge, the realistic MDVRP with all these characteristics has not yet been addressed in the extant literature. This can be very evidently observed from Table 1. This study aims to bridge this apparent research gap by developing a comprehensive decision support model to optimise the freight distribution network and determine optimal delivery routes.

3. Problem overview and case study

3.1. Problem overview

The APN company aims to expand its operations in northern part of the UK but seeks to avoid the substantial capital investment required to establish a new facility. APN already has several well-established facilities across the UK and is therefore focused on optimising its existing distribution network in the north, rather than building a new facility. This problem falls under the category of VRPs, where the objective is to determine optimal delivery routes to meet fixed customer demand while minimising transportation costs. The problem consists of multiple distribution centres, making it a Multi-Depot VRP. Additionally, since each branch requires specific products from designated DCs, the model also reflects characteristics of a multi-product VRP, with different DCs assumed to represent distinct products. The study considers two types of heterogeneous fleets: APN-owned vehicles and third-party logistics (3PL) vehicles. APN and its subsidiary Beta operate 7 and 2 distribution centres, respectively, in the southern UK. These DCs supply products to northern branches via three strategically located APN changeover locations. Vehicles from the APN transportation hub transfer products to northern APN branches through these changeover points. In the northern region, APN has 3 branches, while Beta has 6. A third-party hub is responsible for transferring products to the Beta cross-dock facility, which handles the sorting and distribution of products for click and collect services. Figs. 1 and 2 illustrate the overall product flow and the vehicle routing relationships within the network.

3.2. Case study

The APN distribution network is structured into three distinct segments: the replenishment network, customer delivery network and C&C network. The vehicle routes and their respective functions within each segment are described below.

APN replenishment: All replenishment vehicles from ADC1 directly travel to the northern branches AB1, AB2 and AB3. Additionally, ADC2, ADC4 and ADC6 link their replenishments to ADC1.

Beta replenishment: Beta's replenishments go from BDC1 to BDC2, and then products are delivered to all northern Beta branches through the cross-dock facility located at BCD.

APN Customer Delivery: The customer delivery process for APN is more complex than replenishment. Deliveries from ADC2 are routed through ADC3 before reaching to ACDH1 and ACDH2. Similarly, products from ADC5 are first routed through ADC4, then sent to ACDH1. Additionally, ADC5 also links to both ADC3 and ADC4, which supply two male product categories.

APN C&C: All C&C commodities from APN fulfilment centres are first consolidated at ADC1, from where they are dispatched to the northern branches.

Beta C&C: Products for Beta C&C orders are sent directly to the 3PL logistics hub. From there, products are forwarded to the BCD cross-dock, where they are sorted and distributed to the respective Beta branches by 3PL vehicles.

Changeover Locations (C/O): APN operates three changeover facilities in the southern UK: ACO1, ACO2 and ACO3. Each serves specific destinations. ACO1 handles deliveries for AB1, while ACO2 supplies products to ACDH1. Additionally, ACO3 delivers to AB2, AB3 and ACDH2.

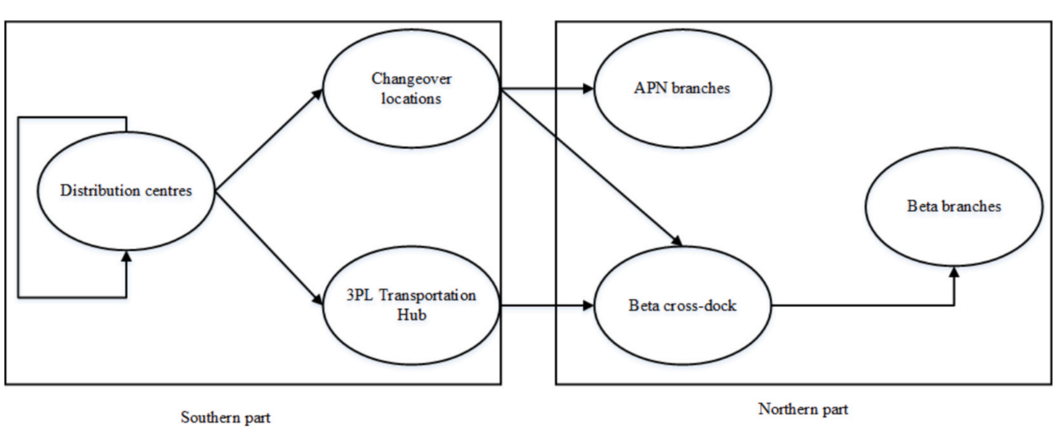

Fig. 1. Available products flow from south to north.

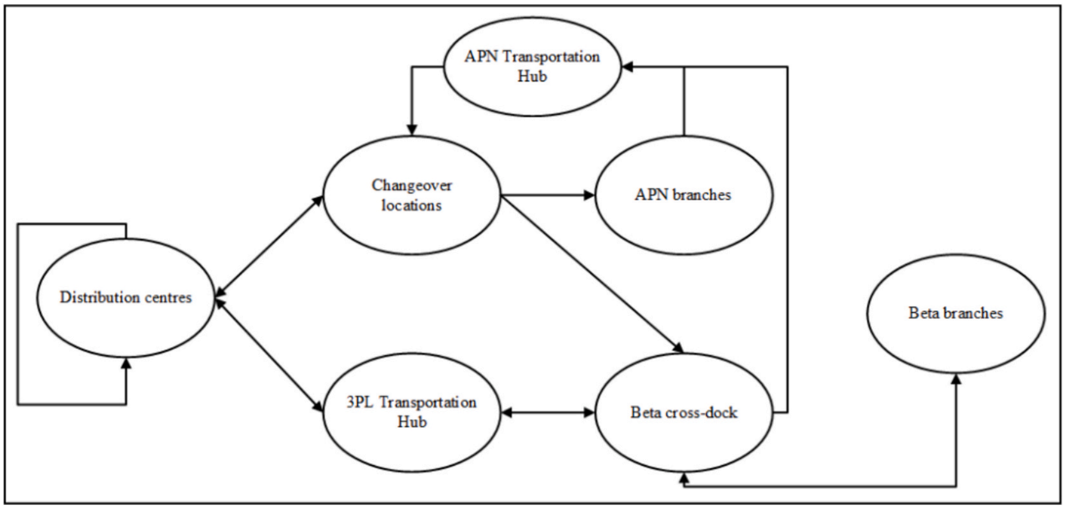

Fig. 2. Vehicle routing relationships.

Transportation Hub (ATH): The APN Transportation Hub (ATH) is the starting point for all APN-operated vehicle routes serving the northern region. For most destinations, vehicles follow a triangular route involving ATH, a changeover point and the target branch. For AB3, due to the long-distance between ACO3 and AB3, an overnight delivery is required. Vehicles return from ACO3 to ATH and proceed to AB3 the following day.

Third-party Logistics (3PL) Transportation Hub: Beta C&C deliveries are managed by a third-party logistics provider. Products from APN fulfilment centres are sent to the 3PL hub, where they are sorted

