OmniaScience

Journal of Industrial Engineering and Management
JIEM, 2024 – 17(2): 463-491 – Online ISSN: 2013-0953 – Print ISSN: 2013-8423
https://doi.org/10.3926/jiem.7007

Considering Sustainability and Resilience in A Location-Routing Problem

Bruna Figueiredo*, Rui Borges-Lopes

Department of Economics, Management, Industrial Engineering and Tourism / CIDMA, University of Aveiro (Portugal)

**Corresponding author: bruna.figueiredo@ua.pt*
rui.borges@ua.pt

Received: November 2023
Accepted: May 2024

Abstract:

Purpose: Growing consumer and government awareness of environmental and social issues has been pushing companies to adopt more sustainable practices. In addition, due to the uncertainty characteristic of today's competitive environment, companies must deal with disruptions efficiently. Sustainability and resilience thus become two crucial considerations in the decision-making process of managers. Despite this, when looking at some classes of problems in literature, cost is still the most, or even the only, objective addressed. This paper proposes a new multi-objective Capacitated Location-Routing Problem (CLRP) which may help decision-makers analyze the impact of considering sustainability and resilience concerns on location and distribution decisions.

Design/methodology/approach: A multi-objective CLRP is addressed with the following objectives: minimization of the logistics network total cost, minimization of the environmental impact of CO_2 emissions, and maximization of the resilience of the distribution network. Aiming to explore the effect that designing a more sustainable and resilient distribution network can have on its operating costs, the ε-constraint method is applied to solve a set of instances based on real-world data.

Findings: Results show that when prioritizing emissions minimization, more vehicles carrying smaller payloads are generally used. Additionally, these solutions are not necessarily associated with shorter travel distances, underlining the influence of factors such as load and vehicle speed on fuel consumption. When focusing on maximizing network resilience usually a greater number of vehicles and facilities are used. Furthermore, findings suggest that costs are more sensitive to improvements in CO_2 emissions compared to resilience.

Originality/value: This paper is an exploratory study addressing a new CLRP which, besides the usual cost objective, considers sustainability and resilience as objectives. The paper evaluates the sensitivity of logistics networks cost to the improvement of their resilience and sustainability. A new multi-objective formulation is proposed and tested in instances based on real-world data. The paper may provide important managerial insights for designing sustainable and resilient logistics networks.

Keywords: logistics, location-routing, multi-objective, sustainability, resilience

To cite this article:

Figueiredo, B., & Borges-Lopes, R. (2024). Considering sustainability and resilience in a location-routing problem. *Journal of Industrial Engineering and Management*, 17(2), 463-491. https://doi.org/10.3926/jiem.7007

1. Introduction

Logistics plays a crucial and well-recognized role in meeting customers expectations. The proper design of a logistics network can contribute to its efficient and effective operation, ensuring the delivery of the right product in the right conditions, while meeting companies goals. Although the main goal of organizations is often to satisfy customers at the lowest possible cost, nowadays other objectives have gained relevance.

In the latter half of the 20th century, the demand for different products grew considerably, driving organizations to operate in modes of production that had long-term impacts on society and environment. Those negative impacts have forced regulatory authorities, manufacturers, and customers to reconsider economic business models and their consequences on the planet (Rajeev, Pati, Padhi & Govindan, 2017). As society awareness regarding environmental and social concerns has intensified, the need for sustainable supply chains have gained important recognition. These supply chains have become crucial in fostering companies efforts towards its sustainability-related goals, providing a balance between profits and the effects on the community and environment (Barbosa-Póvoa, 2014; Barbosa-Póvoa, Silva & Carvalho, 2018). At the same time that organizations need to ensure their competitiveness, they are also pressured to reconsider their supply chains in order to become more sustainable (Mota, Gomes, Carvalho & Barbosa-Póvoa, 2015). Progresses are being made in this regard and, even when under adverse economic scenarios, commitments to sustainable supply chain principles have been high (Barbosa-Póvoa et al., 2018).

Another concept that has recently attracted increasing attention is the resilient supply chain (Kamalahmadi & Parast, 2016; Tordecilla, Juan, Montoya-Torres, Quintero-Araujo & Panadero, 2021). Many supply chain management efforts focused on improving its financial performance, aiming to increase the return on assets. Several initiatives were implemented in this respect, namely frequent introduction of new products, to increase revenues; reduction of the supply base and adoption of just-in-time systems, to reduce costs; and outsourcing, to reduce assets. While effective in stable environments, these approaches have led to longer and more complex supply chains (Tang, 2006). In global supply chains the probability of facing new risks that might not exist at a local level increases (Tordecilla et al., 2021). These risks have a negative impact and can result in significant losses of profitability and competitiveness (Asl, Khajeh, Pasban & Rostamzadeh, 2023), emphasizing the need to design supply chains that are not only efficient but also resilient to disruptions (Kamalahmadi & Parast, 2016). A resilient supply chain should be able to prepare, respond, and recover from disturbances, ensuring a stable operation (Ribeiro & Barbosa-Póvoa, 2018). Meeting customers' expectations is crucial, even at the risk of compromising financial results in stable environments (Ribeiro & Barbosa-Póvoa, 2022). It is therefore critical to build resilient supply chains, even if it may incur additional costs (Carvalho, Duarte & Machado, 2011).

So, to respond to the increasing changes in today's competitive environment, companies need to adopt new approaches for supply chain management. They must face the challenge of planning supply chain networks that are more sustainable and also more resilient to ensure their operation under disruption scenarios. Encouraging companies to adopt more sustainable strategies to replace their traditional practices can prove challenging when it does not involve any external motivations, pressures, or other drivers (Choudhary & Sangwan, 2022). Similarly, many companies may find difficult to justify investing resources in implementing more resilient strategies, when disruptions may never occur (Tang, 2006). Therefore, it is necessary to develop decision support tools that better represent this decision-making context, from operational to strategic levels, enabling the exploration of the concepts simultaneously and the evaluation of possible trade-offs. These tools should help managers to find good compromise solutions by allowing them to analyze potential trade-offs between the costs of implementing green and resilient strategies and the benefits they may produce.

The distribution network at the end of a supply chain is of particular relevance, since it involves a large number of small flows of goods towards retailers or end customers (Prodhon & Prins, 2014). The complexity of its design increases in global supply chains, which may have to deal with a significant geographical dispersion of several customers and a large number of products and modes of transport (Mota et al., 2015). Designing these distribution networks raises two major problems, namely the location of facilities and the design of distribution routes (Prodhon & Prins, 2014). It is already well recognized that these problems represent two interdependent logistics decisions that should be approached in an integrated way as Location-Routing Problems (LRPs) (Salhi & Rand, 1989). This class of problems integrates the decisions of selecting facilities to be opened, allocating demand points to them, and designing the vehicles routes that must serve those points (Lopes, Ferreira, Santos & Barreto, 2013).

This paper addresses the concepts of sustainability and resilience in a multi-objective capacitated LRP (CLRP). The CLRP is a LRP variant that considers capacity constraints on facilities and vehicles and is the most addressed in literature (Lopes, Ferreira & Santos, 2016). The aim of this work is to solve a set of problem instances to explore the impact of sustainability and resilience on location and distribution costs. Thus, three objective functions are considered simultaneously in a multi-objective mixed integer programming model: minimizing the logistics network total cost, minimizing the harmful environmental consequences of its operation, and maximizing its resilience. To the best of the authors' knowledge, this is the first time that these objectives have been explored simultaneously in a LRP. To analyze potential trade-offs between the three objectives considered, a set of instances based on real data are solved using the ε-constraint method. An instance was originally developed, and three others were adapted from cases from literature. The underlying network of each instance has different characteristics.

The remainder of this paper is organized as follows. Section 2 contains a review on multi-objective location-routing models addressing sustainability or resilience as objectives. The proposed mathematical formulation is presented in Section 3, detailing the modelling of sustainability and resilience as objectives. In Section 4, test instances are described, and results obtained are presented and discussed. Finally, preliminary conclusions are drawn in Section 5, and some perspectives for future work are pointed out.

2. Literature Review

Sustainability can be defined in a very broad way, so it can also be interpreted in several manners. For this reason, organizations can follow a more sustainable path by choosing different perspectives of the concept and different implementation strategies (Larrea-Gallegos, Benetto, Marvuglia & Gutiérrez, 2022). Within LRPs, sustainability is often considered according to its three-pillar composition: economy, environment, and society, popularly termed as Triple Bottom Line (Rajeev et al., 2017). Multi-objective approaches are frequently used to deal with potential trade-offs between these dimensions. Most works consider at least one function related to minimizing costs or maximizing profits. By contrast, social issues are still scarcely addressed. Although the three dimensions of sustainability are equally important, most social indicators are qualitative and thus difficult to measure (Jayarathna, Agdas, Dawes & Yigitcanlar, 2021). Considering this pillar, the most frequently applied objectives include those related to the impact of maximizing the created job opportunities (Navazi, Sedaghat & Tavakkoli-Moghaddam, 2019; Ouhader & El-Kyal, 2017; Zhalechian, Tavakkoli-Moghaddam, Zahiri & Mohammadi, 2016) and those concerned with the aspects of equity among customers (Chang, Zhou, Chen & Chen, 2017) or workers (Galindres, Guimarães & Gallego-Rendón, 2023; Rabbani, Navazi, Farrokhi-Asl & Balali, 2018).

The environmental dimension has received more attention from research community. Among the various environmental externalities generated by the logistics networks operation, emission of greenhouse gases has been the most addressed in multi-objective LRPs. Different authors have addressed bi-objective approaches considering the minimization of transportation cost and CO_2 emissions (Alamatsaz, Ahmadi & Mirzapour-Al-e-hashem, 2022; Heidari, Imani, Khalilzadeh & Sarbazvatan, 2022). Ouhader and El-Kyal (2017) consider a two-echelon LRP defining as objectives the maximization of created job opportunities besides the minimization of total cost and CO_2 emissions.

Since the amount of CO_2 released by a vehicle is assumed to be directly proportional to the fuel it consumes (Demir, Bektaş & Laporte, 2014), Zhang and Zhang (2022) and Nasrollahi, Razmi and Ghodsi (2018) consider minimizing this consumption to reduce emissions generated by the logistics networks. In the work of Nasrollahi et al. (2018) the expression used to measure the total fuel consumption is a function of distance travelled, road conditions, vehicle, and load carried by it. The resulting transport-related CO_2 emissions are calculated using a Monte Carlo based approach.

There are certain works that seek to minimize both fuel consumption and associated emissions. Zhalechian et al. (2016) consider the minimization of negative impacts of CO_2 emissions, fuel consumption, and energy wasted on a transportation network, in addition to the minimization of its total cost and the maximization of social benefits. In the adopted expression, fuel consumption and CO_2 emissions are dependent on vehicle characteristics, road conditions, atmospheric conditions, and load carried by vehicles. Toro, Franco, Echeverri and Guimarães (2017) address a bi-objective CLRP, aiming the minimization of operational costs and the minimization of negative environmental impacts. The authors introduce and apply a new mathematical model that calculates fuel consumption and the derived total greenhouse gas emissions based on the forces acting on vehicles during their operation. In the work of Rabbani et al. (2018) CO_2 emissions and fuel consumption are calculated based on the expression presented by Xiao, Zhao, Kaku and Xu (2012), which is dependent on distance travelled and vehicle weight. Galindres et al. (2023) focus their work on a multi-objective CLRP that simultaneously considers the three sustainability dimensions: economic and environmental functions applied by Toro et al. (2017) are used, in addition to the social objective of balancing routes length.

