An optimization model for routing—location of vehicles with time windows and cross-docking structures in a sustainable supply chain of perishable foods

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Abstract

The effective distribution of perishable food items is a critical aspect of managing the food industry's supply chain, given their physical–chemical, biological characteristics and composition, which make them highly susceptible to rapid deterioration. This research presents a transport model incorporating a cross-dock system to efficiently deliver goods from production plants to markets. The model incorporates a vehicle routing model that considers time windows for pick-ups and deliveries, optimal cross-dock center locations, a heterogeneous vehicle fleet of limited capacity, and scheduling product collections, arrivals, and departures. The model is a mixed-integer non-linear optimization model that effectively minimizes logistics costs and environmental impacts by considering various parameters such as speed, waiting times, loading and unloading times, and costs associated with the entire operation. The findings demonstrate that the cross-dock structure is highly conducive to distributing perishable goods, achieved by minimizing collection and distribution operations, adhering to designated time windows, and efficiently allocating resources. The GAMS 23.6.5 software is used to program the model, employing various solution strategies, including experimental tests with scenarios, as well as the "posterior," "Pareto optimization," and "weighted sum" methods. The case study in Sincelejo (Sucre, Colombia) reported the best solution, representing 60% of logistics and 40% of environmental costs. The results show complete compliance with routes, no inventory generation, and the necessity of two inbounds and two outbound vehicles for collection from suppliers and delivery to retailers. This study presents an efficient model for managing the transportation of perishable goods, contributing to sustainable distribution activities, and environmental conservation in the food industry's supply chain.

Keywords Vehicle Routing Problem · Location problem · Cross-docking · Time Windows · Supply Chain · Perishable

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1 Introduction

Logistics is widely recognized as a crucial aspect of modern global commerce, particularly regarding decision-making around product routing and location (Ballou et al. 2002). Distribution, the final stage of logistics activities, employs a network of routes to transport products to make them available to customers at a minimum cost (Medina et al. 2011). The planning of vehicle routes is a crucial issue that needs to be analyzed in depth to optimize logistics costs (Chen et al. 2009). In this situation, several options can be implemented to achieve this goal, such as optimizing routes to reduce fuel consumption, eliminating intermediate stops, and reducing waiting times at destinations (Gómez and Baca 2014). Moreover, handling temperature-controlled cargo and managing capacity constraints and time windows are additional

logistical challenges requiring effective management to ensure efficient and successful logistics operations across various industries, particularly for perishable goods with short lifecycles and requiring prompt and efficient transportation (Agi and Soni 2020).

Logistics costs are a crucial component of modern commerce, accounting for up to 40% of a product's total cost (Onstein et al. 2020). Various factors, including transportation, handling of goods, inventories, and human factors, such as workforce training and development, drive logistics operations' high expense. Companies can adopt various strategies to overcome these challenges, such as outsourcing logistics operations to specialized providers, forming strategic partnerships, and leveraging cross-docking platforms. Outsourcing logistics can result in significant cost savings by optimizing supply chain operations and reducing transportation expenses, while strategic partnerships can help companies to gain access to new markets and distribution networks. Similarly, cross-docking platforms can help companies to streamline their logistics operations by reducing handling time and minimizing inventory costs. Effective logistics operations management is critical for minimizing costs, optimizing supply chain efficiency, and ensuring long-term competitiveness in today's dynamic global marketplace while maintaining high service levels.

Handling products like foods in perishable goods supply chains poses more significant challenges due to their time and handling requirements (Minner and Transchel 2017). In the food industry, it is common for a single producer to be unable to meet the actual demand, which creates the need for consolidation strategies or partnerships between producers (Yang et al. 2019). These links between producers and consumers and potential consolidation points require careful location and routing planning to minimize logistical costs (Chaudhary et al. 2018). Additionally, handling perishable goods requires careful temperature control, inventories, and timely delivery to maintain product quality. Cross-docking structures are necessary to manage these challenges by allowing for the consolidation of goods and reducing delivery times (Golestani et al. 2021). Companies can optimize transportation and logistics costs while ensuring the timely and efficient delivery of their products by implementing these structures.

Cross-docking tools are essential in simplifying logistics and reducing costs for perishable goods supply chains. This new supply chain strategy, which considers the economic, environmental, and social dimensions in a comprehensive and sustainable approach, offers a novel research scope in the wide range of problems related to supply chain network design (Rezaei and Kheirkhah 2018). Cross-docking alongside traditional warehousing can significantly reduce supply chain costs by up to 6.4% (Benrqya 2019). The implementation of cross-docking

benefits the company and the entire perishable food supply chain, making it a suitable tool for improving food distribution (Vasiljevic et al. 2013).

The supply chain of perishable foods is distinguished from other supply chains by the complexity of the goods flowing through the different agents, and it has great relevance in factors such as the quality and safety of food. The time-sensitive nature of perishable products distinguishes their supply chain from that of non-perishable products. It is estimated that most food loss and waste in developing countries occur in the early stages of the food supply chain (Redlingshöfer et al. 2017). This results in not only the waste of the final product but also the waste of natural resources, which implies unnecessary emissions of CO_2 in production and distribution (Halloran et al. 2014). The greatest challenge for perishable food supply chains lies in delivering food on time and at a minimum cost due to the nature of the products, which have a short shelf life, rapid transportation, and are prone to spoilage (Amorim et al. 2012). The design of food supply chains should focus on preventing production loss, improving sales efficiency, and reducing inventory and order cycle time (Kuo and Chen 2010). Additionally, when analyzing the contribution of transport to climate change, the close relationship between transport and energy is highlighted. International concern about the effects of climate change is leading to the creation of transport initiatives that reduce Greenhouse Gas (GHG) emissions and do not affect the environment (Ramudhin et al. 2008).

This study addresses how small-scale producers can implement effective strategies for managing perishable food supply chains, specifically within cheese production. To answer this question, a mathematical model will be developed that considers critical economic and environmental factors in planning distribution routes. The proposed model incorporates a cooperative strategy utilizing a cross-docking platform to minimize logistics costs associated with the product while considering the product's characteristics and time windows. The model uses a mathematical optimization approach that prioritizes the reduction of overall costs and carbon footprint by considering parameters such as vehicle speed, waiting times, loading and unloading times, and the costs associated with the entire operation. The validation of the model will be carried out through the case study of the coastal cheese supply chain in the Department of Sucre, Colombia. Overall, this study aims to provide valuable insights into the development of sustainable and efficient strategies for managing perishable food supply chains.

The structure of the present study consists of, firstly, a contextual introduction to perishable goods supply chains. Section 2 of this paper thoroughly reviews existing solution methods, followed by a detailed description of the research problem in Section 3. Section 4 elaborates on the design of the proposed metaheuristic algorithm, and Section 5 presents

the obtained results. Finally, Section 6 concludes the study and discuss potential future works in this research field.

2 Literature review

This literature review will focus on the following key areas: vehicle routing problems, cross-docking problems, and environmental considerations in logistics. These topics are crucial in addressing perishable food supply chains' challenges and developing an adequate mathematical model to plan optimal distribution routes.

2.1 Cross-docking

The cross-docking is a logistic strategy used by many companies in different industries, especially suitable for distributing fresh products with a short lifespan (Agustina et al. 2014). A definition of cross-docking provided by Kinnear (1997) is: "Receiving product from a vendor or supplier for several final destinations and consolidating

this product with other vendor products for common final delivery destinations". A cross-dock for perishable products streamlines distribution, reduce delivery cycle time, and improves customer satisfaction. In addition, it allows the consolidation of orders and delivery to trucks of full load (FTL) instead of trucks of less load (LTL) to reduce the cost of transport (Cóccola et al. 2015). Therefore, an essential advantage of cross-docking is saving storage costs, transport, inventories and labor compared to the traditional warehouse (Agustina et al. 2014). Table 1 lists the most relevant research on cross-docking in affinity with the following research. In recent years, many studies have been conducted that propose various approaches to increase the efficiency of the supply chain, such as the cross-docking strategy has been applied as a very efficient logistics solution in a wide variety of industry sectors (Wang et al. 2017; Ahkamiraad and Wang 2018). Lee et al. (2006) is probably the first study that considers the Vehicle Routing Problem with cross-docking by proposing a Tabu search to determine the number of vehicles and minimize the total transportation costs.

Table 1 Relevant literature on cross-docking operations

Reference	Description
Ross and Jayaraman (2008)	Evaluation of new heuristics for the location of cross-dock distribution centers in supply chain network design
Liao et al. (2010)	Routing system for vehicles with cross-docking in the supply chain
Cóccola et al. (2012)	Integrated production and distribution model with cross-docking for the supply chain
Hasani-Goodarzi and Tavakkoli-Moghaddam (2012)	Routing problems with capable vehicles, multiple products, cross-docking, partial deliveries, and collection
Hanchuan et al. (2013)	Analysis of logistics costs and influence of factors based on cross-docking
Agustina et al. (2014)	Scheduling and routing of vehicles in a cross-docking center for food supply chains
Mousavi et al. (2014)	Cross-docking center locations and vehicle routing scheduling under conditions of uncertainty: a fuzzy-possibilistic stochastic programming model
Mohtashami (2015)	A multiobjective optimization model for solving cross-docking programming problems using a meta-heuristic based on the NSGA-II and MOPSO algorithms
Ahmadizar et al. (2015)	A model that considers two-tier vehicle routing, cross-docking, and different providers at different prices can supply a given type of product
Goodarzi and Zegordi (2016)	Vehicle location and routing problems in a distribution network with parts suppliers, cross docks, and assembly plants represented as customers
Grangier et al. (2017)	New solution methodology for the Cross-dock structure and vehicle routing problem, based on searching for large neighborhoods with partitioning and matching problems
Maknoon and Laporte (2017)	A mathematical formulation of the cross-dock structure, vehicle routing problem, and an adaptive large neighborhood search heuristic
Wang et al. (2017)	A new vehicle routing problem with the cross-dock structure and divided deliveries, with a mixed-integer linear programming formulation and simulated annealing and tabu search
Ahkamiraad and Wang (2018)	The mixed-integer linear programming model of a particular type of Vehicle Routing Problem with cross-docking enabled and multiple pick-ups, delivery, and time windows
Goodarzi and Zegordi (2016)	Analyze pick-up and delivery for the cross-docking strategy, in which shipments from suppliers to retailers are made directly and through cross-docking
Kaboudani et al. (2020)	Develops a mathematical model for the vehicle routing problem in a distribution network with a cross-docking center, considering both forward and reverse logistics in an integrated model
Vincent et al. (2021)	Vehicle routing problem for heterogeneous fleets with multiple Cross Docks in a distribution system. A mixed integer linear programming model and an adaptive neighborhood simulated annealing algorithm are developed for the problem

Some studies have incorporated product distribution using cross-docking can be analyzed at three levels: strategic, tactical and operational (Agustina et al. 2014), where the strategic decisions are related to the location and design of the cross-dock, while the tactical decisions focus on the consolidation of the process of flow of goods through the supply chain to minimize costs and satisfy demand (Van Belle et al. 2012), and operational planning encompassing scheduling, assignment, transshipment, and routing. Thus, cargo handling at cross-dock terminals is a complex planning task that includes unloading shipments delivered by incoming vehicles, consolidating products into groups according to designated destinations, and the load on outgoing vehicles (Mousavi et al. 2014; Ahmadizar et al. 2015).