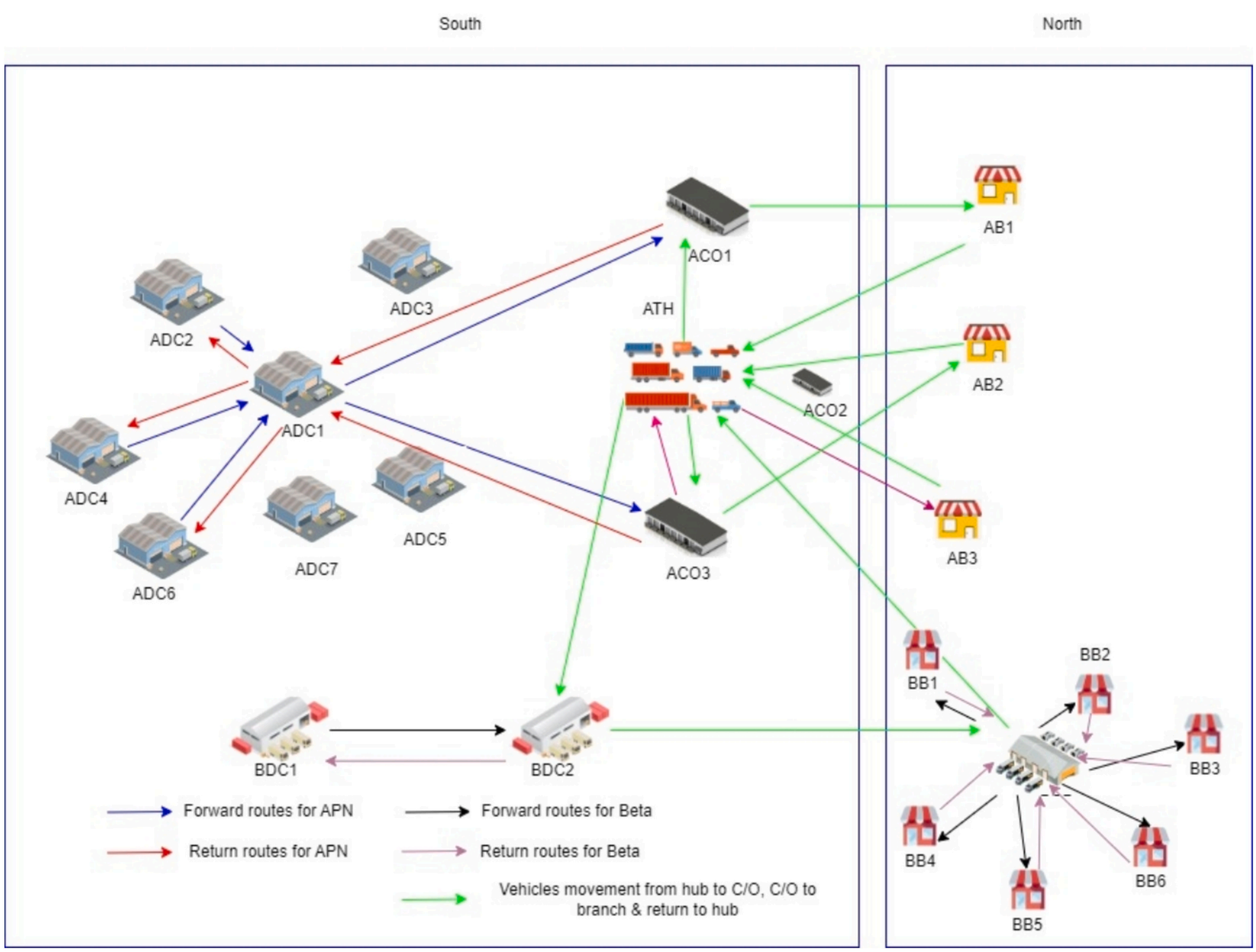

Fig. 3. Replenishment network.

according to Beta branch demand. Those sorted products are then delivered to their respective branches via BCD cross-dock.

Heterogeneous Vehicles: Two types of vehicles operate within the APN network: APN-owned vehicles and 3PL vehicles. In the current scenario, 3PL vehicles exclusively manage Beta C&C deliveries, while APN vehicles cover the remaining routes.

Refer to Figs. 3–5 for detailed visual representations of the distribution network.

4. Research methodology

Fig. 6 presents the detailed research methodology adopted in this study. The methodology is structured into four key stages, each addressing a distinct sub-problem encountered during the development of an operational model for the APN distribution network. The primary objective of Stage 1 is to understand, evaluate and develop a comprehensive map of the existing network operations involving APN, Beta and 3PL logistics limited. This stage begins with a thorough review of relevant literature on distribution networks, followed by multiple rounds of structured interviews with APN personnel to gain in-depth insights into the current logistics setup.

The quantitative data collected from the company includes facility locations, branch-level demand, number of daily dispatches, delivery constraints and trailer type limitations. The company aims to optimise vehicle utilisation for both APN and 3PL logistics, while also minimising the variable costs of APN and 3PL vehicles (including fuel costs and driver wages) and the fixed monthly lease cost associated with 3PL vehicles. The existing distribution network model was mapped and subsequently validated through consultations with APN staff. In the next stage, the study evaluated whether network optimisation could address the identified inefficiencies. Data cleansing was used to detect and remove errors and inconsistencies in the dataset. The computational models used to analyse the current scenario are presented in Tables 2–4.

Within the model, all routes between two facility locations were identified and transportation costs were calculated accordingly. The cost equations for APN and 3PL vehicles are outlined below.

$$\textit{Transportation cost for APN vehicles} = \textit{Number of vehicles travel between the two facility locations} \times (\textit{Fuel cost per km} \times \textit{Distance between locations} + \textit{Driver rate} \times \textit{Time consumed between locations})$$

$$\textit{Transportation cost for 3PL vehicles} = \textit{Number of vehicles travel between two facility locations} \times (\textit{Fuel cost per km} \times \textit{Distance between locations} + \textit{Driver rate} \times \textit{Time consumed between locations}) + \textit{Fixed cost}(\textit{e.g., monthly lease fee})$$

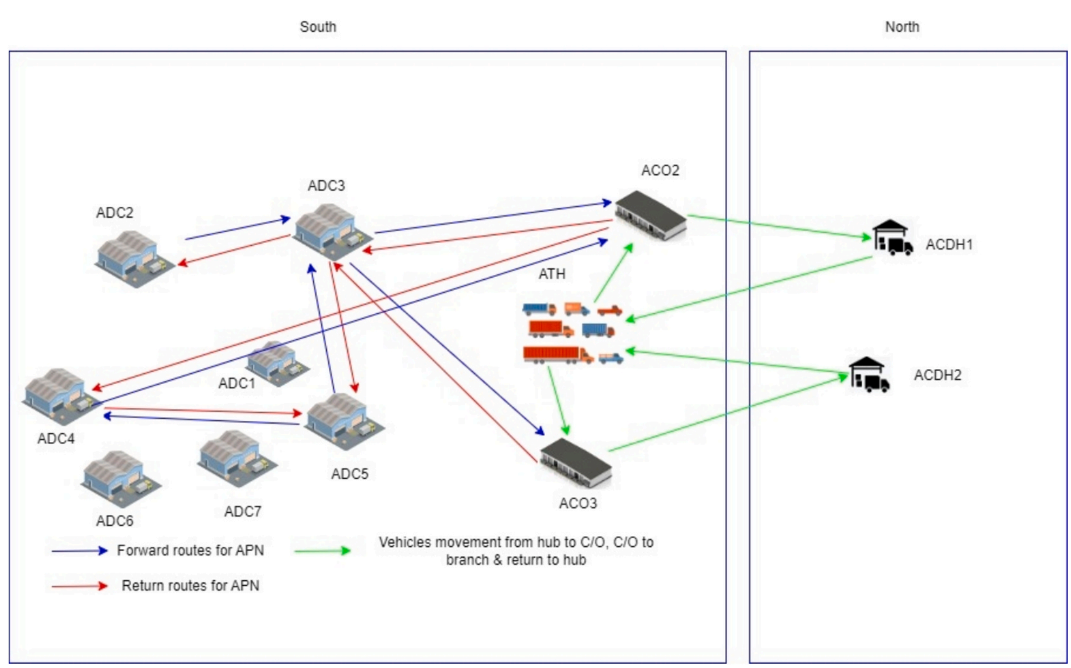

Fig. 4. Customer delivery network.

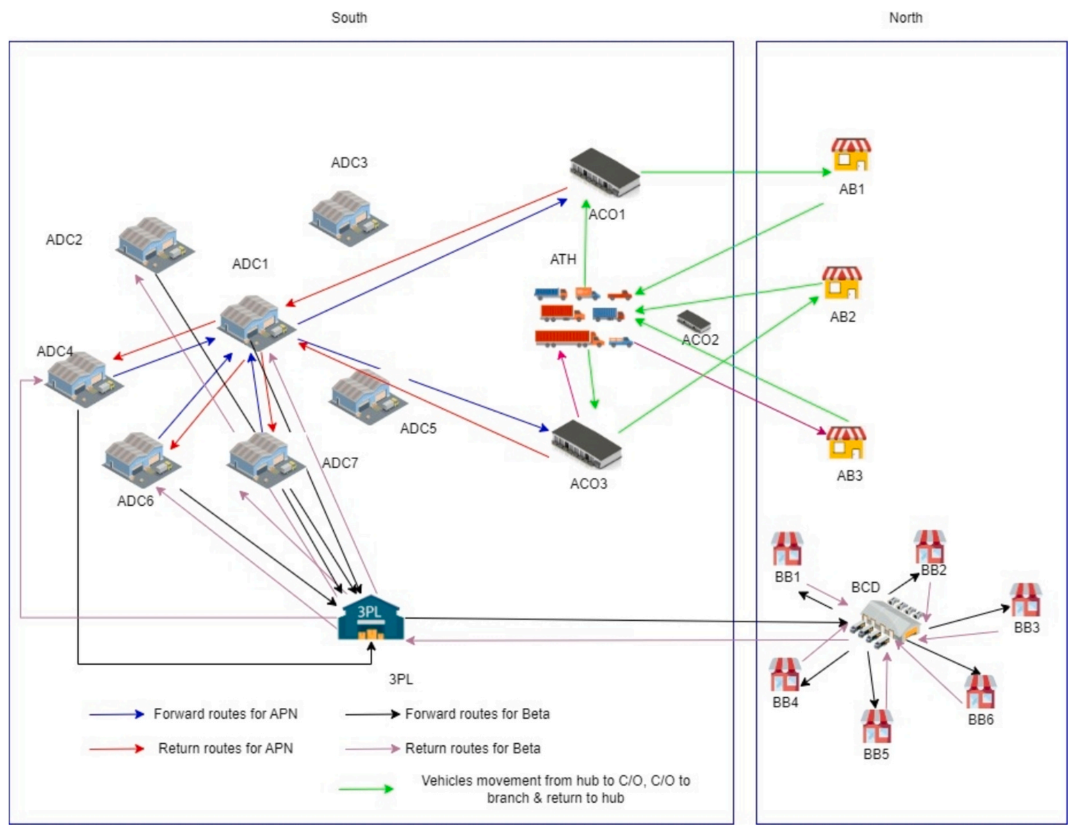

Fig. 5. Click and collect network.