Some works consider in their models not only vehicle emissions, but also emissions associated with the opening and operation of facilities (Aloui, Hamani & Delahoche, 2021; Navazi et al., 2019). In these cases, the environmental impact is quantified using emission conversion factors, corresponding to each of the respective sources or activities.

Qiu, Zhang, Chen, Wang, Pan, Sheng et al. (2020) consider sustainability challenges in a LRP with cold chain logistics. The addressed multi-objective model intends to minimize total logistics costs, greenhouse gas emissions, average waiting time of vehicles and customers, and total quality degradation of cargos. Unlike most works which use factor models to quantify emissions, the authors adopted the Comprehensive Modal Emission Model (CMEM), introduced by Barth, Younglove and Scora (2005).

The challenge of considering the minimization of environmental impacts is also addressed in emergency logistics networks (Shen, Tao, Shi & Qin, 2019) and in logistics networks operating with hazardous materials (Ziaei & Jabbarzadeh, 2021). The priorities of these networks focus on maximizing assisted demand and decreasing exposure to risk, respectively. Thus, the introduction of environmental concerns in these types of networks highlights the growing awareness of these aspects and the recognition of their importance.

Resilience as an objective function is scarcely studied in multi-objective LRP. Song, Liu, Y.Q., Sun, Chen and Xu (2021) consider the maximization of user utility in a combined location-routing-inventory problem under disruption risk.

In the field of emergency logistics, in addition to objectives related to distribution cost and time of delivery assistance, certain works also include the resilience of transport system. Wang, Du and Ma (2014) consider the maximization of the minimum route reliability for all serving vehicles of a relief distribution network, in a post-earthquake scenario. The reliability of a route is defined as the probability that drivers can safely deliver critical supplies to all demand points belonging to that route. This probability, in turn, is calculated based on the possibility of successfully traversing each link included in that route. Chang et al. (2017) consider the maximization of transport capacities of the worst path in a relief distribution network. Khorsi, Chaharsooghi, Kashan and Bozorgi-Amiri (2021) consider the maximization of the minimum reliability of network routes in a post-disaster scenario. To assess this reliability, it is assumed that each arc in the network has multiple states, which are defined by travel time.

The work of Beiki, Seyedhosseini, Mihardjo and Seyedaliakbar (2021) addresses the reliability of a transportation network at the time of a disaster. The model considers different possible routes between potential healthcare centers and demand nodes. The reliability of each one is calculated based on failure percentage and is updated based on route recovery operations.

There are relevant works addressing sustainability and resilience separately. Sustainability is more consolidated, especially the environmental pillar, being a concern even in multi-objective LRPs that deal with emergency and hazmat logistics networks. Resilience is less explored and is mostly considered in the field of emergency logistics. To the best of authors' knowledge, no work has simultaneously discussed resilience and environmental sustainability as objectives.

In fact, few studies have explored the integration of sustainability and resilience in supply chains (Negri, Cagno, Colicchia & Sarkis, 2021). Given that organizations today must face both challenges, Negri et al. (2021) identify the need to better understand potential trade-offs and synergies between resilience and sustainability. In this sense, the authors highlight the need for decision support tools to help organizations understand the impact that integrating both concerns could have on supply chains. These tools should help decision-makers evaluate alternative sustainable and resilient solutions for supply chains, ensuring well-founded planning and management.

This work aims to fill this gap by developing and analyzing a multi-objective LRP that simultaneously addresses sustainability and resilience concerns. This integration brings the proposed model closer to the current decision-making context of supply chain managers. It is a useful tool that can help decision-makers analyze the impact of these concerns on location and distribution decisions.

3. Location-Routing with Sustainability and Resilience Concerns

In this section, a multi-objective mixed-integer programming mathematical model is presented for a single-echelon CLRP. Commodities are transported from facilities to demand points by a fleet of homogeneous vehicles. The goal is to determine which facilities should be opened and how routes should be designed to ensure the fulfilment of all demand points. These decisions should be made considering, simultaneously, the minimization of the logistics network total cost, the minimization of negative environmental consequences resulting from its operation, and the maximization of the network resilience.

The addressed CLRP can be defined on a complete undirected network $G = (V, A)$. V is a set of nodes consisting of a subset I of m potential facilities and a subset $J = V/I$ of n customers. Every arc (i, j) belongs to set A and has an associated non-negative cost c_{ij}, corresponding to the distance separating the nodes i and j, with i and j in V.

Each facility $i \in I$ has an opening cost O_i and a capacity W_i. Each customer $j \in J$ has a demand d_j, fulfilled once, and must be allocated to only one facility. Customer demand is satisfied trough a set K of identical vehicles, which must return to the departure facility at the end of their route. Each vehicle $k \in K$ performs a single route and incurs a fixed cost F. The total payload of each route must not exceed the vehicle capacity Q. The total payload of all routes assigned to a facility should not exceed the capacity of that facility.

The assumptions are presented as follows:

- each customer demand d_j is deterministic and known *a priori*;
- a homogeneous fleet of vehicles with limited capacities are considered;
- each vehicle performs at most one trip;
- each customer demand d_j must be served by one single vehicle (no split-delivery);
- each route must begin and end at the same facility;
- the total load of all routes assigned to a facility should not exceed its capacity;
- the model is single period and single product;
- the speed is known and constant in each arc, although it can vary from one arc to another;
- the total number of alternative paths in each arc is known *a priori*.

The following sections provide a detailed description of the sustainability and resilience modeling.

3.1. Sustainability

To address the environmental pillar of sustainability in the proposed multi-objective CLRP, the minimization of CO_2 emissions generated by the distribution operation was considered. It is already known that transportation is a harmful activity to the environment and human health. Pollutant emissions, noise, land use and safety hazards represent some of the negative externalities that may result from it (Bektaş, Ehmke, Psaraftis & Puchinger, 2019).

According to data provided by Eurostat, in 2020, road transport represented 77.4% of the modal split of freight transport in EU-27 (Eurostat, 2022). Emission of pollutants is the main externality of this mode of transport and also the most concerning. Its reduction has been the main focus of international agreements on climate change, since greenhouse gases contribute to the worsening of global warming (Bektaş et al., 2019). In fact, road transport, particularly on a local and regional level, is mostly performed by trucks. The engines of trucks use fossil fuels in their operation, the burning of which produces harmful pollutants (Demir et al., 2014).

In logistics context, reduction of CO_2 emissions for a more environmentally friendly operational level planning has gained increasing importance. To estimate these emissions, models that directly calculate emissions or models that calculate the fuel consumed by vehicles can be applied, since they are directly proportional (Demir et al., 2014).

In the case of multi-objective LRPs it is quite common to use models based on activities or static conversion factors. These models are considered the simplest, although their application is not the most suitable for calculating input parameters of optimization problems, particularly when variations in load and speed are expected. Macroscopic models calculate emissions using an average speed value at which a certain type of vehicle travels. Microscopic models are more complex and quantify the instantaneous emissions of vehicles (Bektaş et al., 2019).

As this work deals with a problem involving operational decisions regarding the design of freight distribution routes, an adaptation of the Comprehensive Modal Emission Model (CMEM) will be used (Scora & Barth, 2006). CMEM was introduced by Barth et al. (2005), and has been used to test CO_2 reduction strategies (Barth & Boriboonsomsin, 2008). It is a microscopic model, presented for heavy-goods vehicles, which requires vehicle-specific parameters to calculate the estimations. Despite the complexity of the required parameters, the model is very robust and reliable. Moreover, the feasibility of its mathematical modelling makes it one of the most popular models in the optimization of more environmentally friendly transport activities (Demir et al., 2014).

CMEM can consider speed and variations in load carried by vehicles, throughout the distribution activity. The minimization of the distance travelled has been viewed as the most important objective in vehicle routing and freight transportation, often used as a surrogate for cost. However, fuel consumption is dependent on a variety of factors. Speed and payload can influence the amount of fuel consumed by a vehicle and may be important parts of routing decisions (Demir et al., 2014). The allocation of customers to a given route determines the total payload that the vehicle will carry, and the definition of the sequence in which customers are visited determines the payload between those visits. Therefore, both decisions are capable of affecting fuel consumption (Bektaş et al., 2019).

CMEM has been successfully implemented in several works. Bektaş and Laporte (2011) applied a comprehensive emissions model in a pollution routing problem. In this work, the emissions released by a given vehicle when traveling over a certain arc were dependent on factors such as distance, load, and speed. The authors considered some of the factors to be fixed (e.g., gravity and slope), while load and speed could be controlled. Koç, Bektaş, Jabali & Laporte (2014) extended the work of Bektaş and Laporte (2011) by considering a heterogeneous vehicle fleet. Qiu et al. (2020) used the CMEM in a LRP for a cold chain logistics, adding the extra energy required to maintain the freshness of products.

The function used in this paper corresponds to a simplified version of the model, and was based on the work by Koç et al. (2014). The expression used to calculate the fuel consumption was adapted, and speed and load were considered known and constant within each arc, although they may vary from one arc to another. To quantify CO_2 emissions, a conversion factor e_{CO_2e} was used. This factor indicates the amount of CO_2 produced for each liter of fuel consumed. The total emissions of a vehicle over a distance d, is then calculated as

$$Total\ emissions = e_{CO_2e}[\lambda(K_eN_eV_ed/v + M\gamma\alpha d + \beta\gamma dv^2)] \qquad (1)$$

Expression (1) comprises three modules, namely engine module, mass module, and velocity module. The first term, $K_eN_eV_ed/\text{v}$, corresponds to the engine module and is a linear function of the time it takes for the vehicle to travel the distance d. The parameters K_e, N_e, and V_e represent the friction factor, speed, and engine displacement, respectively. The second term, $M\gamma\alpha d$, coincides with the weight module, where M is the total vehicle weight. The last one represents the module of speed $\beta\gamma dv^2$, and is a quadratic function of the vehicle speed v. The parameters

$\lambda = \xi/\kappa\psi$, $\gamma = 1/1000\eta_{tf}\eta$, $\alpha = \tau + g\sin\theta + gC_r\cos\theta$ are constants related to CO_2 emissions, and $\beta = 0.5C_d\rho A$ is a vehicle-specific constant.

3.2. Resilience

Resilience is a priority and a challenge in modern business planning (Christopher & Peck, 2004). Supply chains are now highly vulnerable to risks, of which risks of disruption could have a high impact on business operations, even if they have a low probability of occurrence (Suryawanshi & Dutta, 2022). Some researchers interpret resilience as a reactive capacity when experiencing a disruption, while others perceive resilience as a proactive effort to be prepared in advance for disruptions (Kamalahmadi & Parast, 2016).

Kamalahmadi and Parast (2016) consider that supply chain resilience includes three phases: the anticipation phase, the resistance phase, and the recovery and response phase. The anticipation phase requires adaptability of the supply chain to minimize the likelihood of experiencing sudden disturbances by maintaining a proactive thought and developing proactive plans. The resilience phase involves flexibility to withstand the impact of disturbances, ensuring control over structures and functions, and continuity of operations. The recovery and response phase requires agility so that, through rapid and effective reactive actions, the supply chain can be restored to its pre-disruption state or to a more favorable one. So, adaptability, flexibility, and agility can represent important precedents for resilient supply chains.