Goodarzi and Zegordi (2016) developed a non-linear model for the location and routing problem, where establishing a cross-docking structure is used to analyze the scenarios of direct shipment and indirect shipment with transshipment through transshipment cross-dock. Subsequently, Hasani-Goodarzi et al. (2018) formulated a new two-goal model for the same problem where direct shipping is allowed. From a solution perspective, various models, exact algorithms, and metaheuristics for Vehicle Routing Problems with Cross-docking have been proposed by Liao et al. (2010) and Maknoon and Laporte (2017). Vincent et al. (2021) approach the problem using a heterogeneous fleet of vehicles and multiple cross-docks. Kaboudani et al. (2020) argue that while Vehicle Routing Problem with distribution center structures deals with direct logistics systems, some organizations have recently focused on using it for reverse logistics for defective or unsold products.

The cross-docking strategy offers many benefits in distribution processes compared to the traditional warehouse. Implementing cross-docking for a perishable warehouse streamlines distribution, reduces delivery time, and improves customer satisfaction (Shahabi-Shahmiri et al. 2021). In addition, it allows order consolidation and delivery to full truckloads instead of lesser trucks to reduce transportation costs (Apte and Viswanathan 2000; Cóccola et al. 2015). Therefore, a vital advantage of the cross-docking strategy is the savings in storage, inventory, transportation, and labor costs. Considering that cross-docking is a strategy widely used with vehicle routing, this problem of high importance in logistics is explained in detail below.

Cross-docking has been the subject of various research studies to optimize supply chain network design. Different methodologies have been employed, including mathematical formulations, heuristics, and meta-heuristics. Several studies have focused on vehicle routing problems with cross-docking and divided deliveries, considering multiple products, time windows, and heterogeneous fleets. Other studies have analyzed logistics costs, uncertainty, and factors affecting cross-docking, while others have developed integrated production and distribution models. A few studies have also considered reverse logistics and multiple providers at different prices. The results of these studies provide valuable insights into the location and routing of cross-docking centers, helping organizations enhance their supply chain efficiency and reduce costs.

2.2 Vehicle Routing Problem

The Vehicle Routing Problem (VRP) is a combinatorial optimization problem that extends the Traveling Salesman Problem (TSP) introduced by Flood in 1956 (Konstantakopoulos et al. 2022). Due to its NP-complete nature, VRP is considered one of the most complex problems from a computational complexity standpoint. The problem involves designing vehicle routes at the lowest possible cost to serve customers in different geographic locations (Vidal et al. 2014). The problem's graphical representation is typically done using a graph with nodes and arcs, where the nodes represent the customer locations and the arcs represent the road network that vehicles can use to circulate (Anbuudayasankar et al. 2016).

Vehicle routing problems (VRPs) have been extensively studied due to their practical applications in various domains (Montoya-Torres et al. 2015). Several types of VRPs have been identified and researched in literature, including capacitated VRP, which involves finding routes for a fleet of vehicles with limited capacity to serve customers with known demands, as well as vehicle routing problems with time windows (VRPTW), which involves finding routes that meet delivery time constraints. The location-routing problem (LRP) also considers depot location selection and vehicle routing, while other VRPs include pickup and delivery problem (PDP), multiple-depot VRP, and green VRP.

This study combines Capacitated VRP with Time Windows (VRPTW) and Two-Echelon Location-Routing Problem with Time Windows (2E-LRPTW), where the CVRP variant involves a restrictive fleet capacity, and VRPTW requires serving each customer within a specific time window. The 2E-LRPTW is an NP-hard problem involving optimal facility location and number, the number of products delivered at each echelon, and corresponding routes (Wang et al. 2018). Optimizing the distribution of perishable food products is a significant challenge when combining the Capacitated VRP with Time Windows (VRPTW) and Two-Echelon Location-Routing Problem with Time Windows (2E-LRPTW). While the problem of locating and routing vehicles with time windows (LRPTW) is prevalent in many distribution systems, limited research has been conducted on its application to the perishable food distribution domain (Govindan et al. 2014).

The vehicle routing-location model is a complex problem that involves several factors, such as the type of fleet, time windows, cross-docking, perishable items, multi-product,

and environmental considerations. The literature review reveals that although most studies on vehicle routing problems consider trained vehicles, homogeneous fleets, time windows, and environmental factors, few studies have addressed the optimization of delivery routes for perishable products using heterogeneous fleets with varying capacities, cross-docking strategies and environmental considerations. To bridge this research gap, this study proposes a vehicle routing model that incorporates time windows for pick-ups and deliveries, optimal cross-dock center locations, a heterogeneous vehicle fleet of limited capacity, and scheduling of product collections, arrivals, and departures. To provide an overview of the existing research on vehicle routing problems, Table 2 presents relevant studies on this topic.

The previous table showed various studies on vehicle routing problems with time windows, cross-docking, and perishable products. Chen et al. (2009) proposed a production scheduling and vehicle routing model for perishable food products with time windows. Azi et al. (2010) developed an exact algorithm for a vehicle routing problem with time windows and multiple uses of vehicles. Liao et al. (2010) presented a vehicle routing model with cross-docking in the supply chain. Erdoğan and Miller-Hooks (2012) focused on a green vehicle routing problem. Mousavi and Tavakkoli-Moghaddam (2013) proposed a hybrid simulated annealing algorithm for location and routing scheduling problems with cross-docking. Furthermore, recent studies have extended the problem by considering mixed-integer linear programming and fuzzy possibilistic-stochastic programming (Mousavi et al. 2014), biogeography-based optimization (Goodarzi and Zegordi 2016), and multiobjective optimization (Liang et al. 2023). Finally, Baniamerian et al. (2019), Agrawal et al. (2022), and Ghasemkhani et al. (2022) proposed a hybrid approach algorithm model for solving the routing problems with cross-docking and perishable products.

2.3 Environmental consideration

Most of the studies related to the vehicle routing problem focus on minimizing distances, and travel times, among other objectives. However, in recent years, studies have focused on the emission of greenhouse gases associated with other direct transportation costs (Bravo Urria 2015). Kara et al. (2007) studied the energy-minimizing vehicle routing problem that considers the distance traveled by fleet vehicles and the effect of load on the measurement of energy consumption. Suzuki (2011) proposes a routing model that considers fuel use as a measure to reduce greenhouse gas emissions and incorporates a speed factor and time sales for truck routes. Xiao et al. (2012) developed a vehicle routing model that considers fuel consumption as an objective, establishing a linear relationship between load and fuel consumption.

Moreover, Govindan et al. (2014) developed a multiobjective optimization model for the two-link multi-vehicle routing-location problem with time windows (2E-LRPTW) for the sustainable supply chain of perishable foods. This research focused on minimizing logistics and environmental costs from greenhouse gas emissions. Ashtineh and Pishvaee (2019) evaluated alternative fuels' economic and environmental performance in VRP problems. This approach quantifies the effect emitted by pollutants (NOx, HC and CO) and GHG emissions (CO_2, N_2O). Song et al. (2020) developed a vehicle routing problem considering time windows, different types of vehicles and energy consumption of vehicles.

2.4 The gap in the study

In today's dynamic market, companies must be adaptable to survive in a highly competitive environment. To do so, they must create customized configurations that allow them to respond to the unique characteristics of products and territories where they operate. This is where a company's service offering comes into play, setting them apart from its competition. Although there is a growing body of research on the vehicle routing problem with time windows (VRPTW), it has been little studied in the context of perishable products. Several studies have attempted to tackle this issue, but none have considered integrating cross-docking systems more suitable for fast-moving and perishable items. Cross-docking systems help reduce inventories, increase operational efficiency, and reduce delivery times while reinforcing control in distribution operations (Hasani-Goodarzi and Tavakkoli-Moghaddam 2012). However, cross-docking is a complex planning task involving multiple activities, such as unloading incoming shipments, consolidating products, and loading outgoing delivery vehicles, as highlighted by Mohtashami et al. (2015) and Ahmadizar et al. (2015).

In response to this gap in the literature, the proposed study aims to develop a sustainable and efficient strategy for managing perishable food supply chains utilizing a collaborative cross-docking platform. The proposed model uses mathematical optimization techniques to minimize logistics costs while considering the product's characteristics and time windows. The study will focus on the coastal cheese supply chain in the Department of Sucre, Colombia, and will consider special considerations such as a heterogeneous fleet, time windows, the cross-docking strategy, and the treatment of perishable products with short cycles and special handling requirements. The proposed model will also consider sustainability aspects of energy consumption, reflecting a growing trend in recent years. Overall, validating the proposed model will provide valuable insights into developing sustainable and efficient strategies for managing perishable food supply chains.

Table 2 Relevant literature on the vehicle routing problem

Year	Reference	Characteristic								
		Trained Vehicles	Homogeneous fleet	Heterogeneous Fleet	Time Windows	Cross-docking	Location	Perishables	Multi-product	Environmental consideration
2009	Ai and Kachitvichyanukul (2009)	X	X							
	Baldacci and Mingozzi (2009)	X		X						
	Brandão (2009)	X		X						
	Briäysy et al. (2009)	X		X	X					
	Chen et al. (2009)	X		X	X			X	X	
	Imran et al. (2009)	X		X						
	Lin et al. (2009)	X	X							
	Prescott-Gagnon et al. (2009)	X	X		X					
2010	Azi et al. (2010)	X		X				X		
	Benjamin and Beasley (2010)	X	X		X					
	Chen et al. (2010)	X	X							
	Ghoseiri and Ghannadpour (2010)	X	X		X					
	Qureshi et al. (2010)	X	X		X					
	Li et al. (2010)	X	X		X					
	Liao et al. (2010)	X	X			X				
2011	Santos et al. (2011)	X	X		X					
	Lei et al. (2011)	X	X		X					
2012	Erdoğan and Miller-Hooks (2012)	X	X							X
	Hasani-Goodarzi and Tavakkoli-Moghaddam (2012)	X		X		X			X	X
2013	Xiao et al. (2012)	X	X							X
	Nguyen et al. (2013)	X	X		X					
	Kwon et al. (2013)	X		X						X
	Mousavi and Tavakkoli-Moghaddam (2013)	X		X		X	X			
2014	Agustina et al. (2014)	X	X		X	X			X	
	Belhaiza et al. (2014)	X	X			X				
	Govindan et al. (2014)	X		X	X	X	X			X
	Mousavi et al. (2014)	X		X		X	X		X	
2015	Ahmadizar et al. (2015)	X		X	X	X			X	
	Mohtashami (2015)	X		X		X			X	
	Soysal et al. (2015)	X	X			X				
2016	Birim (2016)	X		X		X				X
	Goodarzi and Zegordi (2016)	X	X			X	X			
2017	Leggieri and Haouari (2017)	X	X							X
	Psychas et al. (2017)	X	X							X