4.1. Major issues identified in the current network

To identify inefficiencies in the existing network, the total transportation cost was broken down into specific components. These components include transportation costs between DCs, between DCs and changeover locations (C/Os), and between changeover locations and APN branches, among others. Figs. 7 and 8 illustrate the proportional breakdown of these cost components.

According to Fig. 7, which focuses on replenishment, the transportation cost from DCs to changeover locations (31 %), from transportation hubs to changeovers (22 %) and from changeovers to APN branches (20 %) are the top three cost contributors. Notably, all components related to changeovers represent a significant portion of the overall transportation cost, suggesting that changeovers have become a focal point in the distribution network. This highlights potential inefficiencies related to the selection and geographic positioning of changeover points, which directly impact routing decisions. In the C&C scenario, a similar cost pattern involving changeovers is observed, although the percentage distribution differs slightly. Additionally, the high fixed costs associated with 3PL vehicles represent another major challenge, ranking as the second-largest cost component after the DC to changeover transportation. Moreover, route analysis using Google Maps revealed that transportation from both ADC4 and ADC7 to ADC1 passes through ADC6. This presents an opportunity to consolidate transportation between these facilities, potentially improving efficiency and reducing costs through route integration.

(Acronyms DC = Distribution Centres, CO = Changeover Locations, AB = APN Branches, BCD = Beta Cross-Dock, ATH = APN Transportation Hubs and BB = Beta Branches).

5. Mathematical modelling of the problem

A Mixed Integer Programming (MIP) model is developed to optimise vehicle routing and minimise total transportation cost, considering key characteristics of the defined problem – namely, multiple depots, multiple product types, heterogeneous fleets and other operational constraints. The model formulation includes assumptions, sets, indices, parameters, decision variables, the objective function and a series of constraints which are described below.

Assumptions:

The model is based on the following assumptions:

- Multiple depots exist, with each depot supplying a fixed percentage of the demand at its corresponding branch.
- Each branch receives products from a predetermined set of DCs.
- The network operates under a less-than-truckload (LTL) scenario.
- The number of vehicles is sufficient to support logistics.
- Vehicles must return to the depot from which they originated.
- In the replenishment network, Beta products should pass through a first changeover location before reaching the Beta cross-dock.
- Each branch and cross-dock are restricted to receiving products from only one changeover location.
- Different DCs represent different product types.

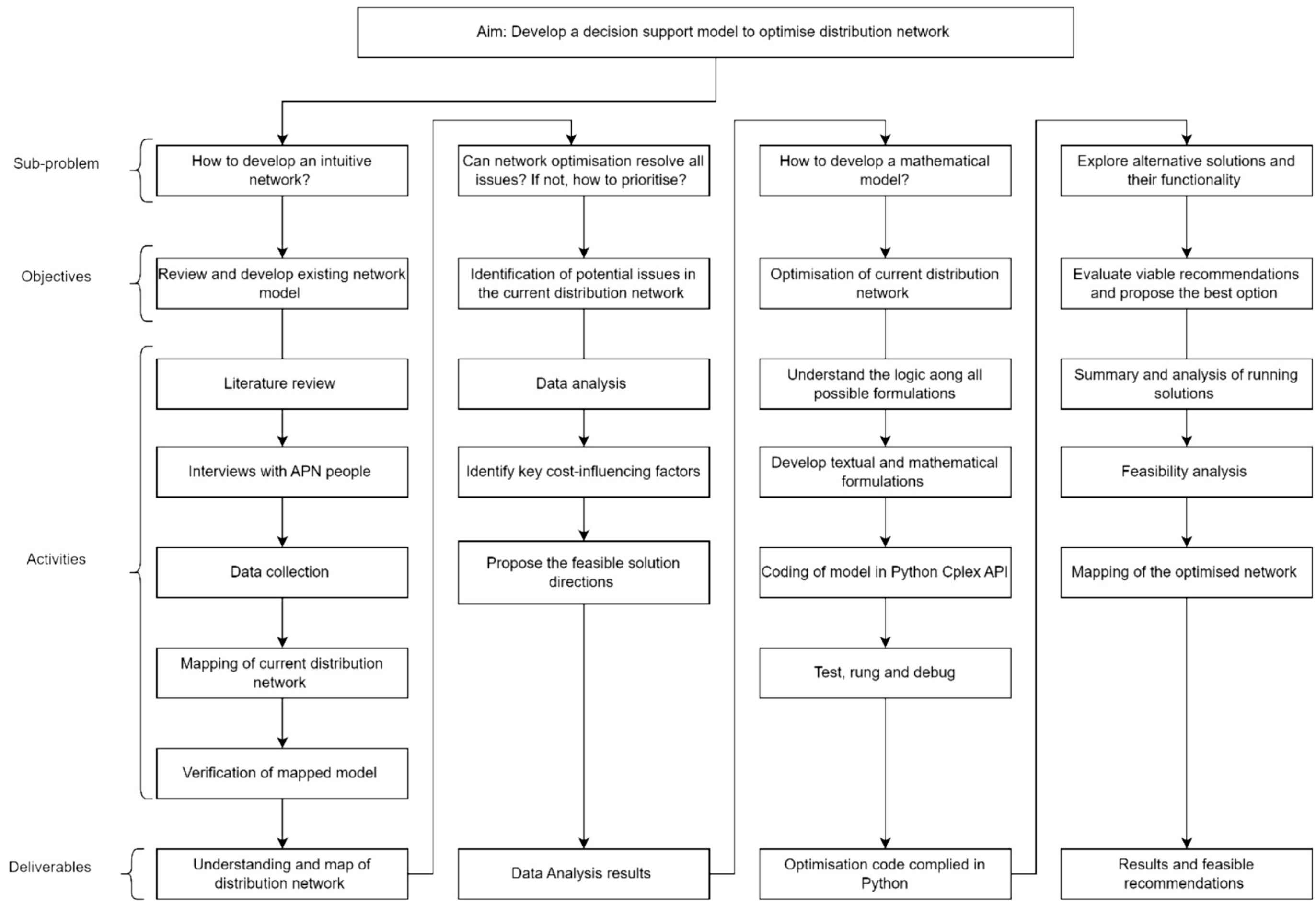

Fig. 6. Research methodology.

Table 2
Transportation costs of existing network for replenishment.

Origin	Destination	Distance	Time	Numbers	Cost	Origin	Destination	Distance	Time	Numbers	Cost
ADC4	ADC1	20.5	0.5	1	19.72	BDC1	BDC2	168.0	2.8	1	135.44
ADC6	ADC1	6.2	0.2	1	6.95	BDC2	BDC1	168.0	2.8	1	135.44
ADC2	ADC1	1.7	0.1	1	2.48	BDC2	BCD	190.0	3.2	1	153.17
ADC1	ADC4	20.5	0.5	1	19.72	BCD	BB1	2.9	0.2	1	4.39
ADC1	ADC6	6.2	0.2	1	6.95	BCD	BB2	10.5	0.3	1	10.31
ADC1	ADC2	1.7	0.1	1	2.48	BCD	BB3	26.5	0.6	1	23.55
ADC1	ACO3	183.0	2.9	1	144.50	BCD	BB4	45.1	0.9	1	39.01
ADC1	ACO1	169.0	2.9	1	137.59	BCD	BB5	47.9	0.9	1	40.33
ACO3	ADC1	183.0	2.9	1	144.50	BCD	BB6	28.7	0.7	1	27.94
ACO1	ADC1	169.0	2.9	1	137.59	BB1	BCD	2.9	0.2	1	4.39
ATH	ACO3	174.0	2.9	2	280.55	BB2	BCD	10.5	0.3	1	10.31
ATH	ACO1	200.0	3.3	2	322.47	BB3	BCD	26.5	0.6	1	23.55
ACO3	AB3	310.0	5.2	1	249.91	BB4	BCD	45.1	0.9	1	39.01
ACO3	AB2	175.0	2.9	1	141.08	BB5	BCD	47.9	0.9	1	40.33
ACO1	AB1	190.0	3.2	1	153.17	BB6	BCD	28.7	0.7	1	27.94
AB2	ATH	2.2	0.1	1	3.39	BCD	ATH	47.7	1.0	1	42.59
AB1	ATH	49.1	1.1	1	44.26					**Sum**	**2677.39**
AB3	ATH	127.0	2.1	1	102.38						

Table 3
Transportation costs of existing APN network for C&C.

Origin	Destination	Distance	Time	Numbers	Cost	Origin	Destination	Distance	Time	Numbers	Cost
ADC7	ADC1	68.1	1.4	1	60.58	ATH	ACO1	200.0	3.3	1	161.23
ADC6	ADC1	6.2	0.2	1	6.95	ATH	ACO3	174.0	2.9	2	280.55
ADC4	ADC1	20.5	0.5	1	19.72	ACO1	AB1	190.0	3.2	1	153.17
ADC1	ADC7	68.1	1.4	1	60.58	ACO3	AB2	175.0	2.9	1	141.08
ADC1	ADC6	6.2	0.2	1	6.95	ACO3	AB3	310.0	5.2	1	249.91
ADC1	ADC4	20.5	0.5	1	19.72	AB1	ATH	49.1	1.1	1	44.26
ADC1	ACO1	169.0	2.9	1	137.59	AB2	ATH	2.2	0.1	1	3.39
ADC1	ACO3	183.0	2.9	1	144.50	AB3	ATH	127.0	2.1	1	102.38
ACO1	ADC1	169.0	2.9	1	137.59					**Sum**	**1874.65**
ACO3	ADC3	183.0	2.9	1	144.50						

Table 4
Transportation costs of existing Beta network for C&C.