Tang (2006) points to the use of different transportation modes and carriers, and the consideration of different alternative routes as strategies for creating more flexibility in transportation. These strategies not only allow organizations to improve their supply management capabilities, but also their ability to quickly change the way their commodities are transported in the face of a disturbance. They are, therefore, useful in normal circumstances of fluctuating supply and demand, and during significant disruptions, allowing a company to become more resilient while strengthening its competitive position (Tang, 2006).

Assessing resilience, through qualitative or quantitative indicators, represents an important part of the study of this concept. These indicators are useful to analyze and implement strategies that increase resilience at the lowest possible cost (Tordecilla et al., 2021). In this paper, resilience is assessed by considering the flexibility of the distribution network in the face of disruptions in links. This flexibility was quantified according to the number of alternative paths between the network nodes. Considering the maximization of alternatives that a driver has to perform the same trip, allows the driver more flexibility to quickly adapt to potential failures in those links. Road transport is subject to traffic conditions, being vulnerable to heavy traffic situations and possible traffic blackouts. Maximizing route options gives the network greater flexibility, allowing distribution routes to be quickly adapted to unforeseeable disruptions. In this way, continuity of operations is ensured, avoiding interruptions to the network flow and failure to meet deliveries and deadlines.

3.3. Mathematical Formulation

The multi-objective CLRP optimization model proposed in this paper is based on the formulation introduced by Prins, Prodhon, Ruiz, Soriano and Calvo (2007) and is presented below. The following decisions variables are used:

$y_i \in \{0,1\}$, $\forall\ i \in I$, where $y_i = 1$, if facility i is opened; or $y_i = 0$, otherwise;

$f_{ij} \in \{0,1\}$, $\forall\ i \in V$, $\forall\ j \in V$, $k \in K$, where $f_{ij} = 1$, if the customer node j is served by a vehicle starting in facility i; or $f_{ij} = 0$ otherwise;

$x_{ijk} \in \{0,1\}$, $\forall\ i \in V$, $\forall\ j \in V$, $k \in K$, where $x_{ijk} = 1$, if vehicle k uses the link from node i to node j; or $x_{ijk} = 0$ otherwise;

$t_{ijk} \in \mathbb{Z}_0^+$, $\forall\ i \in V$, $\forall\ j \in V$, $k \in K$, where t_{ijk} represents the total demand units carried by vehicle k from node i to node j.

$$\text{Minimize} \quad Z_1 = \sum_{i \in I} O_i y_i + \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} c_{ij} x_{ijk} + \sum_{k \in K} \sum_{i \in I} \sum_{j \in J} F x_{ijk} \tag{2}$$

Minimize

$$Z_2 = e_{CO_2e}\left[\sum_{k\in K}\sum_{i\in V}\sum_{j\in V}\lambda K_e N_e V_e x_{ijk} c_{ij} / v_{ij} + \sum_{k\in K}\sum_{i\in V}\sum_{j\in V}\lambda\left(w x_{ijk} + p t_{ijk}\right)\gamma\alpha c_{ij} + \sum_{k\in K}\sum_{i\in V}\sum_{j\in V}\lambda\beta\gamma x_{ijk} c_{ij} v_{ij}^2\right] \tag{3}$$

Maximize

$$Z_3 = \sum_{i\in V}\sum_{j\in V}\sum_{k\in K} n_{ij} x_{ijk} \tag{4}$$

$$\sum_{k\in K}\sum_{i\in V} x_{ijk} = 1 \qquad \forall\, j \in J \tag{5}$$

$$\sum_{k\in K}\sum_{i\in V\setminus\{j\}} t_{ijk} = \sum_{k\in K}\sum_{r\in V\setminus\{j\}} t_{jrk} + d_j \qquad \forall\, j \in J \tag{6}$$

$$t_{ijk} \le Q x_{ijk} \qquad \forall\, i \in V, \forall\, j \in V, \forall\, k \in K \tag{7}$$

$$\sum_{j\in V} x_{ijk} - \sum_{j\in V} x_{jik} = 0 \qquad \forall\, k \in K, \forall\, i \in V \tag{8}$$

$$\sum_{i\in I}\sum_{j\in J} x_{ijk} \le 1 \qquad \forall\, k \in K \tag{9}$$

$$\sum_{u\in J} x_{iuk} + \sum_{u\in V\setminus\{j\}} x_{ujk} \le 1 + f_{ij} \qquad \forall\, i \in I, \forall\, j \in J, \forall\, k \in K \tag{10}$$

$$\sum_{i\in I} f_{ij} \le 1 \qquad \forall\, j \in J \tag{11}$$

$$\sum_{k\in K}\sum_{j\in J} t_{ijk} \le W_i y_i \qquad \forall\, i \in I \tag{12}$$

$$x_{ijk} \in \{0,1\} \qquad \forall\, i \in V, \forall\, j \in V, \forall\, k \in K \tag{13}$$

$$y_i \in \{0,1\} \qquad \forall\, i \in I \tag{14}$$

$$f_{ij} \in \{0,1\} \qquad \forall\, i \in I, \forall\, j \in V \tag{15}$$

$$t_{ijk} \in \mathbb{Z}_0^+ \qquad \forall\, i \in V, \forall\, j \in V, \forall\, k \in K \tag{16}$$

The objective function (2) minimizes the total operating costs and is composed of three terms: the first calculates the total opening costs of facilities; the second, the total variable cost of distribution; and the third, the fixed cost of routes.

The objective function (3) comes from expression (1) and minimizes the CO_2 emissions generated during the distribution considering a homogeneous fleet. v_{ij} is the speed between nodes i and j. The mass M of vehicle k

between nodes i and j includes its curb weight w and the total mass of the cargo it carries on that link. This value can be calculated by multiplying t_{ijk} by the mass p of a demand unit.

Finally, objective function (4) aims to maximize the total number of alternative paths, where n_{ij} represents the total alternative paths between nodes i and j.

Constraints (5) ensure that each customer belongs to only one route and has a single predecessor on it. Constraints (8) and (9) ensure route continuity and guarantee that each vehicle returns to its departure facility. Inequalities (10) imply that a customer can only be allocated to one facility if a route that connects them is opened. Constraints (11) ensure that each customer is allocated to a single facility.

Constraints(6), (7) and (12) were adapted from the work of Toro et al. (2017). Equations (6) refer to the balance of flows, relating the payload carried by vehicles to the demand of visited customers. Inequalities (7) and (12) impose, respectively, vehicles and facilities capacity constraints.

Finally, constraints (13)-(15) establish the binary nature of variables x_{ijk}, y_i, f_{ij}, and constraints (16) define t_{ijk} as a non-negative integer variable. The formulation has a total of $V^2K + I + IV$ binary variables, V^2K non-negative integer variables and $3J + V^2K + KV + K + IJK + I$ constraints.

4. Computational Study

Computational experiments were performed on an Intel Core i7-7500U 2,7 GHz CPU with 12,0 GB of RAM. The model was solved to optimality using version 20.1.03 of IBM ILOG CPLEX Optimization Studio, without setting time limits.

To obtain the Pareto optimal solutions, the ε-constraint method introduced by Haimes, Lasdon and Wismer (1971) was adopted. This procedure allows generating the entire Pareto set (or representative subset) without the decision maker needing to quantify the preference system *"a priori"* through objectives or weights. This is relevant in this work as the goal is not to try to find compromise solutions that best meet the preferences of a particular decision maker, but rather explore the impact that prioritizing a certain objective may have on others. Moreover, the method does not require the objective functions to be on a common scale (Mavrotas, 2009), which is appropriate since the objectives have different dimensional units and discrepant magnitudes.

4.1. Test Instances

To the best of the authors' knowledge, there are no instances in literature for multi-objective CLRPs considering sustainability and resilience aspects. Therefore, one instance was developed based on real-world data, and three others were adapted from case studies in location-routing literature. Complete graphs were considered in all instances discussed.

4.1.1. Portugal Instance

The newly developed instance is based on real data from Aveiro region, Portugal. It is a hypothetical case of a distribution company in retail sector, where customers correspond to stores and facilities to warehouses. Warehouses are to be located, and the tracing of distribution routes are to be determined to assure fulfilment of stores demand.

The instance *Portugal* 18×4 is composed of 18 stores and 4 potential locations for warehouses that coincide with industrial zones in the region. The coordinates of the location of warehouses and stores were obtained using the Geographic Information System (GIS) *Google Maps*. Their location is illustrated in Figure 1.

The demand of each customer was defined according to the following expression:

$$\textit{Total customer demand} \times \textit{population density of the municipality} \times \textit{area of the parish} \times \textit{factor}, \qquad (17)$$

depending on the total number of inhabitants residing in the parish where the store is located. The *factor* values were proportionally established according to the type of store: 0.2 for hypermarkets, 0.15 for supermarkets, and 0.1

for convenience supermarkets. The population density of the municipality was consulted at PORDATA (2020), and the area of the parish was consulted at Direção-Geral do Território (2021).

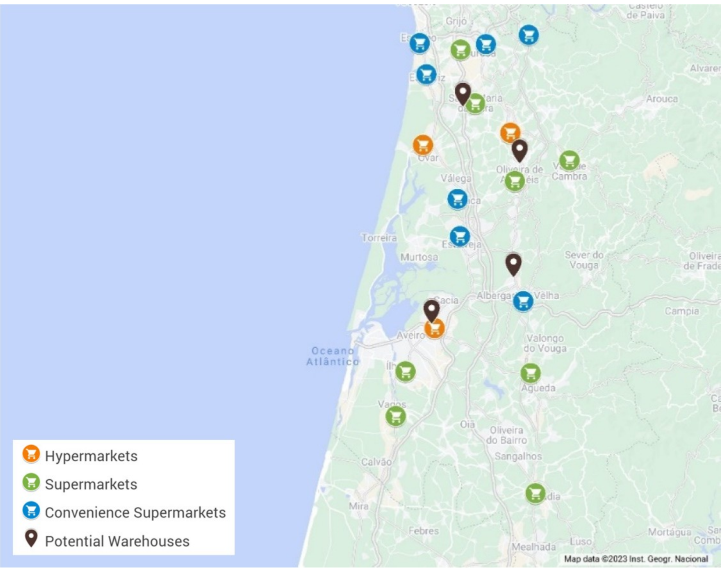

Figure 1. Location of customers and potential warehouse

The opening cost of each facility and the fixed cost of vehicles are proportional and relate to the same time horizon.

The number of alternative paths was obtained from *Google Maps*. The suggestions returned were compared and those with different designations, or different estimated distances, were considered distinct. For example, starting from customer C18 to facility F3, only one feasible alternative was assumed; while starting from the same customer to customer C15, two alternative paths were considered. Both examples are illustrated in Figure 2.