Table 2 (continued)

Year	Reference	Characteristic								
		Trained Vehicles	Homogeneous fleet	Heterogeneous Fleet	Time Windows	Cross-docking	Location	Perishables	Multi-product	Environmental consideration
2018	Chen et al. (2018)	X	X				X			X
	Masmoudi et al. (2018)	X		X	X					X
2019	Marinakis et al. (2019)	X	X		X					
	Zhao et al. (2019)	X	X		X					
	Ashtineh and Pishvaee (2019)	X	X		X					X
	Baniamerian et al. (2019)	X		X	X	X				
2020	Fachini and Armentano (2020)	X		X	X					
	Zhen et al. (2020)	X	X		X					
	Song et al. (2020)	X		X	X				X	X
2021	İlhan (2021)	X	X							
	Srivastava et al. (2021)	X	X		X					
	Wang et al. (2021)	X		X	X					
	Pan et al. (2021)	X	X		X					
2022–2023	Yang et al. (2022)				X		X			X
	Wang et al. (2022)			X	X		X			
	Alamatsaz et al. (2022)	X	X		X		X			X
	Liang et al. (2023)		X		X		X	X		
	Agrawal et al. (2022)			X	X			X		
	Ghasemkhani et al. (2022)			X	X			X	X	
	This study	X		X	X	X	X	X	X	X

3 Materials and methods

The proposed methodology addresses the complex logistics challenges perishable food supply chains face. To this end, the problem will be formulated as a mathematical optimization model considering crucial logistics variables such as distribution costs, inventory, storage, location, routing, and energy consumption. The model will also incorporate restrictive factors, such as vehicle capacity and time windows, within a two-echelon cross-docking strategy. The goal is to provide a comprehensive approach to support the logistics strategy of perishable food supply chains, which are characterized by short life cycles and require special treatment. By applying this methodology, we aim to develop a sustainable and efficient solution that optimizes the use of resources while minimizing costs and environmental impact. The general structure of the proposed model is detailed below.

The two-echelon distribution network for the proposed problem is described by a G (NA) graph, where N is the set of nodes, and A is the set of arcs. The N-node set consists of suppliers (F), potential cross-dock (D) and retailers (R). The set of Arcs A represents the cost and minimum environmental impact routes to join the nodes in the network (see Fig. 1). In each cross-dock, heterogeneous trained vehicles (incoming and outgoing) are available to estimate fixed and unit transportation costs and environmental impacts.

Vehicle routing and product distribution through each cross-dock allow multiple manufacturers with limited production capacity to supply different types of products. The products are picked up from the manufacturers, delivered to the cross-dock by incoming vehicles, and deposited in the entrance area. After receiving the shipped, the products

can be sent directly for the dispatch and distribution process together with other products; otherwise, they are stored while the orders are waiting to be consolidated. Logistics decisions are influenced by the time of deposit and departure, which encourages the distribution disposition for delivery. This system provides guidance on the departure time of the vehicles (from the cross-dock) and ensures that the products are delivered to the retailer at a minimum cost and with the most negligible environmental impact (Agustina et al. 2014) (see Fig. 2).

The multiobjective nature of this research focuses on economic and environmental objectives to find the most suitable locations, the size of each one and the routes of the most efficient vehicles. The first objective minimizes total logistics costs, including costs of opening docks, transportation costs, penalization costs of waiting and delay, and acquisition and product handling at the cross-dock. In this sense, the costs of waiting and delay are preceded by the soft time windows considered by suppliers and retailers that require the services of care and delivery of the desired product in good quality (Agustina et al. 2014).

The cost of the acquisition, the handling of the product, and the cost of transportation represent the operating costs. The second objective minimizes the environmental services generated by the actors in the supply chain and from the harmful GHG emissions expressed in Ton. CO_2 equations are associated with the environmental impacts of opening and handling cross-dock, the suppliers' operational activities and transport's environmental impacts. The problem considered in this research is an extension of the study by Govindan et al. (2014), which analyzed the problem of routing-localization of multiple two-echelon vehicles with

Fig. 1 Configuration of the proposed model
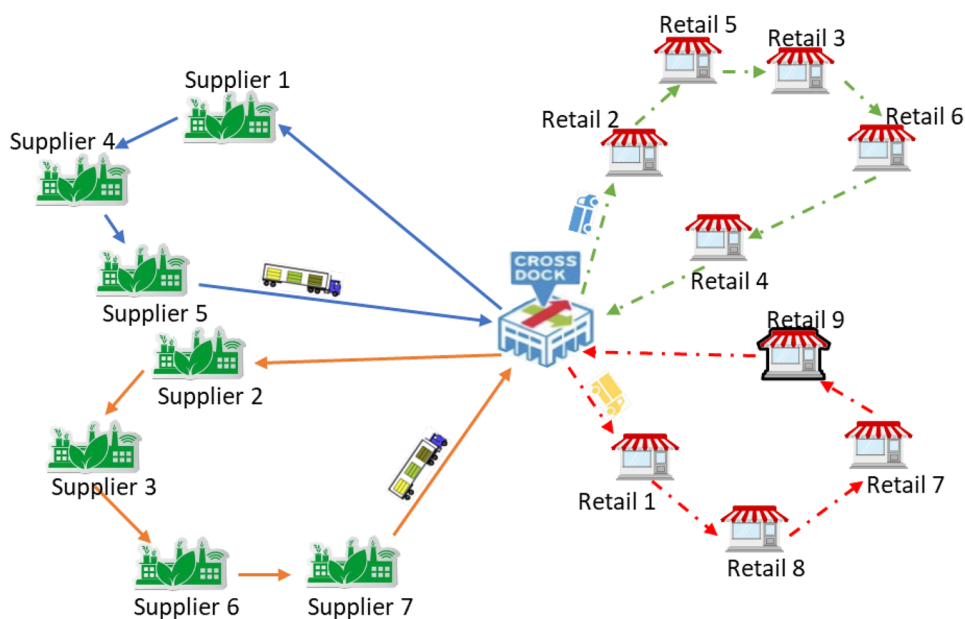
Fig. 2 Cross-Docking system for the perishable food supply chain
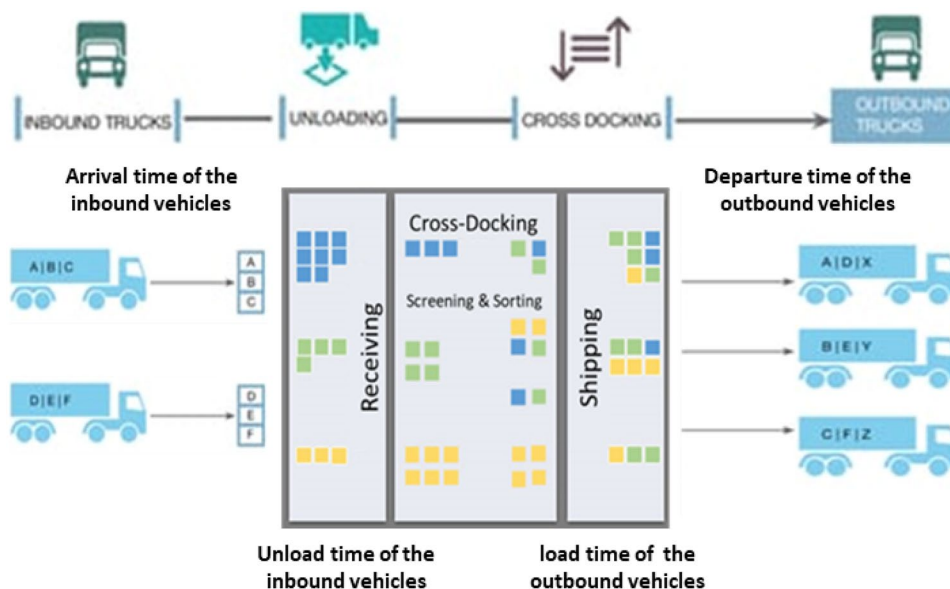
time windows for the optimization of the supply chain network perishable Foods (2E-LRPTW) and the cross-docking strategy were adopted under the described by Ahmadizar et al. (2015). The assumptions, notations and the proposed mathematical model are shown below.

3.1 Assumptions

- The demand of the retailer *r, Dem$_{rp}$*, is a deterministic and independent variable.
- Each retailer must be assigned to a single supplier, cross-dock, and transported by a single inbound and outbound vehicle.
- A heterogeneous fleet of inbound and outbound vehicles with fixed and variable costs is available at each cross-dock.
- All vehicles are available from the beginning of the day, with the maximum time available being less than or equal to the working time per day.
- The maximum storage area for each cross-dock is limited, and storage costs are incurred per unit. Storage time is ignored.
- A retailer's total demand volume can exceed the vehicle's capacity, and several outbound vehicles can visit each retailer.
- All suppliers can produce each type of product at different prices.
- Backorders are not allowed for both retailers and cross-docks.
- Vehicle dispatching cost/time, traveling cost/unit distance, holding cost, service time, and vehicle speed are all known.

- Products must be ordered to avoid expiry in storage.
- Each vehicle must start and end at the same point, and each vehicle can carry out a majority route consisting of a sequence of transport stages.
- The total volume of products assigned to a supplier can exceed the vehicle's capacity, and several inbound vehicles can visit each supplier.
- Unlimited resources are available to load/unload the vehicles in each supplier through the cross-dock and the retailer, eliminating waiting time.
- The collection operation must be carried out during a 480-min (8 h) period, and the delivery operation during a 960-min (16 h) period. The entire cross-docking operation must be completed within a 960-min timeframe.

3.2 Notations

3.2.1 Sets

F   Suppliers $f \in F$.

R   Retailers $r \in R$.

P   Products $p \in P$.

V   Fleet of inbound/outbound vehicles $v \in V_1$, $v' \in V_2$, $V_1 U V_2 = V$.

B   Production technology $b \in B$.

3.2.2 Parameters

QPF_{fbp} — Supplier production capacity f with the type of production technology b of a product p.

$IAPF_{fbp}$ — Environmental impact of the production in the supplier f with the type of production technology b of a product p.

PVF_{fp} — The unit selling price of the supplier f for the product p.

CAD_d — Opening cost of the cross-dock d

$IAAD_d$ — Environmental impacts of opening cross-dock d.

QD_d — Maximum cross-dock storage area capacity d.

Dem_{rp} — Demand of retailer r for product p.

$CAPD_{dp}$ — Holding cost in the cross-dock d of a unit of product p.

$IAMD_{dp}$ — Environmental impacts for handling each unit in cross-dock d of a product p.