Origin	Destination	Distance	Time	Numbers	Cost	Origin	Destination	Distance	Time	Numbers	Cost
ADC1	3PL	73.1	1.5	1	52.16	BCD	BB1	2.9	0.2	1	3.21
ADC2	3PL	72.3	1.5	1	51.79	BCD	BB2	10.5	0.3	1	8.21
ADC7	3PL	42.2	0.8	1	29.86	BCD	BB3	26.5	0.6	1	19.21
ADC4	3PL	60.2	1.2	1	42.83	BCD	BB4	45.1	0.9	1	32.04
ADC6	3PL	71.5	1.4	1	51.00	BCD	BB5	47.9	0.9	1	33.36
3PL	ADC1	73.1	1.5	1	52.16	BCD	BB6	28.7	0.7	1	22.29
3PL	ADC2	72.3	1.5	1	51.79	BB1	BCD	2.9	0.2	1	3.21
3PL	ADC7	42.2	0.8	1	29.86	BB2	BCD	10.5	0.3	1	8.21
3PL	ADC4	60.2	1.2	1	42.83	BB3	BCD	26.5	0.6	1	19.21
3PL	ADC6	71.5	1.4	1	51.00	BB4	BCD	45.1	0.9	1	32.04
3PL	BCD	285.0	4.8	1	192.28	BB5	BCD	47.9	0.9	1	33.36
BCD	3PL	285.0	4.8	1	192.28	BB6	BCD	28.7	0.7	1	22.29
										Sum	**1694.31**
									Total Sum		**3568.95**

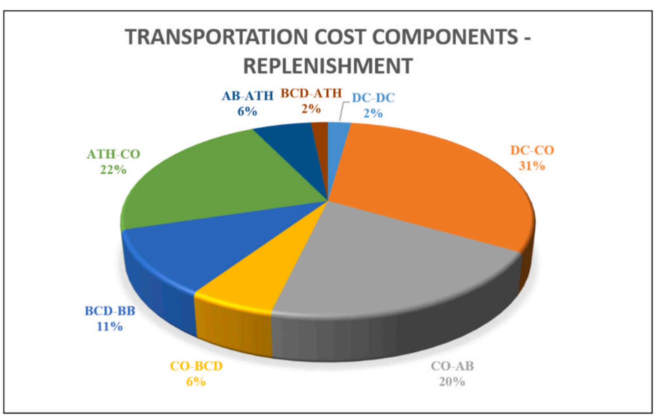

Fig. 7. Existing transportation cost components analysis for replenishment.

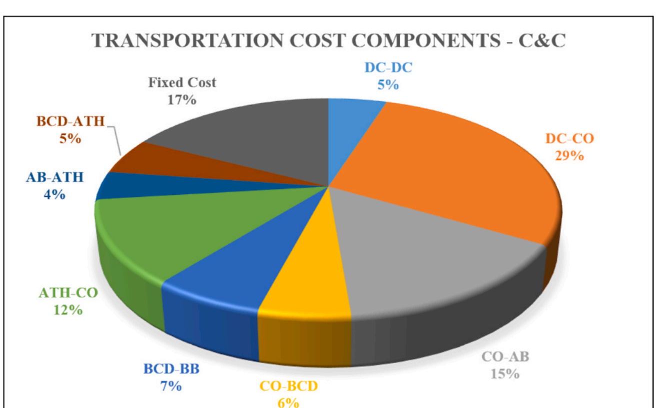

Fig. 8. Existing transportation cost components analysis for C&C.

Model indices and sets.

Notation	Description	Notation	Description
$i \in I$	Fixed distribution centres of APN.	$h \in H$	Fixed transportation hubs of APN.
$j \in J$	Fixed distribution centres of Beta.	$p \in P$	Third party transportation hub.
$k \in K$	Fixed branches of APN.	m, n	Index for individual distribution centre of APN.
$l \in L$	Fixed branches of Beta.	V	Set of different vehicles including APN vehicles (α) and third-party vehicles (β).
$e \in E$	Fixed changeover points of APN.	U	Set of different sales form including Replenishment (R) and Click & Collect (CC).
$g \in G$	Fixed cross-docks of Beta.		

Parameter	Description	Parameter	Description
cf_α	Fuel cost of α vehicles	d_g^h	Distance between Beta cross-dock g and APN transportation hub h
cf_β	Fuel cost of β vehicles	d_k^h	Distance between APN branch k and APN transportation hub h
cd_α	Driver cost of α vehicles	$t_{i_m}^{i_n}$	Traveling time between two APN DCs
cd_β	Driver cost of β vehicles	t_i^j	Travelling time between APN DC i and Beta DC j
cfv_β	Fixed cost of β vehicles	t_i^e	Traveling time between APN DC i and APN changeover point e.
Cap_α	Orders capacity of α vehicles	t_j^e	Traveling time between Beta DC j and APN changeover point e.
Cap_β	Orders capacity of β vehicles	t_h^e	Traveling time between APN transportation hub h and changeover point e.

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Parameter	Description	Parameter	Description
Dem_k^u	Demand at APN branch k for sales form u	t_e^k	Traveling time between APN changeover point e and APN branch k
Dem_l^u	Demand at Beta branch l for sales form u	t_e^g	Traveling time between APN changeover point e and Beta cross-dock g
$d_{i_m}^{i_n}$	Distance between two APN DCs	t_g^l	Traveling time between Beta cross-dock g and Beta branch l
d_i^j	Distance between APN DC i and Beta DC j	t_p^g	Traveling time between 3PL transportation hub p and Beta cross- dock g
d_i^e	Distance between APN DC i and APN changeover point e.	t_g^h	Traveling time between Beta cross-dock g and APN transportation hub h
d_j^e	Distance between Beta DC j and APN changeover point e.	t_k^h	Traveling time between APN branch k and APN transportation hub h
d_h^e	Distance between APN transportation hub h and changeover point e.	$q_i^{k,u}$	Quantity output at APN DCs i to APN branch k sales form u
d_e^k	Distance between APN changeover point e and APN branch k.	$q_i^{l,u}$	Quantity output at APN DCs i to Beta branch l sales form u
d_e^g	Distance between APN changeover point e and Beta cross-dock g	$q_j^{l,u}$	Quantity output at Beta DCs j to Beta branch l sales form u
d_g^l	Distance between Beta cross-dock g and Beta branch l	M_1	A sufficiently large number of vehicles
d_p^g	Distance between 3PL transportation hub p and Beta cross-dock g	M_2	A sufficiently large number of flow throughput

Decision Variables
Binary variables:

$X_{i_m,v}^{i_n,u}$	Equal to 1 if vehicle v travels between two APN DCs for sales form u.
$X_{j,v}^{i,u}$	Equal to 1 if vehicle v travels between two APN DCs i and Beta DC j for sales form u.
$X_{i,v}^{e,u}$	Equal to 1 if vehicle v travels between APN DC i and APN changeover point e for sales form u.
$X_{j,v}^{e,u}$	Equal to 1 if vehicle v travels between Beta DC j and APN changeover point e for sales form u.
$X_{i,v}^{p,u}$	Equal to 1 if vehicle v travels between DC i and transportation hub p for sales form u.
$X_{h,v}^{e,u}$	Equal to 1 if vehicle v travels between APN transportation hub h and changeover point e for sales form u.
$X_{e,v}^{k,u}$	Equal to 1 if vehicle v travels between APN changeover point e and APN branch k for sales form u.
$X_{e,v}^{g,u}$	Equal to 1 if vehicle v travels between APN changeover point e and Beta cross-dock g for sales form u.
$X_{g,v}^{l,u}$	Equal to 1 if vehicle v travels between Beta cross-dock g and Beta branch l for sales form u.
$X_{p,v}^{g,u}$	Equal to 1 if vehicle v travels between 3PL transportation hub p and Beta cross-dock g for sales form u.
$X_{k,v}^{h,u}$	Equal to 1 if vehicle v travels between APN branch k and APN transportation hub h for sales form u.

Integer variables:

$S_{i_m,v}^{i_n,u}$	Number of vehicles v used between two APN DCs for sales form u.
$S_{j,v}^{i,u}$	Number of vehicles v used between APN DC i and Beta DC j for sales form u.
$S_{i,v}^{e,u}$	Number of vehicles v used between APN DC i and APN changeover point e for sales form u.
$S_{i,v}^{p,u}$	Number of vehicles v used between Beta DC i and 3PL transportation hub p for sales form u.
$S_{j,v}^{e,u}$	Number of vehicles v used between Beta DC j and APN changeover point e for sales form u.