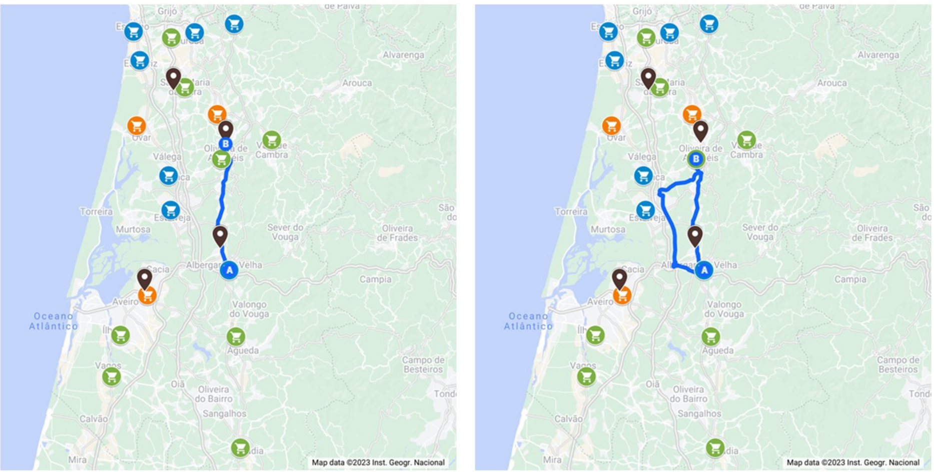

Figure 2. Examples of links with one and two alternative paths

For the distance matrix and speed matrix, the option corresponding to the shortest path was used. Whenever there was more than one alternative with the same length, the one with the shortest estimated duration was selected. The cost of traversing a link from node *i* to *j* correspond to the distance in meters between them.

For the speed matrix, the departure time for each trip was set at 7 am on Monday since the system estimates different durations for the same trips depending on the time and day of departure. In addition, whenever this information was returned as a time interval, the highest value was selected. The vehicles considered in this instance have lower speed limits than those defined for light vehicles and, therefore, are more likely to take a longer time to travel the same distance. Links in which speed was less than 30 km/h were identified as those with the highest risk of disruption. These links will be considered later in the results analysis.

Regarding the vehicles, a homogeneous fleet composed of up to 10 vehicles is assumed. Table 1 shows the values of common parameters for all types of vehicles and the values of specific parameters for the medium duty vehicles considered.

Parameters	Notation	Description	Typical values	Unit of measure
Common parameters	ξ	Fuel-to-air mass ratio	1	dimensionless
	η	Efficiency parameter for diesel engines	0.45	dimensionless
	κ	Heating value of a typical diesel fuel	44	kJ rot^{-1} L^{-1}
	η_{tf}	Vehicle drive train efficiency	0.45	dimensionless
	τ	Acceleration	0	m s^{-2}
	g	Gravitational constant	9.81	m s^{-2}
	θ	Road angle	0	□
	ρ	Air density	1.2041	kg m^{-3}
	C_r	Coefficient of rolling resistance	0.01	dimensionless
	ψ	Conversion factor (g s^{-1} to L s^{-1})	737	dimensionless
Specific parameters	K_e	Engine friction factor	0.20	kJ rev^{-1} L^{-1}
	N_e	Engine speed	36.67	rot s^{-1}
	V_e	Engine displacement	6.9	L
	C_d	Coefficient of aerodynamics drag	0.7	dimensionless
	A	Frontal surface area	8.0	m^2
	w	Curb weight	5,500	kg

Table 1. Parameter values considered for vehicles (Koç et al., 2014)

Since the CO$_2$ emissions depend on the payload of each vehicle, the mass of each demand unit, i.e., the value of p, was defined as 2 kilograms. Finally, it was assumed that each litre of fuel produces 2.32 kilograms of CO$_2$ and, therefore, the value of e_{CO2e} is 2.32, following Pradenas, Oportus and Parada (2013).

4.1.2. United States and Ireland Instances

Three additional instances were adapted from case studies in the literature. In Nucamendi-Guillén, Gómez-Padilla, Olivares-Benitez and Moreno-Vega (2021) the case of a company that uses a single carrier to collect raw material from different suppliers located in United States is addressed. The authors compare the costs of this current approach with the costs of a hypothetical one in which several carriers are considered to transport the raw material to the delivery point. Although the model considers open routes, the instance was adapted for the case of a single-echelon CLRP, becoming instance *US* 13×13.

The work by Validi, Bhattacharya and Byrne (2020) addresses the case of a dairy processing industry supply chain in the east of Ireland. It considers a three-echelon network that includes 2 processing plants, 6 distribution centers, and 22 retailers. Out of this supply chain, two instances of a single echelon were created: *Ireland* 6×2*,* composed of processing plants and distribution centers; and *Ireland* 22×6*,* composed of distribution centers and retailers. Since the exact coordinates of the nodes locations were not known, their approximate locations were determined considering the distances found in the work of Validi (2014).

In *US* and *Ireland* instances, the vehicles characteristics are the same as in *Portugal* 18×4. Furthermore, the data that was missing in these instances to make them suitable for the multi-objective CLRP addressed herein was developed following the same methodology as in *Portugal* 18×4. All the data regarding the previously described instances are presented in Appendix A.

4.1.3. Resilience Metric Analysis

Since the network resilience metric is directly related with the data of the alternative paths matrix, its robustness was analyzed according to two perspectives: how distinct are the alternatives considered, and how does this data change according to the used GIS.

To assess how different are the alternatives of the alternatives considered, the percentage of difference, in terms of the tracing of the different paths, was calculated. For this purpose, 10 links were randomly selected in each instance and the average percentage difference between the two shortest alternatives was calculated. Situations in which the non-coincident length of the paths could not be precisely calculated were not considered. Using the same sample, it was also evaluated how much more expensive the second shortest alternative would be. That is, how much would the cost increase if a disruption occurred on a certain link and another alternative had to be used to avoid interrupting the flow of commodities. The results, presented in Table 2, show that in cases where it is necessary to use the second cheapest alternative there will be no significant cost increase. Nevertheless, this alternative is considerably different from the shortest path. For this reason, it was assumed reasonable to consider the paths as alternatives, even if they have a small overlap.

Instance	Average % of difference	Standard deviation	Average % of cost increase
Portugal 18×4	76.85%	0.16	7.28%
US 13×13	65.76%	0.20	2.21%
Ireland 6×2	54.00%	0.16	1.60%
Ireland 22×6	50.04%	0.23	2.80%

Table 2. Analysis of the alternative paths indicated by *Google Maps*

The number of alternative paths returned by *Google Maps* can bias the results obtained. Therefore, a comparison was made with another GIS: *Bing Maps*. The same 10 links previously selected for each instance were analyzed, and the results show an average difference of 1.98 alternative paths returned (compared to *Google Maps*) with an average standard deviation of 0.90. This leads to believe that the choice of GIS used does not significantly influence the number of alternative paths returned for each link.

4.2. Results

The instances were solved using the ε-constraint method and the results obtained are presented and discussed in the following sections. For each instance the non-dominated solutions that optimize each objective function were analyzed and discussed. Then, the total cost minimization objective function was optimized, while the others related to CO_2 emissions and the number of alternative paths were added as constraints. The aim is to assess the sensitivity of logistics networks costs to the improvement of their resilience and sustainability, and therefore cost minimization prevails as the main objective. Solutions with interesting trade-offs are also analyzed in this section. The set of all non-dominated solutions obtained for each instance are available upon request.

4.2.1. Portugal 18×4

Table 3 shows potentially interesting non-dominated solutions for instance *Portugal* 18×4. The non-dominated solution that minimizes the total cost, S_{P1}, uses a smaller number of vehicles, with a higher average capacity utilization. Only one facility is open and, therefore, its capacity utilization is higher. In this solution, there are two links that have a high risk of disruption. If a second alternative path had to be used in these cases, according to Table 2, the solution would be about 0.15% more expensive.

				Solution characteristics					
Solution	Total cost (monetary units)	Total emissions (kilograms of CO_2)	Total number of alternative paths	Number of vehicles	Cost of routes	Average capacity utilization	Number of facilities	Total cost of facilities	Average capacity utilization of facilities
SP1	403,500*	240.74	75	4	278,500	88%	1	125,000	68%
SP2	729,800	172.27*	77	7	229,800	50%	4	500,000	17%
SP3	1,254,600	696.87	166*	10	879,600	35%	3	375,000	23%
SP4	404,600	239.78	78	5	279,600	71%	1	125,000	68%
SP5	488,550	192.61	74	4	363,550	88%	1	125,000	68%
SP6	407,500	242.52	80	5	282,500	71%	1	125,000	68%

Table 3. Non-dominated solutions for instance *Portugal* 18×4

By using a larger number of vehicles and opening more facilities, the non-dominated solution that minimizes the total emissions, S_{P2}, decreases the distance travelled and the payload of each vehicle. Nonetheless, the solution is more expensive, and the average capacity utilization of vehicles and facilities is lower.

The non-dominated solution S_{P3}, which maximizes the total number of alternative paths, uses a larger number of vehicles, and opens more facilities. Although the payload of each vehicle decreases, vehicles must travel longer distances. The solution is more expensive and emits more CO_2 emissions.

Figure 3 illustrates the Pareto front obtained for this instance.

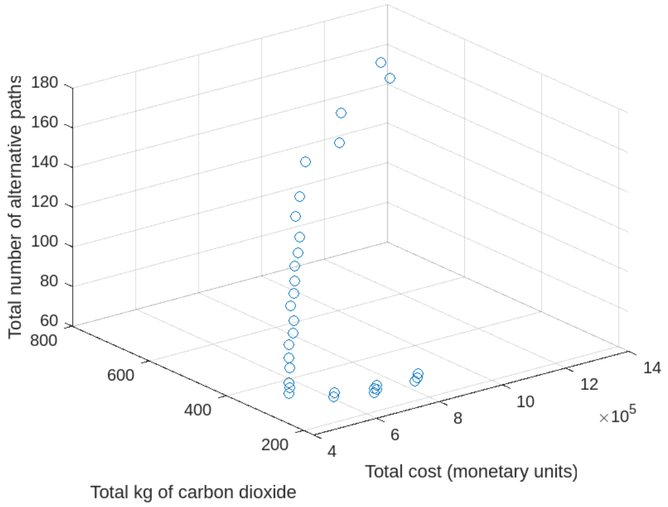

Figure 3. Pareto front of instance *Portugal* 18×4

Looking at the solutions in Table 3 it can be observed several potentially interesting trade-offs. Improving total emissions always implies a more significant increase in total cost, apart from solution S_{P4} in which a 0.3% increase in costs resulted in a 0.4% reduction in the amount of CO_2 emitted. Solution S_{P4} was also one of the few solutions in which an increase in total cost led to a simultaneous improvement in both total emissions and number of alternative paths. However, this improvement was quite disproportionate, since the total number of alternative paths increased by about 4.0%.

In solution S_{P5} there was a potentially good trade-off between costs and emissions: a 21.1% increase in costs was reflected in a 20.0% reduction in the amount of CO_2 emitted. However, there was also a reduction of about 1.3% in the total number of alternative paths.

Regarding the trade-off between costs and alternative paths, it can be concluded that it was possible to significantly increase the total number of alternative paths with a small increase in total cost. For example, in solution S_{P6}, an increase in costs of only 1.0% allowed the network alternative paths to be increased by about 6.7%.

4.2.2. US 13×13

The non-dominated solutions obtained for instance *US* 13×13 are shown in Table 4. On the three solutions that individually optimize each objective function the number of used vehicles is the same, as well as the respective average capacity utilization.

The number of open facilities is the same in the non-dominated solution that minimizes the total cost, S_{U1}, and total emissions, S_{U2}. However, the average capacity utilization is higher when the total network cost is minimized. The distance travelled by vehicles is greater when CO_2 emissions are minimized, corroborating the fact that emissions are dependent on other factors.