$DisD_{Fdf}$ — Travel distance from cross-dock d to supplier f.

$DisD_{Rdr}$ — Travel distance from cross-dock d to retailer r.

$DisF'_{Fff'}$: — Travel distance between supplier f and f'.

$DisR'_{Rrr'}$ — Travel distance between retailers r and r'.

$DisF_{Ddf}$ — Travel distance from supplier f to cross-dock d.

$DisR_{Ddr}$ — Travel distance from retailer r to cross-dock d.

$NVED_d^{Max}$ — The maximum number of vehicles v available in cross-dock d.

$NVSD_d^{Max}$ — The maximum number of vehicles v' available in cross-dock d.

$QVED_{dv}$ — Capacity of vehicle v of cross-dock d.

$QVSD_{dv'}$ — Capacity of vehicle v' of cross-dock d.

$VMVED_{dv}$ — Average speed of vehicle v of cross-dock d.

$VMVSD_{dv'}$ — Average speed of vehicle v' of cross-dock d.

$CFVED_{dv}$ — Fixed cost of vehicle v of cross-dock d.

$CFVSD_{dv'}$ — Fixed cost of vehicle v' of cross-dock d.

$CTDF_{dvf}$ — Unit transportation cost of vehicle v traveling of cross-dock d to supplier f.

$CTDR_{dv'r}$ — Unit transportation cost of vehicle v' traveling of cross-dock d to retailer r.

$CTFF_{vff'}$ — Unit transportation cost of vehicle v traveling of supplier f to supplier f'.

$CTRR_{v'rr'}$ — Unit transportation cost of vehicle v' traveling of retailer r to retailer r'.

$CTFD_{dvf}$ — Unit transportation cost of vehicle v traveling of supplier f to cross-dock d.

$CTRD_{dv'r}$ — Unit transportation cost of vehicle v' traveling of retailer r to cross-dock d.

$IADF_{dvf}$ — Average environmental impact of transporting vehicle v from cross-dock d to supplier f.

$IADR_{dv'r}$ — Average environmental impact of transporting vehicle v' of cross-dock d to retailer r.

$IAFF_{vff'}$ — Average environmental impact of transporting vehicle v of supplier f to supplier f'.

$IARR_{v'rr'}$ — Average environmental impact of transporting vehicle v' of retailer r to retailer r'.

$IAFD_{dvf}$ — Average environmental impact of transporting vehicle v of supplier f to cross-dock d.

$IARD_{dv'r}$ — Average environmental impact of transporting vehicle v' of retailer r to cross-dock d.

μ — Distribution factor of a product.

TCF_{dvfp} — Time required to load in vehicle v of cross-dock d in supplier f a unit of product p.

$TCD_{dv'p}$ — Time required to load in the cross-dock d in vehicle v' a unit of product p.

TDD_{dvp} — Time required in the cross-dock d of vehicle v to unload a unit of product p.

$TDR_{dv'rp}$	Time required to unload vehicle v' of cross-dock d in retailer r a unit of product p.	$Y_{dv'r}$	1 if vehicle v' travels from cross-dock d to the first retailer r; 0 otherwise.
HT	Horizon of time of operation of the cross-dock.	$Y'_{dv'rr'}$	1 if retailer r' is immediately visited after the retailer r by a vehicle v' of cross-dock d; 0 otherwise.
$TT1$	Horizon of time of operation in the second echelon.	$Y''_{dv'r}$	1 if vehicle v' travels from the last retailer r to the cross-dock d; 0 otherwise.
$TT2$	Horizon of time of operation in the second echelon.	g_{fdvrp}	1 if supplier f sends to the cross-dock d in the vehicle v the demand of the retailer r of the product p; 0 otherwise.
φ	Economic factor for environmental emissions.		
HTF_{dvf}	Earliest arrival time of the time window of vehicle v of cross-dock d to supplier f.	$z_{dv'rp}$	1 if cross-dock d sends in the vehicle v' the demand of the retailer r of the product p; 0 otherwise.
$HTR_{dv'r}$	Earliest arrival time of the time window of vehicle v' of cross-dock d to retailer r.	a_{rp}	1 if the product p demanded by retailer r is stored temporarily in the cross-dock; 0 otherwise.
HUF_{dvf}	Latest arrival time of the time window of vehicle v of cross-dock d to supplier f.	t'_{dv}	Departure time of vehicle v from cross-dock d.
$HUR_{dv'r}$	Latest arrival time of the time window of the vehicle v' of cross-dock d to the retailer r.	HLF_{dvf}	Arrival time of vehicle v from cross-dock d to supplier f.
PEF_{dvf}	Waiting for the penalty of vehicle v of cross-dock d to supplier f.	θ_{dvf}	Departure time of vehicle v from cross-dock d from supplier f.
$PER_{dv'r}$	Waiting for the penalty of vehicle v' of cross-dock d to retailer r.	Ψ_{dv}	A finish time of the unloading operation of vehicle v from cross-dock d.
PRF_{dvf}	Delay penalty of vehicle v of cross-dock d to supplier f.	$t_{dv'}$	Departure time of vehicle v' from cross-dock d.
$PRR_{dv'r}$	Delay penalty of vehicle v' of cross-dock d to the retailer r.	$HLR_{dv'r}$	Arrival time of vehicle v' from cross-dock d to retailer r.
		$\theta'_{dv'r}$	Departure time of vehicle v' from cross-dock d from retailer r.

3.2.3 Variables

R_d	1 if cross-dock d is opened; 0 otherwise.	$HLD_{dv'r}$	Arrival time of vehicle v' from cross-dock d to retailer r.
X_{dvf}	1 if vehicle v travels from cross-dock d to the first supplier f; 0 otherwise.	VEF_{dvf}	Waiting time of vehicle v of cross-dock d in the supplier f.
$X'_{dvff'}$	1 if supplier f' is immediately visited after the supplier f by a vehicle v of cross-dock d; 0 otherwise.	VRF_{dvf}	Lateness time of vehicle v of cross-dock d in the supplier f.
X''_{dvf}	1 if vehicle v travels from the last supplier f to the cross-dock d; 0 otherwise.	$VER_{dv'r}$	Waiting time of vehicle v' of cross-dock d in the retailer r.

$VRR_{dv'r}$ Lateness time of vehicle v' of cross-dock d in the retailer r.

$CTLOG$ Total logistics costs.

$CTIA$ Total costs of environmental impacts.

3.3 Mathematical model

This section presents the mathematical formulation of a mixed integer non-linear model for the location and routing problem with time windows and cross-docking with the previously mentioned notations:

$$
\begin{aligned}
Min\ CTLOG = &\sum_{d=1}^{D} \left(CAD_d R_d \right) \\
&+ \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{f=1}^{F} (CFVED_{dv} X_{dvf} + CTDF_{dvf} DisD_{Fdf} X_{dvf} + CTFD_{dvf} DisF_{Ddf} X''_{dvf}) \\
&+ \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{f=1}^{F} \sum_{f'=1}^{F} \left(CTFF_{vff'} DisF'_{Fff'} X'_{dvff'} \right) \\
&+ \sum_{d=1}^{D} \sum_{v'=1}^{V_2} \sum_{r=1}^{R} (CFVSD_{dv'} Y_{dv'r} + CTDR_{dv'r} DisD_{Rdr} Y_{dv'r} + CTRD_{dv'r} DisR_{Ddr} Y''_{dv'r}) \\
&+ \sum_{d=1}^{D} \sum_{v'=1}^{V_2} \sum_{r=1}^{R} \sum_{r=1}^{R} \left(CTRR_{v'rr'} DisR'_{Rrr'} Y'_{dv'rr'} \right) \\
&+ \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{f=1}^{F} \sum_{f=1}^{F} (PEF_{dvf} VEF_{dvf} + PRF_{dvf} VRF_{dvf}) \\
&+ \sum_{d=1}^{D} \sum_{v'=1}^{V_2} \sum_{r=1}^{R} \sum_{r=1}^{R} \left(PER_{dv'r} VER_{dv'r} + PRR_{dv'r} VRR_{dv'r} \right) \\
&+ \sum_{f=1}^{F} \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{r=1}^{R} \sum_{p=1}^{P} (PVF_{fp} Dem_{rp} g_{fdvrp} + CAPD_{dp} Dem_{rp} g_{fdvrp} a_{rp})
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
Min\ CTIA = &\sum_{d=1}^{D} (IAAD_d \varphi R_d) + \sum_{f=1}^{F} \sum_{b=1}^{B} \sum_{d=1}^{D} \sum_{v}^{V_1} \sum_{r}^{R} \sum_{p=1}^{P} \left(IAPF_{fpb} Dem_{rp} \varphi g_{fdvrp} \right) \\
&+ \sum_{d=1}^{D} \sum_{w=1}^{V_2} \sum_{r=1}^{R} \sum_{p=1}^{P} \left(IAMD_{dp} Dem_{rp} \varphi z_{dv'rp} \right) \\
&+ \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{f=1}^{F} (IADF_{dvf} DisD_{Fdf} \varphi X_{dvf} + IAFD_{dvf} DisF_{Ddf} \varphi X''_{dvf}) \\
&+ \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{f=1}^{F} \sum_{f=1}^{F} (IAFF_{vff'} DisF'_{Fff'} \varphi X'_{dvff'}) \\
&+ \sum_{d=1}^{D} \sum_{v'=1}^{V_2} \sum_{r=1}^{R} (IADR_{dv'r} DisD_{Rdr} \varphi Y_{dv'r} + IARD_{dv'r} DisD_{Rdr} \varphi Y''_{dv'r}) \\
&+ \sum_{d=1}^{D} \sum_{v'=1}^{V_2} \sum_{r=1}^{R} \sum_{r'=1}^{R} (IARR_{v'rr'} DisR'_{Rrr'} \varphi Y'_{dv'rr'})
\end{aligned}
\tag{2}
$$

Subject to.