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(*continued*)

$S_{i_m,v}^{i_n,u}$	Number of vehicles v used between two APN DCs for sales form u.
$S_{h,v}^{e,u}$	Number of vehicles v used between APN transportation hub h and APN changeover point e for sales form u.
$S_{e,v}^{k,u}$	Number of vehicles v used between APN changeover point e and APN branch k for sales form u.
$S_{e,v}^{g,u}$	Number of vehicles v used between APN changeover point e and Beta cross-dock g for sales form u.
$S_{g,v}^{l,u}$	Number of vehicles v used between Beta cross-dock g and Beta branch l for sales form u.
$S_{p,v}^{g,u}$	Number of vehicles v used between 3PL transportation hub p and Beta cross-dock g for sales form u.
$S_{k,v}^{h,u}$	Number of vehicles v used between APN branch k and APN transportation hub h for sales form u.
$F_{i_m}^{i_n,u}$	Flow throughput between two APN DCs for sales form u.
$F_i^{e,u}$	Flow throughput between APN DC i and APN changeover point e for sales form u.
$F_j^{e,u}$	Flow throughput between Beta DC j and APN changeover point e for sales form u.
$F_i^{p,u}$	Flow throughput between APN DC i and 3PL transportation hub p for sales form u.
$F_p^{g,u}$	Flow throughput between 3PL transportation hub p and Beta cross-dock g for sales form u.
$F_e^{k,u}$	Flow throughput between APN changeover point e and APN branch k for sales form u.
$F_e^{g,u}$	Flow throughput between APN changeover point e and Beta cross-dock g for sales form u.
$F_g^{l,u}$	Flow throughput between Beta cross-dock g and Beta branch l for sales form u.

Objective function

The different cost elements of the objective function (transportation cost) are described here.

$$\sum_{i_m,i_n} TC_{i_m}^{i_n} = \sum_{i_m,i_n,u,v} S_{i_m,v}^{i_n,u} X_{i_m,v}^{i_n,u}\left(d_{i_m}^{i_n} cf_\alpha + t_{i_m}^{i_n} cd_\alpha\right) \tag{1.1}$$

Eq. (1.1) depicts the total transportation cost between two different APN DCs.

$$\sum_{i_n,i_m} TC_{i_n}^{i_m} = \sum_{i_n,i_m,u,v} S_{i_n,v}^{i_m,u} X_{i_n,v}^{i_m,u}\left(d_{i_n}^{i_m} cf_\alpha + t_{i_n}^{i_m} cd_\alpha\right) \tag{1.2}$$

Eq. (1.2) shows the return transportation cost between two different APN DCs.

$$\sum_{i,e} TC_i^e = \sum_{i,e,v,u} S_{i,v}^{e,u} X_{i,v}^{e,u}\left(d_i^e cf_\alpha + t_i^e cd_\alpha\right) \tag{1.3}$$

Eq. (1.3) denotes the total transportation cost between APN DC i and APN changeover point e.

$$\sum_{e,i} TC_e^i = \sum_{e,i,v,u} S_{e,v}^{i,u} X_{e,v}^{i,u}\left(d_e^i cf_\alpha + t_e^i cd_\alpha\right) \tag{1.4}$$

Similar to Eq. (1.3), Eq. (1.4) represents the transportation cost when vehicles return to APN DC i from APN changeover point e.

$$\sum_{h,e} TC_h^e = \sum_{h,e,v,u} S_{h,v}^{e,u} X_{h,v}^{e,u}\left(d_h^e cf_\alpha + t_h^e cd_\alpha\right) \tag{1.5}$$

Eq. (1.5) denotes the transportation cost between APN transportation hub h and APN changeover point e.

$$\sum_{e,k} TC_e^k = \sum_{e,k,v,u} S_{e,v}^{k,u} X_{e,v}^{k,u}\left(d_e^k cf_\alpha + t_e^k cd_\alpha\right) \tag{1.6}$$

Eq. (1.6) calculates the transportation cost between APN changeover point e and APN branch k.

$$\sum_{k,h} TC_k^h = \sum_{k,h,v,u} S_{k,v}^{h,u} X_{k,v}^{h,u}\left(d_k^h cf_\alpha + t_k^h cd_\alpha\right) \tag{1.7}$$

The transportation cost between APN branch k and APN transportation hub h is represented by Eq. (1.7).

$$\sum_{e,g} TC_e^g = \sum_{e,g,v,u} S_{e,v}^{g,u} X_{e,v}^{g,u} \left(d_e^g cf_\alpha + t_e^g cd_\alpha\right) \tag{1.8}$$

Eq. (1.8) computes the transportation cost between APN changeover point e and Beta Cross-dock g.

$$\sum_{g,l} TC_g^l = \sum_{g,l,v,u} S_{g,v}^{l,u} X_{g,v}^{l,u} \left(d_g^l cf_\alpha + t_g^l cd_\alpha\right) \tag{1.9}$$

Eq. (1.9) indicates the transportation cost between Beta cross-dock g and Beta branch l.

$$\sum_{l,g} TC_l^g = \sum_{l,g,v,u} S_{l,v}^{g,u} X_{l,v}^{g,u} \left(d_l^g cf_\alpha + t_l^g cd_\alpha\right) \tag{1.10}$$

Eq. (1.10) indicates the transportation cost between Beta branch l and Beta cross-dock g.

$$\sum_{g,h} TC_g^h = \sum_{g,h,v,u} S_{g,v}^{h,u} X_{g,v}^{h,u} \left(d_g^h cf_\alpha + t_g^h cd_\alpha\right) \tag{1.11}$$

Eq. (1.11) describes the transportation cost occurred between Beta cross-dock g and APN transportation hub h.

$$Minimise TC = \sum_{i_m,i_n,i,e,h,k,g,l,v,u} \begin{pmatrix} TC_{i_m,v}^{i_n,u} + TC_{i_n,v}^{i_m,u} + TC_{i,v}^{e,u} + TC_{e,v}^{i,u} + TC_{h,v}^{e,u} + TC_{e,v}^{k,u} \\ + TC_{k,v}^{h,u} + TC_{e,v}^{g,u} + TC_{g,v}^{l,u} + TC_{l,v}^{g,u} + TC_{g,v}^{h,u} \end{pmatrix} \tag{1.12}$$

Eq. (1.12) sums up all the transportation cost components to obtain the total transportation cost. This mathematical model aims to optimise the total transportation cost as shown in Eq. (1.12).

Subject to constraints

$$\sum_{i,e} F_j^{e,u} = \sum_i q_i^u \qquad \forall u \in U \tag{2}$$

Constraint (2) ensures that the total throughput from all APN DCs to all APN changeover points e equals to the total output.

$$\sum_{e,k} F_e^{k,u} + \sum_{e,g} F_e^{g,u} = \sum_i q_i^u \qquad \forall u \in U \tag{3}$$

Similarly, constraint (3) makes sure the total throughput from APN changeover points to all APN branches k and Beta cross-dock g equals to the total output.

$$\sum_{e,g} F_e^{g,u} = \sum_{g,l} F_g^{l,u} \qquad \forall u \in U \tag{4}$$

Constraint (4) shows that the total throughput from Beta cross-dock g to all Beta branches l should be equal to the throughput from APN changeover points e to the Beta cross-dock g.

$$\sum_{e,k} F_e^{k,u} = \sum_k Dem_k^u \qquad \forall u \in U \tag{5}$$

$$\sum_e F_e^{k,u} = Dem_k^u \qquad \forall u \in U, \forall k \in K \tag{5a}$$

To link throughput and demand, constraints (5) and (5a) ensure that the total throughput from APN changeover points e to APN branches k equals the total demand at APN branches k.

$$\sum_{e,g} F_e^{g,u} = \sum_l Dem_l^u \qquad \forall u \in U \tag{6}$$

$$\sum_g F_g^{l,u} = Dem_l^u \qquad \forall u \in U, \forall l \in L \tag{6a}$$

Likewise, constraints (6) and (6a) make sure that the total throughput from APN changeover points e to Beta branches l matches the total demand at Beta branches l.

$$\sum_{i_m,i_n} F_{i_m}^{i_n,u} + \sum_{i,e} F_i^{e,u} = \sum_i q_i^u \qquad \forall u \in U \tag{7}$$

$$\sum_{i_m} F_i^{i_m,u} + \sum_e F_i^{e,u} = q_i^u \qquad \forall i \in I, \forall u \in U \tag{7a}$$

Constraints (7) and (7a) imply that the total throughput dispatched from APN DC i equals its total output quantity.

$$\sum_{i_m} F_i^{i_m,u} + \sum_e F_i^{e,u} - \sum_{i_n} F_{i_n}^i = q_i^u \qquad \forall i \in I, \forall u \in U \tag{8}$$

Additionally, to consider whether a specific DC serves as the starting point of a vehicle, Constraint (8) calculates the product flow entering and leaving the same DC.

$$\sum_{i_m} X_{i,v}^{i_m,u} \le 1 \qquad \forall i \in I, \forall v \in V, \forall u \in U \tag{9}$$

Constraint (9) represents that each vehicle departing from an APN DC i can transport products to at most one other DC.