				Solution characteristics					
Solution	Total cost (monetary units)	Total emissions (kilograms of CO_2)	Total number of alternative paths	Number of vehicles	Cost of routes	Average capacity utilization	Number of facilities	Total cost of facilities	Average capacity utilization of facilities
SU1	2,835,000*	1,494.03	109	7	1,785,000	27%	7	1,050,000	13%
SU2	2,856,900	1,471.10*	103	7	1,806,900	27%	7	1,050,000	10%
SU3	4,427,000	3,287.48	120*	7	3,677,000	27%	5	750,000	16%
SU4	2,847,800	1,480.91	109	7	1,947,800	27%	7	900,000	15%
SU5	2,852,500	1,473.09	106	7	1,802,500	27%	7	1,050,000	12%
SU6	2,862,700	1,545.12	112	7	1,812,700	27%	7	1,050,000	14%

Table 4. Non-dominated solutions for instance *US* 13×13

Solution S_{U3}, which maximizes the total number of alternative paths, opens fewer facilities with higher capacity utilization. However, arcs with longer distances are chosen, it is more expensive and emits more CO_2.

In this case, the solution that minimizes the total cost has three links that have a high risk of disruption. If a second alternative path had to be used in these cases, according to Table 2, the solution would only be about 0.07% more expensive.

Compared with solution S_{U1} there is no solution that improves the total emissions and total number of alternative paths at the same time. Only solution S_{U4} shows a 0.9% reduction in the amount of CO_2 emitted, without deteriorating the number of alternative paths of the network.

In this instance, the values of emissions and alternative paths observed in solution S_{U1} are not very far from the individual optimums observed in solutions S_{U2} and S_{U3}, respectively. Thus, even if the total cost is allowed to increase considerably, improvements in total emissions and total number of alternative paths are minor. Still, there are solutions with interesting trade-offs. For example, in S_{U5} there is a 1.4% reduction in CO_2 emitted, while only increasing costs by 0.6%. In S_{U6}, a 1.0% increase in costs results in a 2.8% improvement in the number of alternative paths.

4.2.3. Ireland 6×2

Table 5 shows some of the non-dominated solutions obtained for instance *Ireland* 6×2. As seen in *Portugal* 18×4, the non-dominated solution that minimizes the total cost, S_{Ia1}, uses less vehicles with a higher average capacity utilization. Only one facility is open and thus its capacity utilization is higher. In this solution, if it were necessary to use a second alternative path on links with the highest risk of disruption, according to Table 2, the impact on costs would be minimal as the solution would only be about 0.02% more expensive.

				Solution characteristics					
Solution	Total cost (monetary units)	Total emissions (kilograms of CO2)	Total number of alternative paths	Number of vehicles	Cost of routes	Average capacity utilization	Number of facilities	Total cost of facilities	Average capacity utilization of facilities
SIa1	2,448,400*	473.89	38	2	948,400	69%	1	1,500,000	100%
SIa2	4,625,400	420.69*	41	3	1,625,400	46%	2	3,000,000	50%
SIa3	5,160,800	670.02	55*	4	2,160,800	34%	2	3,000,000	50%
SIa4	4,406,000	445.07	40	2	1,406,000	69%	2	3,000,000	50%
SIa5	2,475,100	501.61	40	2	975,100	69%	1	1,500,000	100%
SIa6	4,624,300	422.25	42	2	3,124,300	69%	1	1,500,000	100%

Table 5. Non-dominated solutions for instance *Ireland* 6×2

In the non-dominated solution that minimizes the total emissions, S_{Ia2}, more facilities are opened with lower average capacity utilization. The solution uses more vehicles carrying less payload. So, even though the distance travelled is longer, CO_2 emissions are lower.

The non-dominated solution that maximizes the total number of alternative paths, S_{Ia3}, uses a larger number of vehicles, opens more facilities, and decreases the payload of each vehicle. However, the distance travelled is quite longer. The solution is more expensive and has more CO_2 emissions.

Compared with solution S_{Ia1}, the reduction of total emissions always implies a very significant increase in costs, since, in these cases, a second facility is always opened. For example, in S_{Ia4}, a 6.1% reduction in CO_2 emitted implies an 80.0% increase in costs. The same is not true for the total number of alternative paths, as many solutions were obtained in which the increase in costs led to similar and often greater improvements in the network alternative paths, as seen in solution S_{Ia5}.

Unlike in *US* 13×13, in this instance, in several solutions an increase in costs resulted in an improvement in total emissions and total number of alternative paths. Solutions S_{Ia4} and S_{Ia6} represent two such cases.

4.2.4. Ireland 22×6

Table 6 includes some of the non-dominated solutions obtained for instance *Ireland* 22×6. As with the previous instances, the non-dominated solution that minimizes the total cost, S_{Ib1}, uses fewer vehicles and opens fewer facilities with higher average capacity utilization. In this solution there are two links that have a high risk of disruption: links that connects customer C19 to facility F3. However, in this case there is no alternative path that connects this customer to the facility to which it has been allocated. Thus, a disruption in this connection could compromise the timely satisfaction of its demand, which represents about 32% of the total demand of this instance.

In the non-dominated solution that minimizes total emissions, S_{Ib2}, vehicles travel shorter routes and carry less payload. More facilities are opened, and a larger number of vehicles are used to do this. As a result, there is a significant increase in costs with little improvement in CO_2 emissions.

Similarly, solution S_{Ib3}, which maximizes the total alternative paths, uses a larger number of vehicles, and opens more facilities. In addition, even though vehicles carry less payload on each route, the distance travelled by them is much greater. Thus, the significant improvement in network resilience is accompanied by a considerable increase in costs and CO_2 emissions.

As in all previous instances, a trade-off can be seen between the three objectives. Reduction of total emissions implies a considerable increase in total cost, as can be seen in solutions S_{Ib4} and S_{Ib5} when compared with S_{Ib1}. Contrarily, improvement of alternative paths did not always require a considerable increase in costs. For example, in solution S_{Ib6}, a 1.0% increase in costs results in a 7.6% improvement in the network alternative paths.

				Solution characteristics					
Solution	Total cost (monetary units)	Total emissions (kilograms of CO2)	Total number of alternative paths	Number of vehicles	Cost of routes	Average capacity utilization	Number of facilities	Total cost of facilities	Average capacity utilization of facilities
SIb1	1,155,300*	585.22	92	4	805,300	73%	2	350,000	66%
SIb2	2,066,700	477.45*	95	8	766,700	37%	6	1,300,000	22%
SIb3	3,768,600	2,203.70	204*	12	3,168,600	24%	3	600,000	38%
SIb4	1,548,300	501.88	94	6	748,300	49%	4	800,000	33%
SIb5	1,803,200	489.30	97	7	753,200	42%	5	1,050,000	27%
SIb6	1,167,000	599.94	99	4	817,000	73%	2	350,000	63%

Table 6. Non-dominated solutions for instance *Ireland* 22×6

For this instance, quite a few solutions were also obtained in which an increase in costs resulted in a simultaneous improvement in total emissions and total number of alternative paths. Solutions S_{Ib4} and S_{Ib5} represent two such cases.

4.2.5. Discussion

Results show that when cost minimization is prioritized, distance travelled, number of opened facilities and number of vehicles are minimized. For this reason, their capacity utilization is usually higher. On the other hand, when the minimization of emissions is prioritized, more vehicles are generally used, carrying a smaller payload. Furthermore, these solutions do not necessarily have associated shorter travel distances, which corroborates that fuel consumption is also dependent on other factors, such as load and speed. In fact, when minimizing emissions, customers with the highest amounts of demand are usually visited first. When the maximization of the network resilience is prioritized, a greater number of vehicles and facilities are also typically used.

Analyzing the set of non-dominated solutions obtained for the instances, it is possible to see that the reduction of CO_2 emissions generally implies a more significant increase in costs. On the other hand, it is possible to improve the number of alternative paths considerably with only a small increase in costs. Furthermore, non-dominated solutions in which the detriment of one objective function resulted in a simultaneous improvement of the other two were very rare.

By observing Tables 3-6, it is also possible to conclude that costs can be extremely sensitive to improvements in resilience and sustainability of logistics networks. Indeed, the prioritization of these objectives can have a considerable impact on the number of vehicles and opened facilities.

Finally, it should also be noted that using alternative paths, when necessary, has no significant impact on total cost and can ensure a continuous flow of the designed network and avoid the non-satisfaction of demand points.

5. Conclusions

This paper introduces a multi-objective formulation for a CLRP, exploring the concepts of sustainability and resilience. Besides the objective of minimizing the logistics network total cost, the minimization of CO_2 emissions resulting from the distribution activity, and the maximization of the network resilience were also considered. Emissions were quantified considering load and speed variations throughout the distribution routes. Resilience was quantified according to the alternative paths, seeking to design a flexible network capable of responding unpredictable disruptions in links.

Results obtained for the instances allow the conclusion that there is a trade-off between costs of logistics networks, emissions released by their operation and their resilience. Designing a more sustainable and resilient logistics network can have considerable impacts on its total cost. The resilience metric used in this work, as well as the emissions estimates, is directly related to routing decisions. These decisions are usually considered at operational planning level and, for this reason, sustainability and resilience have been modelled using metrics that have a degree of detail consistent with this decision level. Despite this, and in line with the concept behind LRPs, this work has led to the conclusion that both concerns have a significant impact on strategic location decisions, usually preferring solutions in which more facilities are opened. Thus, even though from an economic point of view it is not favorable to consider these concerns in isolation, they should not be disregarded. It should also be added that in some specific LRPs both location and routing are handled at an operational level.

This work also shows that it is possible to find solutions that ensure a potentially good compromise between costs of logistics networks, the negative environmental impacts resulting from their operation, and their resilience. Indeed, in some non-dominated solutions, an increase in costs simultaneously improved the total emissions and total number of alternative paths. Still, these cases were scarce, since in most of the non-dominated solutions obtained the detriment of one of the objectives did not necessarily imply a simultaneous improvement of the others. This indicates that cost, environmental sustainability and resilience of distribution networks proved to be distinct and uncorrelated objectives, which should therefore be considered separately.

Even though cost is the prioritized objective in the design of most logistics networks, some strategies can be implemented to improve the resilience and sustainability of these systems. For example, ensuring that the most critical paths have viable alternatives can make networks more resilient to the disruption risks. These would be either because they are most prone to disturbances, or because they connect important customers. Moreover, having a larger number of vehicles available to travel shorter distances, with less payload, can decrease the emissions associated with distribution activity.

Future work includes exploring sustainability and resilience more thoroughly, namely modelling and incorporating the social pillar of sustainability into the formulated problem. Adding to this, it could make sense to incorporate in the cost function a component pertaining to the perceived cost associated with a disruption in a specific link, providing an overall expected cost. In addition, considering the vulnerability of links in a way that is more consistent with real-world situations could make the resilience metric more robust and realistic. Finally, to better support the conclusions obtained, further instances can be developed and tested.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This work was supported by the Center for Research and Development in Mathematics and Applications (CIDMA) through the Portuguese Foundation for Science and Technology (FCT - Fundação para a Ciência e a Tecnologia), references UIDB/04106/2020 and UIDP/04106/2020.