$$W * R_d \geq \sum_{f=1}^{F} \sum_{v=1}^{V_1} \sum_{r=1}^{R} \sum_{p=1}^{P} g_{fdvrp}, \forall\, d = 1, \ldots, D \tag{3}$$

$$\sum_{f=1}^{F} X_{dvf} \leq 1, \forall\, d = 1, \ldots, D; v = 1, .., V_1 \tag{4}$$

$$z_{dv'rp} \leq Y_{dv'r} + \sum_{r'=1}^{R} Y'_{dv'r'r}, \forall\, d = 1, \ldots, D; \\ v' = 1, \ldots, V_2; r = 1, \ldots, R; p \in P_r \tag{5}$$

$$\sum_{f=1}^{F} \sum_{f'=1}^{F} X'_{dvff'} \leq W * \sum_{f=1}^{F} X_{dvf}, \forall\, d = 1, \ldots, D; v = 1, \ldots, V_1 \tag{6}$$

$$\sum_{r=1}^{R} \sum_{r'=1}^{R} Y'_{dv'r'r} \leq W * \sum_{r=1}^{R} Y_{dv'r}, \forall\, d = 1, \ldots, D; v' = 1, .., V_2 \tag{7}$$

$$X_{dvf} + \sum_{f'=1}^{F} X'_{dvf'f} = \sum_{f'=1}^{F} X'_{dvff'} \\ + X''_{dvf}, \forall\, d = 1, \ldots, D; v = 1, .., V_1; f = 1, \ldots, F \tag{8}$$

$$Y_{dv'r} + \sum_{r'=1}^{R} Y'_{dv'r'r} = \sum_{r'=1}^{R} Y'_{dv'rr'} + Y''_{dv'r}, \\ \forall\, d = 1, \ldots, D; v' = 1, .., V_2; r = 1, \ldots, R \tag{9}$$

$$\sum_{d=1}^{D} X_{dvf} \leq 1, \forall\, v = 1, \ldots, V_1; f = 1, \ldots, F \tag{10}$$

$$\sum_{d=1}^{D} Y_{dv'r} \leq 1, \forall\, v' = 1, \ldots, V_2; r = 1, \ldots, R \tag{11}$$

$$X'_{dvff'} + X'_{dvf'f} \leq 1, \forall\, v = 1, \ldots, V_1; \\ f = 1, \ldots, F; f' = 1, \ldots, F; d = 1, \ldots, D \tag{12}$$

$$Y'_{dv'rr'} + Y'_{dv'r'r} \leq 1, \forall\, v' = 1, \ldots, V_2; r = 1, \ldots, R; \\ r' = 1, \ldots, R; d = 1, \ldots, D \tag{13}$$

$$g_{fdvrp} \leq X_{dvf} + \sum_{f'=1}^{F} X'_{dvf'f}, \forall; d = 1, \ldots, D; \\ v = 1, .., V_1; f = 1, \ldots, F; r = 1, \ldots, R; p \in P_r \tag{14}$$

$$z_{dv'rp} \leq Y_{dv'r} + \sum_{r'=1}^{R} Y'_{dv'r'r}, \forall d = 1, \ldots, D; \\ v' = 1, \ldots, V_2; r = 1, \ldots, R; p \in P_r \tag{15}$$

$$\sum_{f=1}^{F} \sum_{v=1}^{V_1} g_{fdvrp} = \sum_{v'=1}^{V_2} z_{dv'rp}, \forall\, d = 1, \ldots, D; r = 1, \ldots, R; p \in P_r \tag{16}$$

$$\sum_{f=1}^{F} \sum_{d=1}^{D} \sum_{v=1}^{V_1} g_{fdvrp} = 1, \forall\, r = 1, \ldots, R; p \in P_r \tag{17}$$

$$\sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{r=1}^{R} \mathrm{Dem}_{rp} g_{fdvrp} \leq \\ \sum_{b=1}^{B} QPF_{fbp}, \forall\, f = 1, \ldots, F; p \in P_r \tag{18}$$

$$\sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{p=1}^{P} \lambda \mathrm{P_p} \mathrm{Dem}_{rp} g_{fdvrp} \leq \\ QVED_{dv}, \forall\, d = 1, \ldots, D; v = 1, \ldots, V_1 \tag{19}$$

$$\sum_{r=1}^{R} \sum_{p \in \mathrm{P}_r} \lambda \mathrm{P_p} \mathrm{Dem}_{rp} z_{dv'rp} \leq \\ QVSD_{dv'}, \forall\, d = 1, \ldots, D; v' = 1, \ldots, V_2 \tag{20}$$

$$HLF_{dvf} = \left(t'_{dv} + \frac{DisD\_F_{df}}{VMVED_{dv}} \right) X_{dvf} \\ + \sum_{f'=1}^{F} \left(\theta_{dvf'} + \frac{DisF'\_F_{f'f}}{VMVED_{dv}} \right) X'_{dvf'f}, \\ \forall\, d = 1, \ldots, D; v = 1, \ldots, V_1; f = 1, \ldots, F \tag{21}$$

$$HLR_{dv'r} = \left(t_{dv'} + \frac{DisD\_R_{dr}}{VMVSD_{dv'}} \right) Y_{dv'r} \\ + \sum_{r'=1}^{R} \left(\theta'_{dv'r'} + \frac{DisR\_R'_{r'r}}{VMVSD_{dv'}} \right) Y'_{dv'r'r}, \forall\, d = 1, \ldots, D; \\ v' = 1, \ldots, V_2; r = 1, \ldots, R \tag{22}$$

$$VEF_{dvf} = HLF_{dvf} - HTF_{dvf} \left(X_{dvf} + \sum_{f'=1}^{F} X'_{dvf'f} \right), \\ \forall\, d = 1, \ldots, D; v = 1, \ldots, V_1; f = 1, \ldots, F \tag{23}$$

$$VER_{dv'r} = HLR_{dv'r} - HTR_{dv'r} \left(Y_{dv'r} + \sum_{r'=1}^{R} Y'_{dv'r'r} \right), \\ \forall\, d = 1, \ldots, D; v' = 1, \ldots, V_2; r = 1, \ldots, R \tag{24}$$

$$VRF_{dvf} = HUF_{dvf} \left(X_{dvf} + \sum_{f'=1}^{F} X'_{dvf'f} \right) - HLF_{dvf}, \\ \forall\, d = 1, \ldots, D; v = 1, \ldots, V_1; f = 1, \ldots, F \tag{25}$$

$$VRR_{dv'r} = HUR_{dv'r} \left(Y_{dv'r} + \sum_{r'=1}^{R} Y'_{dv'r'r} \right) - HLR_{dv'r}, \\ \forall\, d = 1, \ldots, D; v' = 1, \ldots, V_2; r = 1, \ldots, R \tag{26}$$

$$\theta_{dvf} = HLF_{dvf} + \sum_{r=1}^{R} \sum_{p \in \mathrm{P}_r} TCF_{dvfp} \mu \mathrm{Dem}_{rp} g_{fdvrp}, \\ \forall\, d = 1, \ldots, D; v = 1, \ldots, V_1; f = 1, .., F \tag{27}$$

$$\Psi_{dv} = \sum_{f=1}^{F} \left(\left(\theta_{dvf} + \frac{DisF\_D_{df}}{VMVED_{dv}} \right) X''_{dvf} + \sum_{r=1}^{R} \sum_{p \in P_r} TDD_{dvp} \mu Dem_{rp} g_{fdvrp} \right), \forall\, d = 1, \dots, D; v = 1, \dots, V_1 \tag{28}$$

$$t_{dv'} \geq z_{dv'rp} \sum_{f=1}^{F} \sum_{v=1}^{V_1} \Psi_{dv} g_{fdvrp} \\ + \sum_{r'=1}^{R} \sum_{p' \in P_r} TCD_{dv'p'} \mu Dem_{r'p'} Z_{dv'r'p'}, \\ \forall\, d = 1, \dots, D; v' = 1, \dots, V_2; r = 1, .., R; p \in P_r \tag{29}$$

$$HLD_{dv'} = \sum_{r=1}^{R} \left(\theta'_{dv'r} + \frac{DisD\_R_{dr}}{VMVSD_{dv'}} \right) Y''_{dv'r}, \\ \forall\, d = 1, \dots D; v' = 1, \dots, V_2 \tag{30}$$

$$\theta'_{dv'r} = HLR_{dv'r} + \sum_{p \in P_r} TDR_{dv'rp} \mu Dem_{rp} Z_{dv'rp}, \\ \forall\, d = 1, \dots, D; v' = 1, \dots, V_2; r = 1, .., R \tag{31}$$

$$c \sum_{f=1}^{F} \sum_{d=1}^{D} \sum_{v=1}^{V_1} \sum_{v'=1}^{V_2} \\ \left(t_{dv'} - \Psi_{dv} - \sum_{r'=1}^{R} \sum_{p' \in P_r} TCD_{dv'p'} \mu Dem_{r'p'} Z_{dv'r'p'} \right) \\ g_{fdvrp} Z_{dv'rp} \leq W * a_{rp}, \forall\, r = 1, \dots, R; p \in P_r \tag{32}$$

$$\sum_{f=1}^{F} \sum_{v=1}^{V_1} \sum_{r=1}^{R} \sum_{p \in P_r} \lambda P_p Dem_{rp} g_{fdvrp} a_{rp} \\ - \sum_{v'=1}^{V_2} \sum_{r=1}^{R} \sum_{p \in P_r} \lambda P_p Dem_{rp} Z_{dv'rp} a_{rp} \leq QD_d, \forall\, d = 1, \dots, D \tag{33}$$

$$\sum_{r=1}^{R} \left(\theta'_{dv'r} + \frac{DisD\_R_{dr}}{VMVSD_{dv'}} \right) Y''_{dv'r} \leq HT, \\ \forall\, d = 1, \dots, D; v' = 1, \dots, V_2 \tag{34}$$

The mathematical formulation aims to minimize the total logistics costs of the perishable food supply chain, and Eq. (1) is the cornerstone of this approach. The first term accounts for the cost of opening the cross-docks, while the second and third terms represent the transport costs in the first echelon. The fourth and fifth terms, on the other hand, refer to transport costs in the second echelon. The sixth and seventh terms signify the penalty costs incurred if the suppliers' and retailers' time window constraints are violated, respectively. Lastly, the eighth term represents the cost of product acquisition and handling in the cross-dock.
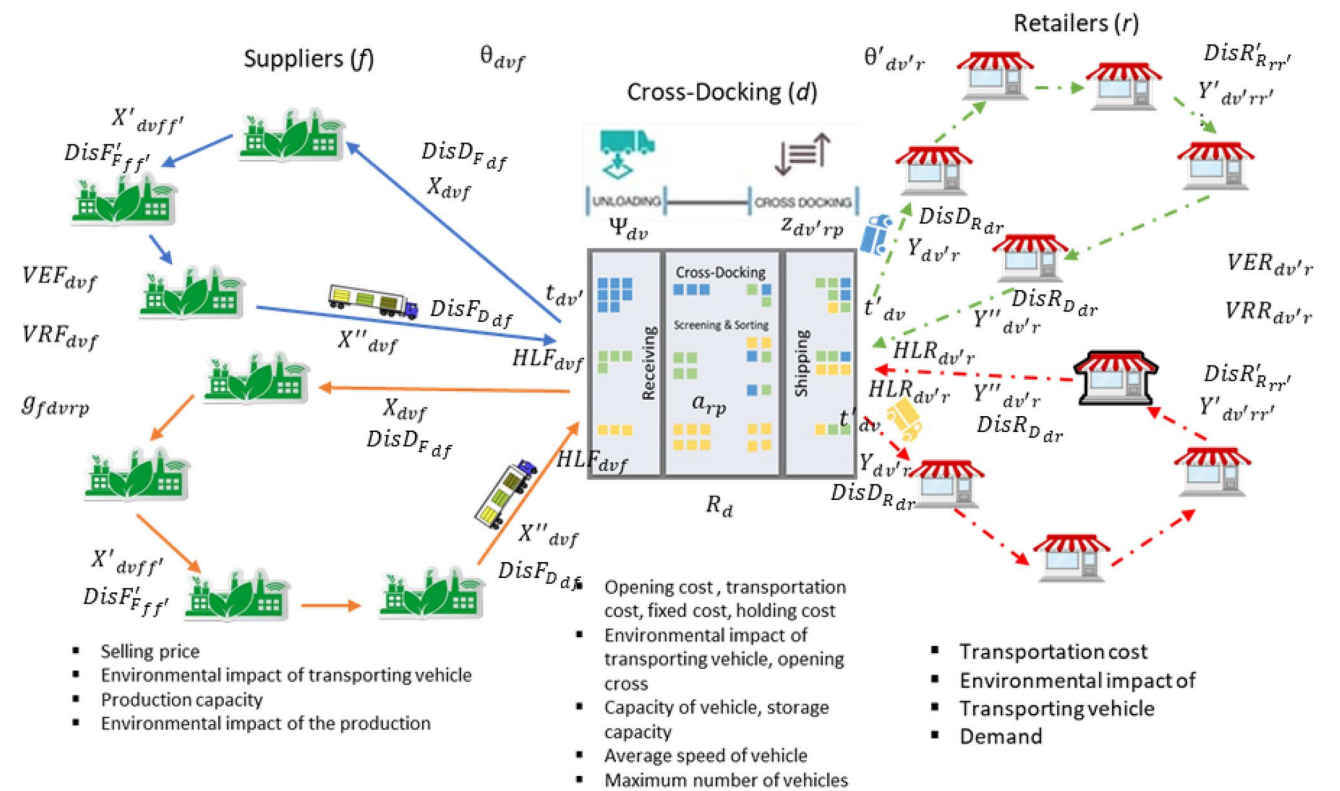