$$\sum_e X_{e,v}^{k,u} = 1 \qquad \forall k \in K, \forall v \in V, \forall u \in U \tag{10}$$

$$\sum_e X_{e,v}^{g,u} = 1 \qquad \forall g \in G, \forall v \in V, \forall u \in U \tag{11}$$

Constraints (10) and (11) guarantee that vehicle deliveries to APN branches k and Beta cross-dock g are routed through only one designated changeover point.

$$F_a^b \le S_a^b Cap_\alpha \qquad \forall a, b \in different\ locations, \forall \alpha \in V \tag{12}$$

$$F_a^b \le S_a^b Cap_\beta \qquad \forall a, b \in different\ locations, \forall \beta \in V \tag{13}$$

The relationship between vehicle capacity and the corresponding throughput is defined by constraints (12) and (13).

$$\sum_{e,k,v} S_{e,v}^{k,u} + \sum_{e,g,v} S_{e,v}^{g,u} = \sum_{h,e,v} S_{h,v}^{e,u} \qquad \forall u \in U \tag{14}$$

Constraint (14) confirms that the number of vehicles dispatched from APN transportation hub h to changeover point e is equal to the number of vehicles travelled from changeover point e to APN branches k and Beta cross-docks g.

$$\sum_v S_{e,v}^{k,u} = \sum_v S_{k,v}^{h,u} \qquad \forall e \in E, \forall k \in K, \forall h \in H, \forall u \in U \tag{15}$$

Constraint (15) explains that the number of vehicles departing from each APN branch k to APN transportation hub h is equal to the number of vehicles go from the corresponding APN changeover point e to the same APN branch k.

$$\sum_v S_{e,v}^{g,u} = \sum_v S_{g,v}^{h,u} \qquad \forall e \in E, \forall g \in G, \forall h \in H, \forall u \in U \tag{16}$$

Similarly, constraint (16) confirms that the number of vehicles travelling from the Beta cross-dock g to APN transportation hub h matches the number of vehicles dispatched from the APN changeover point e to the same Beta cross-dock g.

$$\sum_v S_{i,v}^{e,u} = \sum_v S_{e,v}^{i,u} \qquad \forall i \in I, \forall e \in E, \forall u \in U \tag{17}$$

Constraint (17) represents the transportation flow before the APN changeover point. The number of vehicles travelling from each APN DC to a specific APN changeover point should be equal to the number of vehicles returning from the corresponding APN changeover point to the same APN DC.

$$\sum_{v} S_{i_n,v}^{i_m,u} = \sum_{v} S_{i_m,v}^{i_n,u} \qquad \forall i_n, i_m \in I, i_n \neq i_m, \forall u \in U \tag{18}$$

Regarding vehicle flow on the road, Constraint (18) ensures that the number of vehicles behind and in front of a specific APN DC remains consistent.

$$F_a^b \leq M_2 X_a^b \qquad \forall a, b \in \textit{different locations} \tag{19}$$

$$S_a^b \leq M_1 X_a^b \qquad \forall a, b \in \textit{different locations} \tag{20}$$

Constraints (19) and (20) show the relationship between binary variables and flow throughput, as well as the number of vehicles, respectively, using the Big M method.

$$F_a^b \geq X_a^b \qquad \forall a, b \in \textit{different locations} \tag{21}$$

$$S_a^b \geq X_a^b \qquad \forall a, b \in \textit{different locations} \tag{22}$$

Additionally, to prevent the issue where the binary variables may be smaller than the corresponding integer variables, Constraints (21) and (22) are introduced to correct this discrepancy.

$$X_a^b \in (0, 1) \qquad \forall a, b \in \textit{different locations} \tag{23}$$

$$F_a^b \in \mathbb{Z}^+ \qquad \forall a, b \in \textit{different locations} \tag{24}$$

$$S_a^b \in \mathbb{Z}^+ \qquad \forall a, b \in \textit{different locations} \tag{25}$$

Finally, the constraints for the binary and integer variables constraints are defined by constraints (23) and (24)-(25), respectively.

6. Model implementation and numerical results

6.1. Data collection

The mathematical model was implemented in Python and computational experiments were performed on a PC with an Intel Core i5 processor (2.90 GHz) and 8 GB of RAM. The data required to solve the model, including branch demand, delivery restrictions and vehicle types was provided by APN company. The transportation cost for APN vehicles includes both fuel and driver costs, with fuel costing £0.47 per mile and driver costs at £20.17 per hour. Third-party logistics limited utilises three types of vehicles: 42-cage, 3-compartment vehicles, 48-cage 2-compartment vehicles and 81-cage 4-compartment vehicles. The fixed cost for all these vehicles is £1685 per month, with a driver cost of £12.28 per hour. The fuel cost for the first two vehicle types is £0.47 per mile, while the fuel cost for the third vehicle type is slightly higher at £0.51 per mile. Distances between any two locations in the network range from 0.5 to 492 miles and the time consumed for transportation

Table 5
Summary of the optimal results for Replenishment.

Replenishment		
Scenarios		Costs in £
Centre	Sub-combine	
Current		2677.39
ADC1, Beta	/	2346.66
ADC1, Beta	ADC4-ADC6	**2340.51**
ADC4	/	2500.71
ADC1	/	2463.84
ADC6, Beta	/	**2346.41**
ADC4, Beta	/	2380.43
All DCs	/	2762.39
Beta	/	2448.59
ALL DCs	3PL	3015.51
ADC1, Beta	3PL	2614.08

Table 6
Summary of the optimal results for C&C.

C&C		
Scenarios		Cost
Centre	Sub-combine	
Current		3568.95
ADC1	/	2143.74
ADC4	/	2159.06
ADC4	ADC2 –ADC1	2126.01
ADC4	ADC1-ADC6	2133.52
ADC4	ADC2 –ADC6	2132.85
ADC4	ADC2 – ADC1 – ADC6	**2100.46**
ADC4	ADC2-ADC6, ADC1-ADC6	**2107.30**
ADC1	ADC7-ADC6	2145.33
ADC1	ADC4-ADC6, ADC7-ADC6	2139.17
ADC1	ADC4-ADC6	2137.59
ADC1	ADC7-ADC4-ADC6	2119.14
All DCs	/	3140.15
ADC1, ADC4	ADC2-ADC1, ADC6-ADC1, ADC7-ADC4	2392.19
All DCs	3PL	3028.80
ADC1	3PL	2632.64

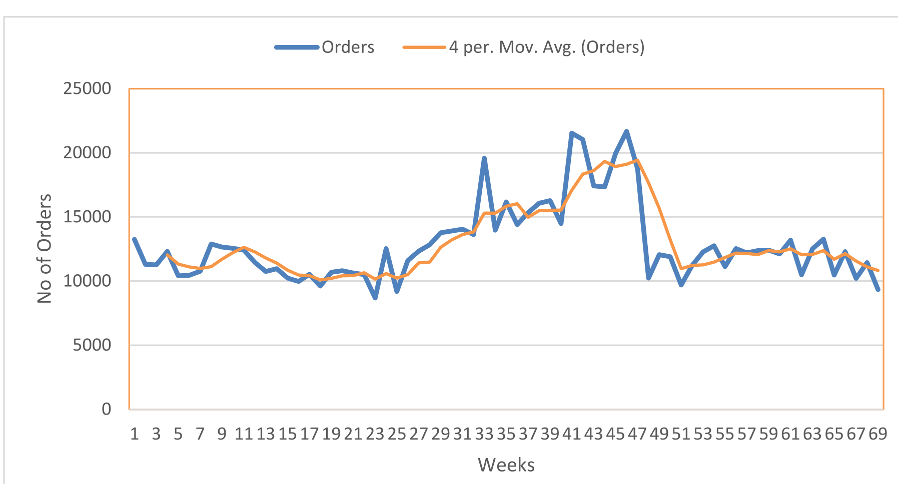

Fig. 9. AB2 replenishment weekly demand.

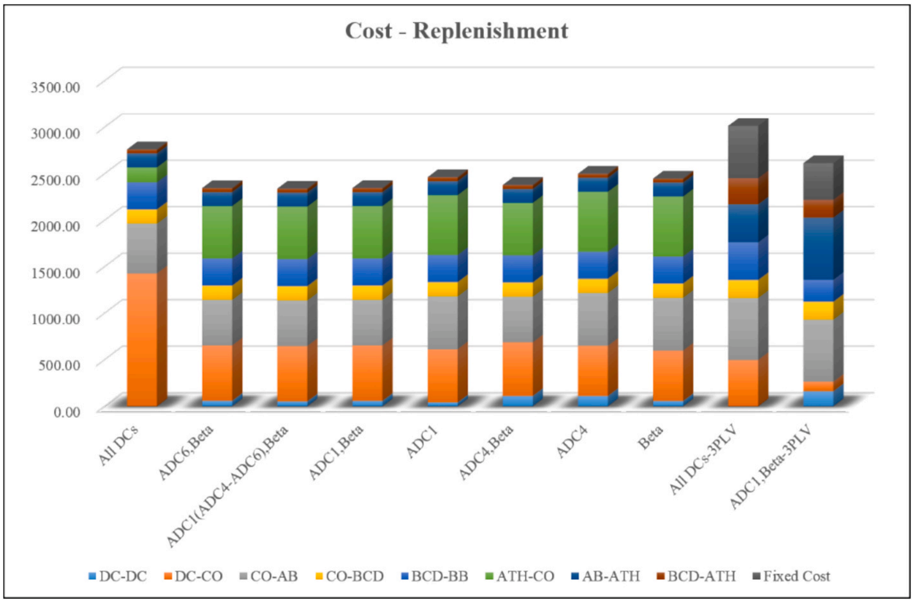

Fig. 10. Cost components analysis of optimal solutions for Replenishment.