References

Alamatsaz, K., Ahmadi, A., & Mirzapour-Al-e-hashem, S.M.J. (2022). A multiobjective model for the green capacitated location-routing problem considering drivers' satisfaction and time window with uncertain demand. *Environmental Science and Pollution Research*, 29(4), 5052-5071. https://doi.org/10.1007/s11356-021-15907-x

Aloui, A., Hamani, N., & Delahoche, L. (2021). An integrated optimization approach using a collaborative strategy for sustainable cities freight transportation: A case study. *Sustainable Cities and Society*, 75, 1-16. https://doi.org/10.1016/j.scs.2021.103331

Asl, R.S., Khajeh, M.B., Pasban, M., & Rostamzadeh, R. (2023). A systematic literature review on supply chain approaches. *Journal of Modelling in Management*, 18(2), 372-415. https://doi.org/10.1108/jm2-04-2021-0089

Barbosa-Póvoa, A.P. (2014). Process supply chains management - where are we? Where to go next? *Frontiers in Energy Research*, 2, 1-13. https://doi.org/10.3389/fenrg.2014.00023

Barbosa-Póvoa, A.P., Silva, C. da, & Carvalho, A. (2018). Opportunities and challenges in sustainable supply chain: An operations research perspective. *European Journal of Operational Research*, 268(2), 399-431. https://doi.org/10.1016/j.ejor.2017.10.036

Barth, M., & Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. *Transportation Research Record: Journal of the Transportation Research Board*, 2058(1), 163-171. https://doi.org/10.3141/2058-20

Barth, M., Younglove, T., & Scora, G. (2005). *Development of a heavy-duty diesel modal emissions and fuel consumption model* Technical Report UCB-ITS-PRR-2005-1. California PATH Program, Institute of Transportation Studies, University of California at Berkeley.

Beiki, H., Seyedhosseini, S.M., Mihardjo, L.W.W., & Seyedaliakbar, S.M. (2021). Multiobjective location-routing problem of relief commodities with reliability. *Environmental Science and Pollution Research*, 1-10. https://doi.org/10.1007/s11356-020-11891-w

Bektaş, T., Ehmke, J.F., Psaraftis, H.N., & Puchinger, J. (2019). The role of operational research in green freight transportation. *European Journal of Operational Research*, 274(3), 807-823. https://doi.org/10.1016/j.ejor.2018.06.001

Bektaş, T., & Laporte, G. (2011). The pollution-routing problem. *Transportation Research Part B: Methodological*, 45(8), 1232-1250. https://doi.org/10.1016/j.trb.2011.02.004

Carvalho, H., Duarte, S., & Machado, V.C. (2011). Lean, agile, resilient and green: Divergencies and synergies. *International Journal of Lean Six Sigma*, 2(2), 151-179. https://doi.org/10.1108/20401461111135037

Chang, K., Zhou, H., Chen, G., & Chen, H. (2017). Multiobjective location routing problem considering uncertain data after disasters. *Discrete Dynamics in Nature and Society*, 2017, 1-7. https://doi.org/10.1155/2017/1703608

Choudhary, K., & Sangwan, K.S. (2022). Green supply chain management pressures, practices and performance: A critical literature review. *Benchmarking: An International Journal*, 29(5), 1393-1428. https://doi.org/10.1108/bij-05-2021-0242

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *The International Journal of Logistics Management*, 15(2), 1-14. https://doi.org/10.1108/09574090410700275

Demir, E., Bektaş, T., & Laporte, G. (2014). A review of recent research on green road freight transportation. *European Journal of Operational Research*, 237(3), 775-793. https://doi.org/10.1016/j.ejor.2013.12.033

Direção-Geral do Território (2021). *Carta Administrativa Oficial de Portugal*. Available at: https://www.dgterritorio.gov.pt/

Eurostat (2022). *Modal split of freight transport*. European Comission. Available at: https://ec.europa.eu/eurostat/

Galindres, L.F., Guimarães, F.G., & Gallego-Rendón, R.A. (2023). Multi-objective sustainable capacitated location routing problem formulation in sustainable supply-chain management. *Engineering Optimization*, 55(3), 526-541. https://doi.org/10.1080/0305215x.2021.2014476

Haimes, Y.Y., Lasdon, L.S., & Wismer, D.A. (1971). On a bicriterion formulation of the problems of integrated system identification and system optimization. *IEEE Transactions on Systems, Man, and Cybernetics (SMC),* 1(3), 296-297. https://doi.org/10.1109/tsmc.1971.4308298

Heidari, A., Imani, D.M., Khalilzadeh, M., & Sarbazvatan, M. (2022). Green two-echelon closed and open location-routing problem: Application of NSGA-II and MOGWO metaheuristic approaches. *Environment, Development and Sustainability*, 1-37. https://doi.org/10.1007/s10668-022-02429-w

Jayarathna, C.P., Agdas, D., Dawes, L., & Yigitcanlar, T. (2021). Multi-objective optimization for sustainable supply chain and logistics: A review. *Sustainability*, 13(24), 1-31. https://doi.org/10.3390/su132413617

Kamalahmadi, M., & Parast, M.M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. *International Journal of Production Economics*, 171, 116-133. https://doi.org/10.1016/j.ijpe.2015.10.023

Khorsi, M., Chaharsooghi, S.K., Kashan, A.H., & Bozorgi-Amiri, A. (2021). Pareto-based grouping meta-heuristic algorithm for humanitarian relief logistics with multistate network reliability. *OR Spectrum*, 43(2), 327-365. https://doi.org/10.1007/s00291-021-00630-3

Koç, Ç., Bektaş, T., Jabali, O., & Laporte, G. (2014). The fleet size and mix pollution-routing problem. *Transportation Research Part B: Methodological*, 70, 239-254. https://doi.org/10.1016/j.trb.2014.09.008

Larrea-Gallegos, G., Benetto, E., Marvuglia, A., & Gutiérrez, T.N. (2022). Sustainability, resilience and complexity in supply networks: A literature review and a proposal for an integrated agent-based approach. *Sustainable Production and Consumption*, 30, 946-961. https://doi.org/10.1016/j.spc.2022.01.009

Lopes, R.B., Ferreira, C., & Santos, B.S. (2016). A simple and effective evolutionary algorithm for the capacitated location-routing problem. *Computers & Operations Research*, 70, 155-162. https://doi.org/10.1016/j.cor.2016.01.006

Lopes, R.B., Ferreira, C., Santos, B.S., & Barreto, S. (2013). A taxonomical analysis, current methods and objectives on location-routing problems. *International Transactions in Operational Research*, 20(6), 795-822. https://doi.org/10.1111/itor.12032

Mavrotas, G. (2009). Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied Mathematics and Computation*, 213(2), 455-465. https://doi.org/10.1016/j.amc.2009.03.037

Mota, B., Gomes, M.I., Carvalho, A., & Barbosa-Póvoa, A.P. (2015). Towards supply chain sustainability: Economic, environmental and social design and planning. *Journal of Cleaner Production*, 105, 14-27. https://doi.org/10.1016/j.jclepro.2014.07.052

Nasrollahi, M., Razmi, J., & Ghodsi, R. (2018). A computational method for measuring transport related carbon emissions in a healthcare supply network under mixed uncertainty: An empirical study. *Promet - Traffic & Transportation*, 30(6), 693-708. https://doi.org/10.7307/ptt.v30i6.2779

Navazi, F., Sedaghat, A., & Tavakkoli-Moghaddam, R. (2019). A new sustainable location-routing problem with simultaneous pickup and delivery by two-compartment vehicles for a perishable product considering circular economy. *IFAC-PapersOnLine*, 52(13), 790-795. https://doi.org/10.1016/j.ifacol.2019.11.212

Negri, M., Cagno, E., Colicchia, C., & Sarkis, J. (2021). Integrating sustainability and resilience in the supply chain: A systematic literature review and a research agenda. *Business Strategy and the Environment*, 30(7), 2858-2886. https://doi.org/10.1002/bse.2776

Nucamendi-Guillén, S., Gómez-Padilla, A., Olivares-Benitez, E., & Moreno-Vega, J.M. (2021). The multi-depot open location routing problem with a heterogeneous fixed fleet. *Expert Systems with Applications*, 165, 1-14. https://doi.org/10.1016/j.eswa.2020.113846

Ouhader, H., & El-Kyal, M. (2017). Combining facility location and routing decisions in sustainable urban freight distribution under horizontal collaboration: How can shippers be benefited? *Mathematical Problems in Engineering*, 2017, 1-18. https://doi.org/10.1155/2017/8687515

PORDATA (2020). *Densidade populacional*. Available at: https://www.pordata.pt/

Pradenas, L., Oportus, B., & Parada, V. (2013). Mitigation of greenhouse gas emissions in vehicle routing problems with backhauling. *Expert Systems with Applications*, 40(8), 2985-2991. https://doi.org/10.1016/j.eswa.2012.12.014

Prins, C., Prodhon, C., Ruiz, A., Soriano, P., & Calvo, R.W. (2007). Solving the capacitated location-routing problem by a cooperative Lagrangean relaxation-granular tabu search heuristic. *Transportation Science*, 41(4), 470-483. https://doi.org/10.1287/trsc.1060.0187

Prodhon, C., & Prins, C. (2014). A survey of recent research on location-routing problems. *European Journal of Operational Research*, 238(1), 1-17. https://doi.org/10.1016/j.ejor.2014.01.005

Qiu, F., Zhang, G., Chen, P.K., Wang, C., Pan, Y., Sheng, X. et al. (2020). A novel multi-objective model for the cold chain logistics considering multiple effects. *Sustainability*, 12(19), 1-28. https://doi.org/10.3390/su12198068

Rabbani, M., Navazi, F., Farrokhi-Asl, H., & Balali, M.H. (2018). A sustainable transportation-location-routing problem with soft time windows for distribution systems. *Uncertain Supply Chain Management*, 6(3), 229-254. https://doi.org/10.5267/j.uscm.2017.12.002

Rajeev, A., Pati, R.K., Padhi, S.S., & Govindan, K. (2017). Evolution of sustainability in supply chain management: A literature review. *Journal of Cleaner Production*, 162, 299-314. https://doi.org/10.1016/j.jclepro.2017.05.026

Ribeiro, J.P., & Barbosa-Póvoa, A.P. (2018). Supply chain resilience: Definitions and quantitative modelling approaches - a literature review. *Computers & Industrial Engineering*, 115, 109-122. https://doi.org/10.1016/j.cie.2017.11.006

Ribeiro, J.P., & Barbosa-Póvoa, A.P. (2022). A responsiveness metric for the design and planning of resilient supply chains. *Annals of Operations Research*, 1-53. https://doi.org/10.1007/s10479-022-04521-w

Salhi, S., & Rand, G.K. (1989). The effect of ignoring routes when locating depots. *European Journal of Operational Research*, 39(2), 150-156. https://doi.org/10.1016/0377-2217(89)90188-4

Scora, G., & Barth, M. (2006). *Comprehensive Modal Emissions Model (CMEM), version 3.01: User's Guide*. Technical Report. University of California, Riverside, Center for Environmental Research and Technology. https://www.cert.ucr.edu/sites/default/files/2019-07/CMEM_User_Guide_v3.01d.pdf

Shen, L., Tao, F., Shi, Y., & Qin, R. (2019). Optimization of location-routing problem in emergency logistics considering carbon emissions. *International Journal of Environmental Research and Public Health*, 16(16), 1-18. https://doi.org/10.3390/ijerph16162982

Song, Y., Liu, Y.Q., Sun, Q., Chen, M.F., & Xu, H.T. (2021). A joint optimization model considering the product user's risk preference for supply system disruption. *Mathematical Problems in Engineering*, 2021, 1-18. https://doi.org/10.1155/2021/5081753