Fig. 3 Mathematical Model of Cross-Docking system for the perishable food supply chain

Table 3 Weights of the objective functions of the mathematical model

Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CTLOG	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1
CTIA	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9

Equation (2) aims to minimize the environmental costs of carbon footprints and greenhouse gas emissions. The objective function is composed of seven terms. The first term quantifies the environmental impact associated with the opening of the cross-dock. The second term is the sum of the environmental impacts resulting from the operating activities of the manufacturers. The third term represents the environmental impact of handling a product unit at the cross-dock. The fourth and fifth terms correspond to the environmental impacts of transport in the first echelon. Finally, the sixth and seventh terms quantify the environmental impacts of transport in the second echelon.

The constraints of the mathematical model are classified into four groups. The first group is related to the location of the facilities (Eq. 3). The second group is related to routing inbound and outbound vehicles (Eqs. 4–20). The third group of restrictions is related to verifying the compliance of the time windows allocated to each vehicle in both echelons (Eqs. 21–31). Finally, the fourth group is related to the operations carried out in the cross-docking system (Eqs. 32–34).

Equation (3) limits the maximum number of open and used cross-docks. Equations (4) and (5) ensure that each cross-dock inbound and outbound vehicle will visit a supplier and retailer at the beginning of their tour. Equations (6) and (7) indicate that the starting point of each vehicle route in the first and second echelon is associated with the cross-dock, and each vehicle visits suppliers or retailers only if they leave the cross-dock d. Equations (8) and (9) ensure the route's continuity in the first and second echelons; if a vehicle arrives at a supplier or retailer, it must leave that manufacturer or retailer.

Equations (10) and (11) ensure that each inbound and outbound vehicle visits a supplier or retailer from a single cross-dock d. Equations (12) and (13) imply that an inbound or outbound vehicle of a cross-dock d will only visit or leave a supplier f' or retailer r' maximum once, respectively. Equation (14) guarantees that each product is received from a supplier f by only one inbound vehicle if the inbound vehicle v visits supplier f. Equation (15) guarantees that each product is delivered to a retailer r by only one outbound vehicle v' if the outbound vehicle v' visits that retailer r. Equation (16) balances the flow of each product p through each cross-dock d.

Equation (17) ensures that the total demand for each retailer's product must be assigned to a single manufacturer f and a cross-dock d and transported by only one inbound v and outbound v' vehicle. Equation (18) implies that the total quantity of each product provided by a supplier f does not exceed the supplier's maximum capacity of product p. Equations (19) and (20) ensure that the total demand for the products transported in inbound and outbound vehicles does not exceed their capacity.

Equations (21) and (22) determine the arrival time of each inbound v and outbound v' vehicle of cross-dock d to the supplier and retailer, respectively. Equations (23) and (24) determine the waiting time of the inbound vehicle v and outbound v' if they arrive before the earliest time window established by the supplier and retailer, respectively. Equations (25) and (26) determine the lateness time of the inbound v and outbound v' vehicles if they arrive after the latest time window established by the supplier and retailer, respectively. Equation (27) determines the departure time of each inbound v vehicle of cross-dock d from each supplier f. Equation (28) determines the finish time of the unloading operation of each inbound vehicle v in cross-dock d.

Equation (29) indicates the dependence of the outbound vehicles on the inbound vehicles and ensures that each outgoing vehicle cannot leave its cross-dock d unless the load has been completed. Equation (30) determines the arrival time of each outbound vehicle to the retailer r. Equation 31 determines the departure time of each outbound vehicle v' of cross-dock d from each retailer r. Equation (32) checks if the products are temporarily stored in the cross-dock d.

Table 4 Parameter values associated with coastal cheese suppliers

F	P	B	The capacity of production (Kg)	Environmental impact (Ton CO_2 eq./ Kg)	Unit Price ($ COP)
f1	p1	b1	-	-	-
		b2	-	-	
	p2	b1	1000	0.05044	7500
		b2	-	-	
f2	p1	b1	600	0.04664	8000
		b2	-	-	
	p2	b1	600	0.04764	8000
		b2	-	-	
f3	p1	b1	-	-	9200
		b2	685	0.05506	
	p2	b1	-	-	-
		b2	-	-	

Supplier (F), product (P), type of technology (B), kneaded coastal cheese (p1), chopped coastal cheese (p2), artisanal process (B1), industrial process (B2)

Table 5 The demand of coastal cheese retailers of the department of Sucre

Retail	Product	Demand (Kg)
r1	p1	150
	p2	100
r2	p1	135
	p2	30
r3	p1	333
	p2	850

Equation 33 is required to continuously check the viability of the capacity of each cross-dock *d*. Equation (34) implies that pick-up, cross-docking and delivery processes must be performed during the time horizon *HT*. Figure 3 shows a general scheme of the proposed mathematical model with its respective parameters and variables.

4 Results

The feasibility of the proposed mathematical model is evaluated regarding solution quality through tests using a real application case in this section. The methodology adopted two optimization methods, Pareto optimization and weighted sums. Initially, weights are assigned to each objective function (CTLOG and CTIA), and 17 tests are conducted with a variation of 0.05, as shown in Table 3. In this case, the minimum values for each objective function for the Pareto optimum are prioritized. The problem is formulated as a mixed-integer non-linear multi-objective model (MINLP) and programmed in the Gams 23.6.5 programming language using the DICOPT solver.

4.1 Real application case: coastal cheese supply chain in the department of Sucre, Colombia

The mathematical model solution for the case study in the city of Sincelejo (Sucre, Colombia) aims to identify potential cross-docks and optimize cost-effective and environmentally friendly routes for collecting two types of coastal cheese (mixed from curd and chopped) from various municipalities

in the Sucre department. These cheeses are then delivered to vendors in Sincelejo and nearby cities.

Therefore, the scenario chosen to validate the mathematical model is composed of three suppliers (F), two types of technology (B), two potential cross-docks (D), three retailers (R), two products (P), two inbound vehicles (v), and two outbound vehicles (v′). The input data required for the suppliers and retailers related to the product type are presented in Tables 4 and 5, respectively. To calculate the environmental impact of the production of each supplier, expressed in the carbon footprint, the SIMAPRO software and the ReCiPe Midpoint method are utilized, with a functional unit of 1 kg of coastal cheese in the production process.

The two possible locations for the cross-docks in the department of Sucre are determined by considering the origins of the demand, the suppliers, the means of transport, and their capabilities (see Table 5) (Kalenatic et al. 2008). The associated parameters, such as costs and environmental impacts of opening, capacity, and storage costs for the two types of coastal cheese, as well as the environmental impact associated with their management, are shown in Table 6. At the operational level, each cross-dock has a time horizon (HT) of 960 min, which spans from 3:00 a.m. to 7:00 p.m. Regarding loading and unloading times for each inbound and outbound vehicle, expert personnel in the cheese industry in Cartagena (Bolívar) have indicated that these operations for this type of product are given at a rate of 20 kg per 0.6 min, such that each kg of the product takes 0.03 min, considering only human personnel. In this regard, the environmental impact of handling the two types of coastal cheese within each cross-dock is negligible.

Parameters related to the distance traveled between cross-dock and supplier ($DisD_{Fdf}$), distance traveled between supplier and cross-dock ($DisF_{Ddf}$), distance traveled between suppliers ($DisF'_{Fff'}$), distance traveled between cross-dock and retailer ($DisD_{Rdr}$), distance traveled between retailers and cross-dock ($DisR_{Ddr}$), distance traveled between retailers ($DisR'_{Rrr'}$) are given in Tables 7, 8 and 9.

The fleet of vehicles for each coastal cheese supply chain echelon is configured with van-type trucks. Each vehicle has an average speed of one kilometer per minute, and the capacity of each vehicle is as follows: v1 (1.5

Table 6 Parameter values associated with possible cross-docks in the Department of Sucre

Cross-dock	Opening cost ($ COP)	Opening environmental impact (Ton CO_2)	Storage capacity	Product	Storage cost ($ COP/Kg)	Environmental impact (Ton CO_2)
d1	350,000,000	1.6	5000	p1	27	-
				p2	27	-
d2	300,000,000	1.3	4000	p1	26	-
				p2	26	-

Table 7 Distance between cross-dock, suppliers, y retailers

Cross-dock	DisD_F Supplier			DisD_R Retailer			Cross-dock	DisF_D Supplier			DisR_D Retailer		
	f1	f2	f3	r1	r2	r3		f1	f2	f3	r1	r2	r3
d1	37	53.1	4.5	4.3	3.8	176	d1	37	53.7	4.5	3.8	3.3	176
d2	38.6	54.8	2.4	4.0	1.8	173	d2	38.6	55.4	2.4	4.0	1.8	173

Table 8 Distance between selected coastal cheese suppliers

Suppliers	f1	f2	f3
f1	-	16.7	41
f2	16.7	-	57.8
f3	41	57.2	-

Table 9 Distance between selected coastal cheese retailers

Retailers	r1	r2	r3
r1	-	2.3	175
r2	2.3	-	177
r3	175	177	-

tons), v2 (2.0 tons), v'1 (1.5 tons), v'2 (2.0 tons). The fixed costs of each vehicle are as follows: v1 ($52,626), v2 ($59,376), v'1 ($90,403), and v'2 ($97,153). The cost per transport unit is as follows: v1 ($269.2/km), v2 ($284.4/km), v'1 ($269.2/km), and v'2 ($284.4/km). Regarding the penalization costs for waiting and lateness in each node, when cost per time information is not available, uniform distributions are used, as indicated by Govindan et al. (2014), with PEF (U(1,5)), PER (U(1,5)), PRF (U(5,10)), and PRR (U(5,10)).