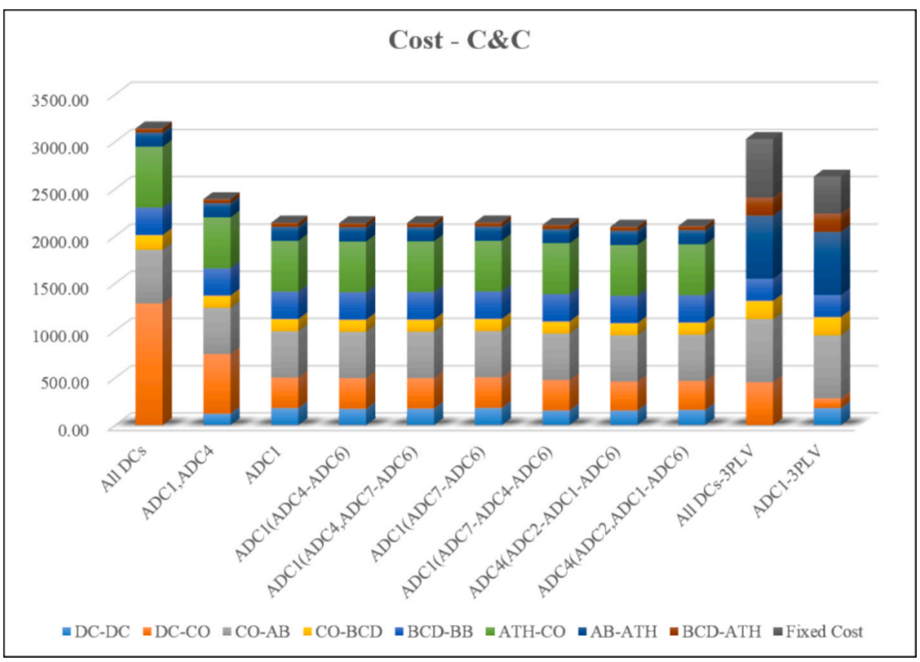

Fig. 11. Cost components analysis of optimal solutions for C&C.

between locations varies from 0.02 to 8.38 h. The weekly demand for products across the branches is illustrated in Fig. 9.

6.2. *Replenishment results*

The model was solved using CPLEX solver in Python and a summary of the results is presented in Table 5. The two smallest costs, £2,340.51, and £2,346.41, are highlighted in bold. In the table, the term “Centre” refers to a scenario where commodities from all other DCs are consolidated at the central DC. The “Sub-Combine” scenario indicates that some sub-routes are involved in the delivery process between DCs.

We also assessed the corresponding vehicle routes for the two smallest cost scenarios. The first optimal result suggests that products departing from APN DCs will be consolidated at ADC1, from where Beta DC will directly deliver to ACO1. Similarly, the second optimal result indicates that commodities should be consolidated at ADC6 for APN replenishment, while Beta replenishment will be delivered directly to ACO1. However, due to current restrictions, ADC6 is a small DC that cannot serve as a cross-dock to handle all replenishment orders simultaneously. Therefore, the ‘ADC6, Beta centre’ scenario is not a viable recommendation and should be excluded. Nevertheless, the other proposed routes in the recommendations are feasible for implementation.

6.3. *Click & collect results*

A summary of the results obtained from running the optimisation model is presented in Table 6, with the two lowest costs highlighted in bold.

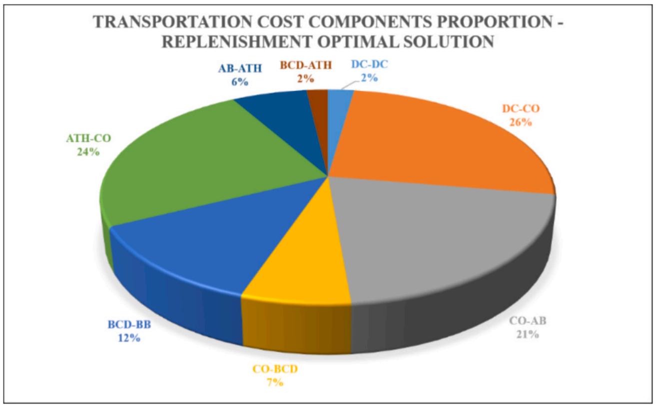

Fig. 12. Cost components analysis of optimal solution for replenishment.

Table 7
Comparison of costs in current and replenishment optimal scenario.

	Current in £	Optimal in £	Difference (Optimal-Current) in £	Percentage of total difference
DC-DC	58.30	**52.14**	−6.15	1.83 %
DC-CO	835.05	**595.89**	−239.16	70.99 %
CO-AB	544.16	**490.49**	−53.68	15.93 %
CO-BCD	153.17	153.17	0.00	0.00 %
BCD-BB	291.08	291.08	0.00	0.00 %
ATH-CO	603.01	**565.12**	−37.89	11.25 %
AB-ATH	150.03	150.03	0.00	0.00 %
BCD-ATH	42.59	42.59	0.00	0.00 %
Sum	2677.39	**2340.51**	−336.88	100.00 %

Table 8
Comparison of current and replenishment optimal scenario in percentage.

	Current	Optimal
DC-DC	**2.18 %**	2.23 %
DC-CO	31.19 %	**25.46 %**
CO-AB	**20.32 %**	20.96 %
CO-BCD	**5.72 %**	6.54 %
BCD-BB	**10.87 %**	12.44 %
ATH-CO	**22.52 %**	24.15 %
AB-ATH	**5.60 %**	6.41 %
BCD-ATH	**1.59 %**	1.82 %
Sum	100.00 %	100.00 %

The results identified two optimal scenarios, both using ADC4 as the integration centre. However, similar to ADC6, ADC4 lacks sufficient space to function as a cross-dock, necessitating a focus on alternative consolidation centres. After excluding ADC4 as a viable integration centre, the recommended scenario is to use ADC1 as the integration centre, with a sub-combined route from ADC7 through ADC4 to ADC6.

6.4. Cost analysis

In this subsection, the cost components of optimal solutions obtained for replenishment and C&C are analysed. The summary of these cost components is illustrated in bar charts for replenishment (Fig. 10) and C&C (Fig. 11). Comparing these figures reveals that the proportion of each cost element is similar to the existing scenario. The transportation cost related to changeovers occupies the largest share, highlighting the importance of changeovers discussed in Section 4.1. Additionally, both replenishment and C&C scenarios do not recommend using 3PL vehicles

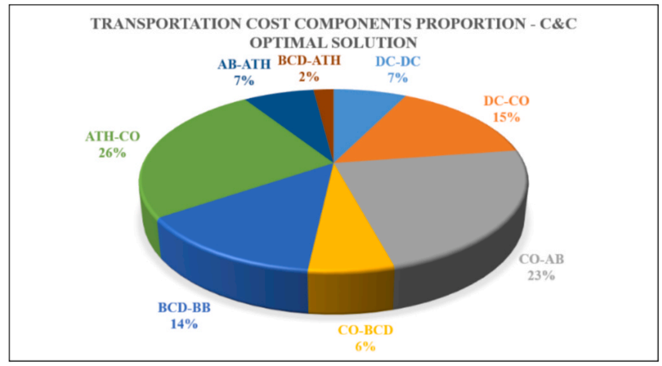

Fig. 13. Cost components analysis for C&C optimal solution.

Table 9
Comparison of costs in current and C&C optimal scenario in number.

	Current in £	Optimal in £	Difference (Optimal-Current) in £	Percentage of total difference
DC-DC	174.50	**154.85**	−19.64	1.35 %
DC-CO	1019.46	**325.02**	−694.44	47.90 %
CO-AB	544.16	**490.49**	−53.68	3.70 %
CO-BCD	192.28	**126.57**	−65.71	4.53 %
BCD-BB	**236.64**	291.08	54.44	−3.76 %
ATH-CO	**441.78**	538.52	96.74	−6.67 %
AB-ATH	150.03	150.03	0.00	0.00 %
BCD-ATH	192.28	**42.59**	−149.69	10.32 %
Fixed Cost	617.83	**0.00**	−617.83	42.61 %
Sum	3568.95	**2119.14**	−1449.82	100.00 %

Table 10
Comparison of current and C&C optimal scenario in percentage.