Suryawanshi, P., & Dutta, P. (2022). Optimization models for supply chains under risk, uncertainty, and resilience: A state-of-the-art review and future research directions. *Transportation Research Part E: Logistics and Transportation Review*, 157, 1-45. https://doi.org/10.1016/j.tre.2021.102553

Tang, C.S. (2006). Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics Research and Applications*, 9(1), 33-45. https://doi.org/10.1080/13675560500405584

Tordecilla, R.D., Juan, A.A., Montoya-Torres, J.R., Quintero-Araujo, C.L., & Panadero, J. (2021). Simulation-optimization methods for designing and assessing resilient supply chain networks under uncertainty scenarios: A review. *Simulation Modelling Practice and Theory*, 106, 1-23. https://doi.org/10.1016/j.simpat.2020.102166

Toro, O.E.M., Franco, J.F., Echeverri, M.G., & Guimarães, F.G. (2017). A multi-objective model for the green capacitated location-routing problem considering environmental impact. *Computers & Industrial Engineering*, 110, 114-125. https://doi.org/10.1016/j.cie.2017.05.013

Validi, S. (2014). *Low carbon multi-objective location-routing in supply chain network design*. Doctoral dissertation, Dublin City University Business School, DCU Online Research Access Service. Avaialable at: https://doras.dcu.ie/19742/

Validi, S., Bhattacharya, A., & Byrne, P.J. (2020). Sustainable distribution system design: A two-phase DoE-guided meta-heuristic solution approach for a three-echelon bi-objective AHP-integrated location-routing model. *Annals of Operations Research*, 290, 191-222. https://doi.org/10.1007/s10479-018-2887-y

Wang, H., Du, L., & Ma, S. (2014). Multi-objective open location-routing model with split delivery for optimized relief distribution in post-earthquake. *Transportation Research Part E: Logistics and Transportation Review*, 69, 160-179. https://doi.org/10.1016/j.tre.2014.06.006

Xiao, Y., Zhao, Q., Kaku, I., & Xu, Y. (2012). Development of a fuel consumption optimization model for the capacitated vehicle routing problem. *Computers & Operations Research*, 39(7), 1419-1431. https://doi.org/10.1016/j.cor.2011.08.013

Zhalechian, M., Tavakkoli-Moghaddam, R., Zahiri, B., & Mohammadi, M. (2016). Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, 89, 182-214. https://doi.org/10.1016/j.tre.2016.02.011

Zhang, H.X., & Zhang, C.M. (2022). Multiobjective green time-dependent location-routing problem and algorithms. *Advances in Operations Research*, 2022, 1-16. https://doi.org/10.1155/2022/1811689

Ziaei, Z., & Jabbarzadeh, A. (2021). A multi-objective robust optimization approach for green location-routing planning of multi-modal transportation systems under uncertainty. *Journal of Cleaner Production*, 291, 1-12. https://doi.org/10.1016/j.jclepro.2020.125293

Appendix A. Instances description

Instance *Portugal* 18×4 represents a hypothetical case of a distribution company in retail sector and is based on real data from Aveiro region, Portugal. Table 7, 8 and 9, include the data related to customers, facilities, and vehicles, respectively.

Customer	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
Demand (demand units)	4,402	6,361	1,377	248	559	3,099	409	2,804	745	338	2,249	651	272	288	1,591	508	768	717

Table 7. Demand of customers in instance *Portugal* 18×4

Facility	F1	F2	F3	F4
Capacity (demand units)	40,000	40,000	40,000	40,000
Opening cost (monetary units)	125,000	125,000	125,000	125,000

Table 8. Capacity and opening cost of facilities in instance *Portugal* 18×4

Fleet available (number of homogeneous vehicles)	10
Capacity of each vehicle (demand units)	7,750
Fixed cost of each vehicle (monetary units)	1,000

Table 9. Data related to the fleet of instance *Portugal* 18×4

Table 10, 11 and 12 correspond, respectively, to the matrices of distances, speed, and alternative paths of instance *Portugal* 18×4.

Nodes	F1	F2	F3	F4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
F1					37.20	33.30	0.85	46.20	47.80	9.10	53.10	54.60	17.80	41.30	40.10	15.60	32.90	41.50	30.60	22.70	17.00	17.30
F2					27.40	30.10	16.40	43.00	40.20	23.80	38.30	40.70	15.50	38.10	33.70	30.20	32.50	29.60	20.20	19.40	14.00	3.70
F3					5.40	18.80	33.60	28.60	22.80	41.00	19.90	22.40	35.30	23.60	13.60	47.40	52.40	12.70	3.30	12.30	15.80	23.60
F4					11.10	9.40	39.40	13.10	11.70	46.80	12.50	16.80	46.20	9.30	2.30	53.20	62.90	21.40	18.30	17.20	22.30	36.60
C1	37.20	27.40	5.40	11.10		15.90	38.30	22.90	17.10	45.60	15.40	18.40	37.20	18.30	8.20	52.00	54.70	12.30	8.60	15.60	19.40	25.40
C2	33.30	30.10	18.80	9.40	15.90		34.10	16.60	18.20	41.60	21.10	25.40	44.40	11.70	10.90	48.00	62.00	27.20	20.50	12.00	17.00	32.70
C3	0.85	16.40	33.60	39.40	38.30	34.10		46.50	48.10	9.40	50.10	52.40	17.60	41.60	40.30	15.80	34.80	41.80	30.90	23.00	17.20	17.60
C4	46.20	43.00	28.60	13.10	22.90	16.60	46.50		7.00	53.80	11.70	18.90	57.40	4.80	13.30	60.30	74.10	32.90	30.40	24.30	29.30	46.40
C5	47.80	40.20	22.80	11.70	17.10	18.20	48.10	7.00		61.40	5.10	12.20	54.40	6.70	9.10	66.30	72.00	26.90	25.20	25.70	30.90	42.70
C6	9.10	23.80	41.00	46.80	45.60	41.60	9.40	53.80	61.40		60.70	62.00	22.70	49.00	47.70	8.00	29.00	49.80	38.60	30.50	24.80	26.00
C7	53.10	38.30	19.90	12.50	15.40	21.10	50.10	11.70	5.10	60.70		7.60	52.30	11.40	9.90	67.10	69.80	25.00	24.60	26.90	31.70	40.50
C8	54.60	40.70	22.40	16.80	18.40	25.40	52.40	18.90	12.20	62.00	7.60		53.60	19.20	14.30	68.40	71.20	23.10	25.90	30.20	35.10	41.90
C9	17.80	15.50	35.30	46.20	37.20	44.40	17.60	57.40	54.40	22.70	52.30	53.60		54.70	46.30	27.50	18.80	40.20	30.20	32.60	28.40	11.70
C10	41.30	38.10	23.60	9.30	18.30	11.70	41.60	4.80	6.70	49.00	11.40	19.20	54.70		10.10	55.50	71.10	29.10	26.30	19.50	24.50	44.30
C11	40.10	33.70	13.60	2.30	8.20	10.90	40.30	13.30	9.10	47.70	9.90	14.30	46.30	10.10		54.10	63.80	19.30	16.70	16.70	22.50	34.50
C12	15.60	30.20	47.40	53.20	52.00	48.00	15.80	60.30	66.30	8.00	67.10	68.40	27.50	55.50	54.10		25.60	56.20	45.00	36.90	31.30	31.70
C13	32.90	32.50	52.40	62.90	54.70	62.00	34.80	74.10	72.00	29.00	69.80	71.20	18.80	71.10	63.80	25.60		58.40	47.20	49.40	45.10	28.80
C14	41.50	29.60	12.70	21.40	12.30	27.20	41.80	32.90	26.90	49.80	25.00	23.10	40.20	29.10	19.30	56.20	58.40		13.90	23.50	26.20	28.50
C15	30.60	20.20	3.30	18.30	8.60	20.50	30.90	30.40	25.20	38.60	24.60	25.90	30.20	26.30	16.70	45.00	47.20	13.90		10.50	13.30	18.40
C16	22.70	19.40	12.30	17.20	15.60	12.00	23.00	24.30	25.70	30.50	26.90	30.20	32.60	19.50	16.70	36.90	49.40	23.50	10.50		5.90	21.60
C17	17.00	14.00	15.80	22.30	19.40	17.00	17.20	29.30	30.90	24.80	31.70	35.10	28.40	24.50	22.50	31.30	45.10	26.20	13.30	5.90		17.30
C18	17.30	3.70	23.60	36.60	25.40	32.70	17.60	46.40	42.70	26.00	40.50	41.90	11.70	44.30	34.50	31.70	28.80	28.50	18.40	21.60	17.30	

Table 10. Distances matrix of instance *Portugal* 18×4 (in kilometers)

Nodes	F1	F2	F3	F4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
F1					12.40	11.10	7.08	11.00	11.38	12.64	12.64	14.00	12.36	11.47	12.15	11.82	12.19	12.58	14.57	12.61	12.88	13.11
F2					13.05	11.15	12.42	11.03	12.18	11.33	12.77	15.07	12.92	11.55	12.48	11.19	15.48	12.33	12.02	12.44	12.96	12.33
F3					11.25	11.19	12.44	13.62	12.67	12.42	12.76	14.36	13.07	13.11	11.33	12.15	14.56	13.23	7.86	11.39	13.17	14.05
F4					10.28	13.06	10.94	12.13	12.19	12.00	9.47	12.73	19.25	12.92	7.67	11.82	17.47	13.72	11.73	13.03	13.27	21.79
C1	12.40	13.05	11.25	10.28		12.05	12.77	12.72	10.96	12.67	9.87	12.78	13.78	11.73	9.76	12.38	15.19	11.39	10.24	11.82	12.44	14.11
C2	11.10	11.15	11.19	13.06	12.05		10.33	11.53	12.64	10.67	13.53	12.10	11.38	12.19	12.98	11.43	11.48	10.07	11.39	11.11	10.90	10.90
C3	7.08	12.42	12.44	10.94	12.77	10.33		11.07	10.69	9.79	11.13	11.64	10.48	10.67	11.19	10.97	11.60	12.67	12.88	10.95	11.03	11.28
C4	11.00	11.03	13.62	12.13	12.72	11.53	11.07		11.67	10.55	10.83	12.12	17.39	10.00	12.31	10.05	17.64	12.19	12.67	11.57	10.85	11.05
C5	11.38	12.18	12.67	12.19	10.96	12.64	10.69	11.67		20.47	7.08	10.17	12.95	12.41	10.83	20.09	12.00	12.81	10.50	15.30	18.39	12.94
C6	12.64	11.33	12.42	12.00	12.67	10.67	9.79	10.55	20.47		11.90	12.16	12.61	11.67	11.36	11.11	16.11	12.77	11.70	11.30	11.81	12.38
C7	12.64	12.77	12.76	9.47	9.87	13.53	11.13	10.83	7.08	11.90		10.56	12.45	9.50	9.17	11.18	11.63	11.90	11.71	11.21	10.57	12.27
C8	14.00	15.07	14.36	12.73	12.78	12.10	11.64	12.12	10.17	12.16	10.56		12.76	10.67	10.83	11.40	11.87	11.00	14.39	12.58	13.00	12.70
C9	12.36	12.92	13.07	19.25	13.78	11.38	10.48	17.39	12.95	12.61	12.45	12.76		18.23	12.86	13.10	13.06	11.17	12.58	15.52	13.52	12.19
C10	11.47	11.55	13.11	12.92	11.73	12.19	10.67	10.00	12.41	11.67	9.50	10.67	18.23		14.03	10.88	19.75	13.86	12.52	11.61	11.67	13.42
C11	12.15	12.48	11.33	7.67	9.76	12.98	11.19	12.31	10.83	11.36	9.17	10.83	12.86	14.03		11.27	17.72	13.40	10.71	11.60	12.50	14.38
C12	11.82	11.19	12.15	11.82	12.38	11.43	10.97	10.05	20.09	11.11	11.18	11.40	13.10	10.88	11.27		14.22	12.49	11.54	11.18	11.59	11.74
C13	12.19	15.48	14.56	17.47	15.19	11.48	11.60	17.64	12.00	16.11	11.63	11.87	13.06	19.75	17.72	14.22		13.90	14.30	16.47	15.03	17.14
C14	12.58	12.33	13.23	13.72	11.39	10.07	12.67	12.19	12.81	12.77	11.90	11.00	11.17	13.86	13.40	12.49	13.90		12.87	13.06	16.79	11.88
C15	14.57	12.02	7.86	11.73	10.24	11.39	12.88	12.67	10.50	11.70	11.71	14.39	12.58	12.52	10.71	11.54	14.30	12.87		10.94	12.31	12.78
C16	12.61	12.44	11.39	13.03	11.82	11.11	10.95	11.57	15.30	11.30	11.21	12.58	15.52	11.61	11.60	11.18	16.47	13.06	10.94		9.83	12.00
C17	12.88	12.96	13.17	13.27	12.44	10.90	11.03	10.85	18.39	11.81	10.57	13.00	13.52	11.67	12.50	11.59	15.03	16.79	12.31	9.83		12.01
C18	13.11	12.33	14.05	21.79	14.11	10.90	11.28	11.05	12.94	12.38	12.27	12.70	12.19	13.42	14.38	11.74	17.14	11.88	12.78	12.00	12.01	