The environmental impact of transportation, as stipulated by DECC (2011) and taking into account that the fuel consumed is diesel/ACPM, is as follows: v1 (0.000226 Ton CO_2 per km), v2 (0.000270 Ton CO_2 per km), v'1 (0.000226 Ton CO_2 per km), v'2 (0.000270 Ton CO_2 per km). However, the inbound vehicles in the first echelon have a working time of 8 h (480 min), while in the second echelon, the working time includes 16 h (960 min). Furthermore, for planning vehicle routes in each coastal cheese

supply chain echelon, time windows are indicated for each supplier and retailer, including the earliest and latest time expressed in minutes (see Table 10).

5 Analysis of results

The results of each test presented in Table 11 enable the construction of the Pareto frontier consisting of the non-dominated solutions of tests p1, p6, p7, and p17 (Fig. 3).

Using the multicriteria solution methodology for the multi-objective problem, the solution for the total minimum cost ($34,184,197) is obtained with a relative distribution of 0.1 for the CTLOG objective and 0.9 for the CTIA objective. However, due to the significant cost difference between these two objectives, a more thorough analysis is conducted on the results obtained for each problem and non-dominated solutions to reduce the biases generated by this condition. Among the non-dominated solutions that comprise the Pareto frontier, the solution from test p7 is selected and run with relative weights of 0.6 for the CTLOG objective and 0.4 for the CTIA objective. The value obtained for the CTLOG objective is $316,609,660, which is the lowest among all the problems, and the value obtained for the CTIA objective is $2,058,180. The defined weights for each objective are considered to generate routes at a minimum cost, which are also environmentally friendly, to reduce the environmental impact of the costeño cheese production chain in the Sucre department. The results of the mathematical model solution from test p7 are analyzed in greater detail and are presented below (Fig. 4).

Table 10 Time windows of suppliers and retailers for inbound and outbound vehicles

Time Windows													
Cross-dock	Inbound vehicle	Earliest time			Latest time			Outbound vehicle	Earliest time			Latest time		
		f1	f2	f3	f1	f2	f3		r1	r2	r3	r1	r2	r3
d1	v1	60	0	60	240	120	240	v'1	120	240	240	180	480	540
	v2	60	0	60	240	120	240	v'2	120	240	240	180	480	540
d2	v1	60	0	60	240	120	240	v'1	120	240	240	180	480	540
	v2	60	0	60	240	120	240	v'2	120	240	240	180	480	540

Table 11 Numerical results for the analysis of the weighted sum method.

Test	CTLOG ($ COP)	Beta	CTIA	(1 - Beta)	BB	Test	CTLOG ($ COP)	Beta	IA (Ton. CO2 eq)	(1 - Beta)
p1	317,628,750	0.9	2,023,140	0.1	286,068,189	p1	317,628,750	0.9	809,256	0.1
p2	689,634,630	0.85	2,063,650	0.15	586,498,983	p2	689,634,630	0.85	825,46	0.15
p3	338,067,110	0.8	2,054,660	0.2	270,864,620	p3	338,067,110	0.8	821,864	0.2
p4	323,059,440	0.75	2,054,710	0.25	242,808,258	p4	323,059,440	0.75	821,884	0.25
p5	323,377,950	0.7	2,054,440	0.3	226,980,897	p5	323,377,950	0.7	821,776	0.3
p6	325,687,190	0.65	2,016,620	0.35	212,402,491	p6	325,687,190	0.65	806,648	0.35
p7	316,609,660	0.6	2,023,080	0.4	190,775,028	p7	316,609,660	0.6	809,232	0.4
p8	683,591,370	0.55	2,107,720	0.45	376,923,728	p8	683,591,370	0.55	843,088	0.45
p9	340,566,560	0.5	2,022,910	0.5	171,294,735	p9	340,566,560	0.5	809,164	0.5
p10	406,696,100	0.45	2,030,660	0.55	184,130,108	p10	406,696,100	0.45	812,264	0.55
p11	322,950,840	0.4	2,058,180	0.6	130,415,244	p11	322,950,840	0.4	823,272	0.6
p12	368,020,470	0.35	2,023,140	0.65	130,122,206	p12	368,020,470	0.35	809,256	0.65
p13	337,921,100	0.3	2,023,120	0.7	102,792,514	p13	337,921,100	0.3	809,248	0.7
p14	700,931,890	0.25	2,165,790	0.75	176,857,315	p14	700,931,890	0.25	866,316	0.75
p15	398,890,790	0.2	2,030,450	0.8	81,402,518	p15	398,890,790	0.2	812,18	0.8
p16	367,900,110	0.15	2,023,080	0.85	56,904,635	p16	367,900,110	0.15	809,232	0.85
p17	323,687,710	0.1	2,017,140	0.9	34,184,197	p17	323,687,710	0.1	806,856	0.9

Figure 5 illustrates that only cross-dock d2 is in Sincelejo, which shows lower values for the considered parameters than cross-dock d1. For the transportation of products to suppliers and retailers, two inbound and outbound vehicles are required. Table 12 presents the capacities and utilization of these vehicles and the values of the variables g and z. The values assigned to these two variables correspond to the routes of each vehicle and the nodes visited, as depicted in Fig. 5.

Then, the results of the variables related to the operational activities of the inbound and outbound vehicles and the cross-dock are as follows: In the first echelon, the departure time of the inbound vehicles from the cross-dock (t'), the arrival time of the inbound vehicle at suppliers (HLF),

from the cross-dock or any supplier, waiting time (VEF) and lateness time (VRF) of the inbound vehicle in the supplier, departure time of the inbound vehicle from the supplier (θ), and finish time of unloading operation of the inbound vehicle in the cross-dock (Ψ) are presented. Additionally, travel times between each node (TR) and the time windows of each supplier (HTF and HUF) are shown to corroborate the results of the variables (see Table 11).

In the second echelon, the variables related to the operational activities of the outbound vehicle and the retailers are as follows: the departure time of the outbound vehicle from the cross-dock (t), the arrival time of the outbound vehicle to the retailer (HLR) from the cross-dock or any retailer, waiting time (VER) and lateness time (VRR) of the outbound vehicle

Fig. 4 Pareto Frontier of mathematical model solutions for the actual application case
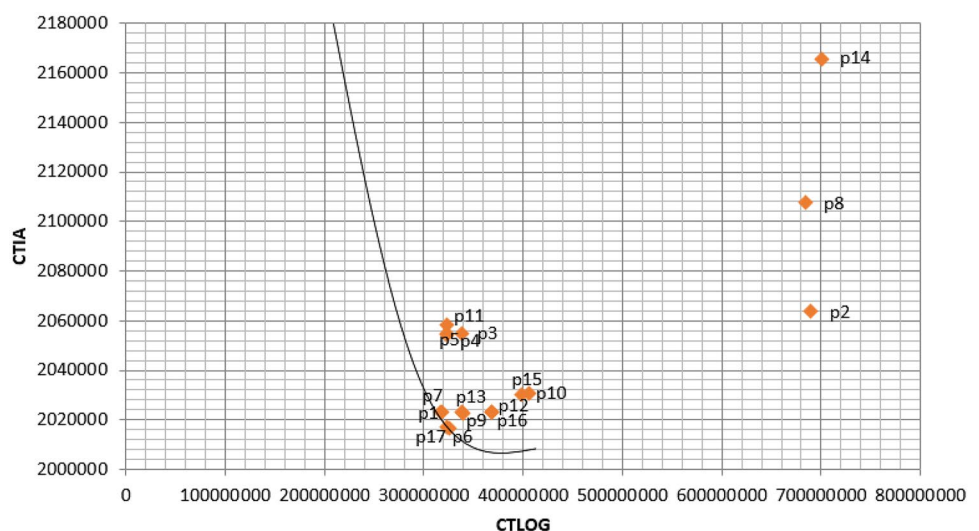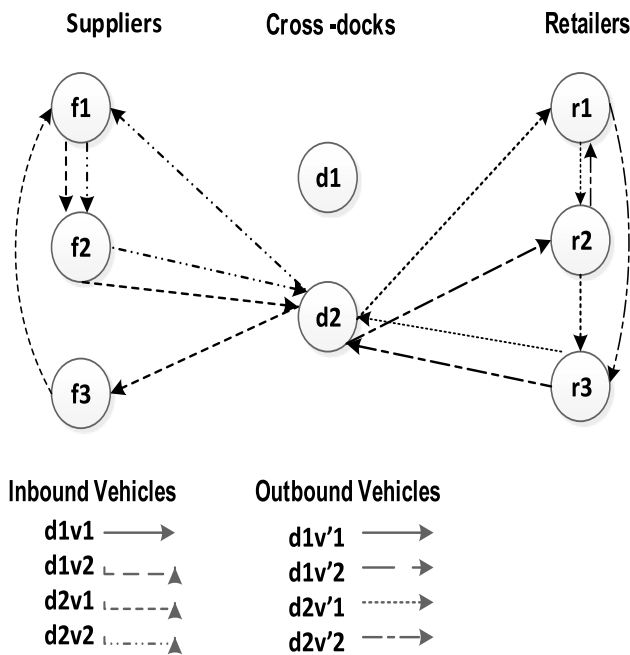
Fig. 5 Solution of the mathematical model for the real application case

at each retailer, departure time of the outbound vehicle from the retailer (θ') and the return time of the outbound vehicle to the cross-dock (HLD), which are shown in Table 11. Similarly, it is possible to observe the travel times between each node (TR) and the earliest (HTR) and latest (HUR) time windows at each retailer to verify the values of the variables obtained.