	Current	Optimal	Difference (Optimal-Current)
DC-DC	**4.89 %**	7.31 %	2.42 %
DC-CO	28.56 %	**15.34 %**	−13.23 %
CO-AB	**15.25 %**	23.15 %	7.90 %
CO-BCD	**5.39 %**	5.97 %	0.59 %
BCD-BB	**6.63 %**	13.74 %	7.11 %
ATH-CO	**12.38 %**	25.41 %	13.03 %
AB-ATH	**4.20 %**	7.08 %	2.88 %
BCD-ATH	5.39 %	**2.01 %**	−3.38 %
Fixed cost	17.31 %	**0.00 %**	−17.31 %
Sum	**100.00 %**	100.00 %	0.00 %

due to their high fixed costs. Furthermore, the transportation cost between third-party transportation hubs and APN branches is higher than that between APN changeover points and APN branches. This phenomenon indicates that the location of APN changeover points is more suitable for APN transportation than third-party transportation hubs.

6.5. Comparison between optimal solution and the existing model for replenishment

The proportion of cost components for the optimal solution for replenishment is illustrated in Fig. 12.

Additionally, Tables 7 and 8 compare the cost of each component between optimal solution and the existing model, with lower costs for each cost component highlighted in bold.

According to Tables 7 and 8, the optimal solution primarily optimises the transportation cost from the DC to the changeover point, resulting in savings of £239.16. Given the importance of changeover, the optimal solution also focuses significantly on changeover selection, which accounts for nearly 98 % of the total savings. Additionally, the optimal transportation costs between DCs and changeover points, from ATH to changeover points and from changeover points to AB are lower than those in the existing model, leading to total savings of £336.88 for the optimal scenario. This savings is for a single route and considering that APN runs approximately 100 trips per month on these routes, it translates to an annual savings of about £400,000 with the optimal route.

6.6. Comparison between optimal solution and existing model for Click & collect

Similar to the previous section, Fig. 13 presents a pie chart illustrating the proportion of cost components for the C&C optimal solution.

Additionally, Tables 9 and 10 compare the cost of each component between the optimal solution and the existing model. This comparative analysis clearly demonstrates the efficiency improvements achieved through optimisation. By identifying areas with significant cost differences – particularly in changeover-related transportation and third-party logistics – these results offer practical guidance for enhancing the C&C network's cost effectiveness.

Based on Tables 9 and 10, the optimisation of the C&C scenarios also successfully reduces costs related to changeovers, as well as the fixed cost. While switching to APN vehicles results in a slight increase in variable costs – specifically, an additional £151.18 for transportation between the Beta cross-dock and Beta branches as well as between APN transportation hubs and changeovers – the fixed costs savings amount to £617.83. This trade-off indicates that fully utilising APN vehicles is a cost-effective strategy. Moreover, the optimisation model proves to be highly efficient by targeting the two most critical factors: the selection of changeover locations and the type of vehicles deployed. Overall, the proposed model achieves a savings of £1,449.82 per C&C route, translating to an expected annual saving of approximately £800,000.

6.7. Implications of cost elements

When comparing the optimal routes for both replenishment and C&C scenarios, an interesting observation emerges, aside from the routes between DCs, all other transportation paths remain consistent across solutions. Prior analysis of cost components confirms that the MIP model for VRP naturally optimises the most significant component, which has the highest contribution to transportation cost. Moreover, across different scenarios, when a particular cost component consistently represents the largest share, the optimal routing decisions related to that component remain unchanged. This suggest that variations in less significant cost elements have minimal influence on the optimisation of the more critical and high-cost components. These comparisons provide insights into how variations in facility capacity or routing decisions impact the overall cost. This enables decision-makers to anticipate operational outcomes under different planning conditions.

7. Conclusions and implications

7.1. Discussion

This study has investigated the freight distribution network of APN, Beta and the 3PL service provider and made several insightful recommendations to enhance delivery operations across northern UK. A key motivation behind this work was to develop a robust mathematical model capable of optimising overall transportation costs while considering the network's structural and operational complexity. The proposed decision support model successfully reduced annual transportation costs by approximately £1.2 million compared to the current scenario. The key finding for the replenishment scenario suggests consolidating deliveries from ADC4 and ADC6 into a single vehicle route, bypassing ADC4 via ADC6. The analysis also highlights ACO3 as the most efficient changeover point for delivering to all APN branches, while Beta replenishment should be routed through ACO1. In the C&C scenario, the recommended strategy involves integrating the route from ADC7 to ADC1. This allows products from ADC7 to pass through ADC4 and be loaded onto a shared vehicle at ADC6. The consolidated vehicle would then transport combined loads from ADC7, ADC4 and ADC6. Similar to replenishment, ACO3 is identified as the most effective changeover point for all C&C deliveries. Importantly, the study concludes that third-party logistics support is not required under the optimal model. APN's own fleet is sufficient to meet delivery demands, making it cost-effective to rely exclusively on internal resources.

7.2. Theoretical implications

This study contributes several important theorical advancements to the literature on vehicle routing and distribution networks. While many existing VRP studies have addressed aspects such as multiple depots, vehicle capacities, and transportation time constraints (Ramos et al., 2020; Wang et al., 2019), they have often overlooked key real-world complexities such as heterogeneous fleets, multiple product types, and the role of satellite facilities like cross-docks (Abad et al., 2018; Huang et al., 2019; Soto-Concha et al., 2025). Moreover, there is a notable gap in the logistics literature regarding models that are driven by actual industry challenges. Specifically, limited attention has been given to the integration of third-party logistics hubs, inter-depot routing, multiple echelons and driver-related costs (Konstantakopoulos et al., 2022; Li et al., 2019). This study addresses these limitations by formulating and solving a complex MDVRP grounded in the operational context of a leading UK retailer. The proposed decision support model incorporates a wide range of real-world constraints and parameters such as fleet heterogeneity, cross-docking, delivery restrictions and cost trade-offs – offering a novel and practical contributions to VRP theory and its application in large-scale logistics operations.

7.3. Managerial implications

The findings of this study offer several actional insights for managers at the case company seeking to enhance the efficiency of their freight distribution network and reduce transportation costs. Under the replenishment scenario, two key recommendations emerge: 1. Integration of DCs: Currently, each DC independently dispatches products to ADC1 without route consolidation. The optimal solution proposes integrating shipments between ADC4 and ADC6 by redirecting products from ADC4 to ADC6, consolidating them there, and then forwarding the combined load to ADC1. This consolidation approach significantly improves vehicle utilisation, reduces unnecessary travel and thereby minimises fuel consumption and carbon emissions. 2. Strategic selection of changeover facilities: The current operation allocates ACO1 to handle deliveries to AB1 and Beta transportation, while ACO3 is responsible for AB2 and AB3. However, the optimisation results suggest that ACO3 should handle all APN branch deliveries, indicating that it offers greater logistical feasibility and cost-efficiency compared to ACO1 and ACO2.

For the C&C network, three strategic recommendations are proposed. 1. Route integration across DCs: Freight should be consolidated across ADC7, ADC4 and ADC6. Specifically, products from ADC7 should be routed to ADC4, consolidated into a single vehicle and transported to ADC6. From there, products from all three sites (ADC7, ADC4 and ADC6) should be delivered to ADC1 using a single vehicle, improving route efficiency and reducing the total number of trips required. 2: Optimised changeover location: ACO3 is identified as the most effective changeover point, managing all C&C transportation. This supports a streamlined and centralised distribution approach, improving service reliability and operational simplicity 3: Avoidance of third-party logistics: The analysis demonstrates that 3PL providers introduce significant fixed costs without corresponding efficiency gains. It is therefore recommended that APN rely solely on its in-house fleet for both replenishment and C&C deliveries to enhance cost-effectiveness and control. By implementing these recommendations, managers can significantly improve operational efficiency, reduce transportation costs and streamline logistics operations across the network. In addition to operational benefits, the implementation of these strategies can contribute meaningfully to sustainability goals. By consolidating routs, reducing the number of trips and improving vehicle utilisation, the company can significantly cut GHG emissions associated with freight transport. Thus, the study not only support cost optimisation but also promotes environmentally responsible distribution practices.

8. Limitations and future scope

Like any research, this study has certain limitations that present opportunities for future investigation. One of the main limitations is that the model does not perform a join optimisation of replenishment and C&C operations. In practice, these two streams could potentially be integrated to exploit synergies, particularly by incorporating factors such as inventory holding costs and delivery lead times. Additionally, the current model assumes fixed facility locations and does not support the optimisation or selection of new facility sites. Introducing facility location planning could further improve cost-efficiency and service coverage. Additionally, although the current model implicitly supports environmental benefits through reduced distances, it does not directly optimise for sustainability metrices such as GHG emissions. With growing pressure on companies to meet sustainability goals, future research could incorporate GHG minimisation as a direct objective alongside cost for multi-objective optimisation. Moreover, the model is built on deterministic demand assumptions. In reality, demand can be highly uncertain and variable. Incorporating probabilistic or stochastic demand modelling would allow for better responsiveness and resilience in the distribution network. Finally, future enhancements could include additional objectives and constraints, such as minimising delivery lead times, maximising service level and evaluating societal impacts. These extensions would align the model more closely with real-world multi-objective decision-making in complex supply chains.

CRediT authorship contribution statement

D.G. Mogale: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Abhijeet Ghadge:** Writing – review & editing, Writing – original draft, Supervision, Investigation. **Sarat Kumar Jena:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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