Table 12 Numerical results for the analysis of the weighted sum method

| CTLOG	Beta	CTIA	Beta
316,609,660	0.6	806,648	0.35
317,628,750	0.9	806,856	0.9
322,950,840	0.4	809,164	0.5
323,059,440	0.75	809,232	0.4
323,377,950	0.7	809,232	0.85
323,687,710	0.1	809,248	0.7
325,687,190	0.65	809,256	0.1
337,921,100	0.3	809,256	0.65
338,067,110	0.8	812,180	0.8
340,566,560	0.5	812,264	0.55
367,900,110	0.15	821,776	0.3
368,020,470	0.35	821,864	0.2
398,890,790	0.2	821,884	0.25
406,696,100	0.45	823,272	0.6
683,591,370	0.55	825,460	0.15
689,634,630	0.85	843,088	0.45
700,931,890	0.25	866,316	0.75

Table 13 shows that the variable values obtained confirm that each supplier's product demands are picked up by the inbound vehicle assigned and delivered to each retailer by the outbound vehicle, following the pre-determined routes and through a single cross-dock, satisfying the assumption of a single supply approach. Additionally, it is observed that waiting times are encountered in the first echelon by vehicle v1 at supplier f3 and vehicle v2 at supplier f1. In the second echelon, waiting times are encountered by vehicle v′1 at retailer r2, and both waiting and lateness times are observed for vehicle v′2 at retailers r2 and r1. It is important to note that although penalties were incurred, some are influenced by limited time windows at specific nodes (time horizon—960 min).

Finally, the best solution is reported by the p7 test, representing 60% of the objective function of total logistics costs and 40% of the total environmental cost function. Finally, the p7 test reports the best solution, representing 60% of the total logistics cost objective function and 40% of the total environmental cost function. The results show the complete compliance of the routes with total synchronization in the cross-docking system, which allows for no inventory generation. This favors the transit of perishable products through cross-docking, especially when considering the synchronization in the loading system of the outgoing vehicles to retailers. The defined routes guarantee operation on a typical day of system operation and the operability and availability of the vehicles involved. For collection from suppliers and delivery to retailers, two inbound and two outbound vehicles are necessary. Therefore, the opening of a cross-docking structure and the efficient scheduling of vehicle routes are viable options to improve sustainable distribution activities for cheese produced in the Sucre department, considering the economic and environmental benefits and thus contributing to environmental conservation. The results indicated that to supply the total demand of retailers with three suppliers, only the d2 cross-dock located in the city of Sincelejo should be opened. Table 14 detects a minor penalty for violating a time window. However, this is justifiable because its elimination would imply using a more extensive fleet of vehicles, thus increasing the operational costs.

The problem of designing a distribution network with a direct transit system to transport perishable products, consolidating them in heterogeneous trucks that guarantee supply to meet market demands at the correct times, is one of the most critical factors in achieving competitive advantage in food supply chains. One of the essential approaches to address this is the consideration of setting up cross-docking systems as a distribution strategy with one or more cross-docks where products received from inbound vehicles with the same destinations are sorted, consolidated, and loaded immediately into outbound vehicles to be delivered to customers through effective vehicle routing structures, where sustainability principles are considered. While cross-docking

Table 13 Results of the vehicles used and the variables g and z associated with the first and second echelons.

Cross-dock	Echelon	Vehicle	Capacity (Kg)	Use (Kg)	G	z
d2	First Second	v1	1500	598	f1.d2.v1.r1.p2 f1.d2.v1.r2.p2 f2.d2.v1.r3.p1 f3.d2.v1.r2.p1	
		v2	2000	1000	f1.d2.v2.r3.p2 f2.d2.v2.r1.p1	
		v′1	1500	980		d2.v′1.r1.p2 d2.v′1.r2.p2 d2.v′1.r3.p2
		v′2	2000	618		d2.v′2.r1.p1 d2.v′2.r2.p1 d2.v′2.r3.p1

is an economical distribution strategy for various situations, linking them in the distribution of perishable products helps minimize the total transportation cost and increase customer satisfaction through faster and timely shipments.

The result section of the study provides an overview of the solution obtained by solving the distribution network problem. It suggests that setting up a cross-docking system is a viable option to improve the sustainable distribution activities of coastal cheese produced in the department of Sucre. The results show that opening a cross-docking structure and efficient programming of vehicle routes can help minimize the total transportation cost and increase customer satisfaction through faster and timely shipments. Cross-docking is a distribution strategy involving transferring products from inbound to outbound vehicles with minimal handling and storage time. By consolidating and sorting products in a central facility, cross-docking helps minimize the cost of inventory holding and handling, thus reducing logistics costs. Additionally, the quick transfer of products through a single point helps improve transportation efficiency, reducing the

time and cost required to move products from one location to another. Cross-docking is an effective strategy to optimize distribution networks and achieve a competitive advantage in the food supply chain industry.

As Castellucci et al. (2021) proposed, cross-docking systems contribute to the elimination or reduction of storage and order picking as costly and high-risk activities in the life cycle of products in food product distribution networks. In this sense, it is clear how the consideration of cross-docking systems reduces storage costs and delivery times to customers by synchronizing loading and unloading activities. Theophilus et al. (2021) proposed that although cross-docking systems have been widely used in supply chains for product distribution, they had not received adequate attention in the distribution of perishable products, which is why they developed a new mixed-integer programming mathematical formulation for optimizing vehicle scheduling in a cold chain using cross-docking systems, with the sole aim of minimizing the total cost incurred during vehicle service.

Table 14 Results of the vehicles used and the variables g and z associated with the first and second echelons

Cross-dock	Echelon	Inbound vehicle	t′ (min)	TR (min)	Supplier	HLF (min)	HTF (min)	HUF (min)	VEF (min)	VRF (min)	θ (min)	Ψ (min)
d2	First	v1	24.6	2.4	f3	27.0	60	240	33.0	-	31.1	176.0
				41	f1	72.1	60	240	-	-	76.0	
				16.7	f2	92.7	0	120	-	-	102.7	
		v2	5.3	38.6	f1	43.9	60	240	16.1	-	69.4	176.0
				16.7	f2	86.1	0	120	-	-	90.6	
		Outbound vehicle	**T (min)**	**TR (min)**	**Retailer**	**HLR (min)**	**HTR (min)**	**HUR (min)**	**VER (min)**	**VRR (min)**	**θ′ (min)**	**HLD (min)**
	Second	v′1	176.0	3.8	r1	180.0	120	180	-	-	183.0	561.7
				2.3	r2	185.3	240	480	54.7	-	186.2	
				177	r3	363.2	240	540	-	-	388.7	
		v′2	176.0	1.8	r2	177.8	240	480	62.2	-	181.9	546.6
				2.3	r1	184.2	120	180	-	4.2	188.7	
				175	r3	363.7	240	540	-	-	373.6	

6 Conclusions

In conclusion, this study contributes significantly to the literature on vehicle routing and state-of-the-art in the following ways. Firstly, it proposes a novel mixed-integer mathematical formulation for multi-objective optimization of the vehicle routing-location problem with time windows and cross-docking systems in the supply chain of perishable goods. Unlike previous studies on vehicle routing with cross-docking structures, this model incorporates environmental impacts generated using vehicles as a decision-making criterion for cross-docking location. Secondly, the study models storage areas, reducing the maximum area for the temporary storage of perishable products at each cross-dock. This guarantees that products are ordered to prevent expiration during storage, minimizing the costs associated with additional transportation, loading, and unloading operations. The model also considers the use of heterogeneous fleets of vehicles with different types, speeds, and fixed and variable costs, resulting in more realistic routing structures that align with real-world conditions.

Furthermore, the model's validation through an application case in Sucre's coastal cheese supply chain department demonstrates that cross-docking structures and efficient vehicle routing could contribute significantly to sustainable distribution activities while considering economic and environmental benefits. The proposed mixed-integer model generates optimal Pareto solutions by simultaneously optimizing logistical and environmental costs using multicriteria decision theory mathematical techniques such as the weighted sum method. Future research could consider using metaheuristics to solve more significant problems and explore alternative decision-making criteria. Overall, this study presents one of the most comprehensive representations of reality in the vehicle routing literature, making a significant contribution to optimizing supply chain activities for perishable goods.

The model used in this study is quite complex, as it involves many variables and parameters. The problem being addressed is challenging, as it requires the optimization of multiple factors, including routing, location, and cross-docking. Designing an efficient distribution network to transport perishable goods involves considering several variables, such as supplier locations, demand locations, transportation costs, and environmental impact. To solve this complex problem, the study employs mathematical modeling techniques, such as mixed-integer linear programming (MILP), to develop an optimal solution. Despite the challenges posed by the complexity of the problem, the study provides valuable insights into the design of a sustainable and efficient distribution network.

6.1 Managerial implications

The proposed model for managing perishable food supply chains using a cooperative strategy and cross-docking platform has significant administrative implications and benefits for companies and organizations involved in the food industry. This section outlines the critical implications and benefits of implementing the proposed model in real-life scenarios. Below are some implications and benefits of the proposed model:

- Customized configurations for different products and territories to respond to specific characteristics: Companies should design tailor-made configurations that consider the particularities of each product and territory where they are produced and marketed. This involves analyzing demand, distance, production capacity, and transportation modes to optimize the supply chain.
- Optimization of logistics costs and carbon footprint: This refers to minimizing transportation, storage, and handling costs while reducing greenhouse gas emissions from the entire supply chain. This can be achieved by optimizing vehicle routes, reducing waiting times, and using more energy-efficient modes of transportation.
- Reduction of inventories and delivery time: By implementing a cross-docking platform, the proposed model enables companies to eliminate excessive storage and handling, thereby reducing inventories and delivery time. This leads to improved product quality and customer satisfaction.
- Reinforcement of control in distribution operations: The proposed model provides a more efficient and transparent way to manage distribution operations, enabling companies to have better control over their supply chain and reduce the risk of product spoilage or loss.
- Considering special handling requirements for perishable products with short cycles involves designing logistics processes that consider the specific handling requirements of perishable products with short cycles, such as maintaining temperature-controlled environments or reducing handling times.
- Incorporation of sustainability aspects related to energy consumption: The proposed model considers sustainability aspects related to energy consumption, such as using more energy-efficient modes of transportation or optimizing delivery routes to reduce carbon emissions.

Benefits:

- Increased operational efficiency: The proposed model enables companies to optimize their logistics processes, reduce waiting times, and eliminate excessive

storage and handling, leading to increased operational efficiency.

- Improved customer satisfaction: The proposed model enhances customer satisfaction by reducing delivery time and improving product quality, increasing loyalty and sales.
- Enhanced product quality and safety: By reducing handling times and using temperature-controlled environments, the proposed model improves product quality and safety, reducing the risk of spoilage or contamination.
- Reduced waste and losses: The proposed model enables companies to reduce waste and losses by eliminating excessive storage and handling and optimizing delivery routes.
- Increased competitiveness and market share: By improving operational efficiency, product quality, and customer satisfaction, the proposed model can increase a company's competitiveness and market share.
- Positive impact on the environment and society: The proposed model positively impacts the environment by reducing carbon emissions, contributing to a more sustainable and equitable food system.
- The proposed model offers a practical and sustainable solution for managing perishable food supply chains, benefiting companies and society. Its successful implementation requires a collaborative effort among stakeholders, including producers, distributors, retailers, and customers, as well as support from government agencies and regulatory bodies. By adopting the proposed model, companies can achieve their business objectives while contributing to a more sustainable and equitable food system.

Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any authors.

Competing interests The authors declare that they do not have any conflict of interest.

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