Table 11. Speed matrix of instance *Portugal* 18×4 (in meters per second)

Nodes	F1	F2	F3	F4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
F1					6	4	2	4	6	3	4	3	4	4	6	4	6	3	4	2	4	4
F2					4	6	3	6	6	4	6	5	3	6	6	6	5	4	2	6	5	2
F3					3	4	4	6	4	4	4	5	4	5	5	2	5	2	3	4	5	1
F4					3	3	6	6	5	4	5	6	5	4	4	6	6	3	5	6	5	3
C1	6	4	3	3		3	3	6	4	3	4	4	3	5	3	4	4	3	3	4	3	2
C2	4	6	4	3	3		3	3	5	4	6	6	6	5	4	4	6	5	5	3	4	5
C3	2	3	4	6	3	3		5	6	3	6	6	6	5	6	5	5	4	4	2	4	3
C4	4	6	6	6	6	3	5		3	6	5	6	5	4	6	6	6	6	6	6	5	5
C5	6	6	4	5	4	5	6	3		6	3	4	5	3	4	6	6	5	5	6	5	4
C6	3	4	4	4	3	4	3	6	6		5	4	6	5	5	3	4	4	4	5	3	4
C7	4	6	4	5	4	6	6	5	3	5		4	5	4	4	5	6	5	5	6	6	4
C8	3	5	5	6	4	6	6	6	4	4	4		4	6	5	4	4	4	5	6	6	6
C9	4	3	4	5	3	6	6	5	5	6	5	4		6	5	5	4	6	4	6	6	3
C10	4	6	5	4	5	5	5	4	3	5	4	6	6		4	6	6	6	6	6	6	4
C11	6	6	5	4	3	4	6	6	4	5	4	5	5	4		6	6	4	4	5	5	3
C12	4	6	2	6	4	4	5	6	6	3	5	4	5	6	6		3	5	6	5	4	6
C13	6	5	5	6	4	6	5	6	6	4	6	4	4	6	6	3		5	6	5	5	5
C14	3	4	2	3	3	5	4	6	5	4	5	4	6	6	4	5	5		3	5	4	4
C15	4	2	3	5	3	5	4	6	5	4	5	5	4	6	4	6	6	3		3	3	2
C16	2	6	4	6	4	3	2	6	6	5	6	6	6	6	5	5	5	5	3		1	3

Nodes	F1	F2	F3	F4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
C17	4	5	5	5	3	4	4	5	5	3	6	6	6	6	5	4	5	4	3	1		3
C18	4	2	1	3	2	5	3	5	4	4	4	6	3	4	3	6	5	4	2	3	3	

Table 12. Alternative paths matrix of instance *Portugal* 18×4

Instance *US* 13×13 was adapted from the case study presented in the work of Nucamendi-Guillén et al. (2021). The 13 suppliers were considered customers, and the 13 possible carriers were considered potential locations for facilities. The amount of raw material to be collected from each supplier was treated as demand (Table 13). Since each carrier had a fleet of vehicles available, the sum of their respective capacities was assumed to be the capacity of facility (Table 14). In the original instance the vehicle with the highest capacity could carry up to 75 units of demand, and for this reason this was the capacity limit considered for the homogeneous fleet (Table 15). The mass of a demand unit was defined as 206 kilograms.

Customer	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Demand (demand units)	10	8	15	11	13	9	10	12	9	14	12	8	12

Table 13. Demand of customers in instance *US* 13×13

Facility	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
Capacity (demand units)	180	255	140	100	160	235	155	200	145	245	110	235	170
Opening cost (monetary units)	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000

Table 14. Capacity and opening cost of facilities in instance *US* 13×13

Available fleet (number of homogeneous vehicles)	7
Capacity of each vehicle (demand units)	75
Fixed cost of each vehicle (monetary units)	10,000

Table 15. Data related to the fleet of instance *US* 13×13

Table 16, 17 and 18 correspond, respectively, to the matrices of distances, speed, and alternative paths of instance *US* 13×13.

Nodes	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
F1														1622	1697	1519	1452	1407	893	1347	1526	1623	1064	202	47.4	98
F2														766	938	610	544	54.1	582	94.6	565	613	666	1229	1399	1526
F3														154	332	29.7	58.8	548	653	638	1205	1237	1204	1316	1462	1576
F4														98.8	88.8	246	317	804	907	897	1420	1447	1440	1570	1662	1682
F5														1475	1653	1334	1267	1237	708	1146	1340	1436	878	9.8	159	287
F6														1329	1506	1178	1112	605	1055	573	9.5	97.3	487	1334	1489	1640
F7														788	929	630	558	533	26.9	557	1056	1099	709	716	862	990
F8														1663	1750	1577	1504	1551	1001	1452	1632	1729	1170	307	150	20.8
F9														56.2	166	204	267	761	864	855	1377	1401	1397	1527	1643	1651
F10														1401	1602	1260	1202	752	750	652	465	561	66.8	885	1040	1168
F11														1343	1521	1192	1126	640	1089	608	74	28.4	562	1425	1580	1707
F12														204	395	69.2	13.3	506	594	586	1148	1181	1146	1276	1422	1504

Nodes	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
F13														783	954	627	560	85.2	518	31.1	593	638	632	1166	1336	1463
C1	1622	766	154	98.8	1475	1329	788	1663	56.2	1401	1343	204	783		185	151	211	711	814	809	1327	1354	1347	1477	1623	1661
C2	1697	938	332	88.8	1653	1506	929	1750	166	1602	1521	395	954	185		332	401	886	984	984	1506	1533	1526	1639	1802	1733
C3	1519	610	29.7	246	1334	1178	630	1577	204	1260	1192	69.2	627	151	332		69.1	554	662	652	1194	1218	1202	1335	1482	1572
C4	1452	544	58.8	317	1267	1112	558	1504	267	1202	1126	13.3	560	211	401	69.1		490	601	580	1141	1174	1138	1271	1417	1498
C5	1407	54.1	548	804	1237	605	533	1551	761	752	640	506	85.2	711	886	554	490		547	114	616	664	722	1226	1372	1512
C6	893	582	653	907	708	1055	26.9	1001	864	750	1089	594	518	814	984	662	601	547		499	1066	1111	694	709	856	984
C7	1347	94.6	638	897	1146	573	557	1452	855	652	608	586	31.1	809	984	652	580	114	499		582	628	604	1139	1309	1436
C8	1526	565	1205	1420	1340	9.5	1056	1632	1377	465	74	1148	593	1327	1506	1194	1141	616	1066	582		101	488	1329	1483	1611
C9	1623	613	1237	1447	1436	97.3	1099	1729	1401	561	28.4	1181	638	1354	1533	1218	1174	664	1111	628	101		586	1450	1604	1732
C10	1064	666	1204	1440	878	487	709	1170	1397	66.8	562	1146	632	1347	1526	1202	1138	722	694	604	488	586		866	1021	1148
C11	202	1229	1316	1570	9.8	1334	716	307	1527	885	1425	1276	1166	1477	1639	1335	1271	1226	709	1139	1329	1450	866		159	287
C12	47.4	1399	1462	1662	159	1489	862	150	1643	1040	1580	1422	1336	1623	1802	1482	1417	1372	856	1309	1483	1604	1021	159		133
C13	98	1526	1576	1682	287	1640	990	20.8	1651	1168	1707	1504	1463	1661	1733	1572	1498	1512	984	1436	1611	1732	1148	287	133	

Table 16. Distances matrix of instance *US* 13×13 (in kilometers)

Nodes	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
F1														18.93	25.69	27.19	27.56	26.47	25.23	27.31	26.03	26.21	25.44	17.72	17.56	16.33
F2														25.53	25.63	24.21	25.19	11.27	22.05	21.02	17.44	18.58	18.20	27.24	27.14	27.14
F3														15.10	17.85	9.00	16.33	24.04	23.16	24.73	21.05	26.20	26.27	27.38	24.61	27.45
F4														19.37	24.67	25.63	13.90	25.28	25.62	25.34	27.02	25.12	25.97	27.63	19.24	25.91
F5														27.62	27.83	27.28	27.75	27.31	26.22	27.52	26.24	26.42	25.63	6.28	17.67	19.93
F6														26.98	27.25	25.94	26.29	17.09	18.32	16.75	8.80	8.54	23.87	26.22	25.99	26.46
F7														25.26	18.57	15.00	16.03	25.38	11.21	25.09	18.53	18.69	26.09	25.39	25.20	27.73
F8														18.48	25.72	19.05	19.24	27.56	25.28	27.25	26.08	26.24	25.56	21.32	22.73	13.33
F9														13.38	23.06	24.29	12.71	24.87	24.83	25.00	24.68	19.96	25.73	27.42	25.57	25.69
F10														25.80	26.92	25.30	26.36	18.16	25.51	17.81	24.22	23.97	15.90	22.69	25.72	25.85
F11														24.87	27.41	22.84	23.17	16.67	20.98	16.34	8.22	13.52	24.02	26.78	26.47	26.51
F12														11.33	15.67	8.87	6.33	23.43	16.23	16.84	20.66	18.93	25.57	25.62	27.49	19.09
F13														26.10	26.07	24.88	17.28	18.93	26.16	17.28	17.34	17.15	17.56	25.91	27.35	27.34
C1	18.93	25.53	15.10	19.37	27.62	26.98	25.26	18.48	13.38	25.80	24.87	11.33	26.10		25.69	16.78	12.13	25.21	24.67	25.44	24.30	19.45	22.68	27.57	27.46	18.46
C2	25.69	25.63	17.85	24.67	27.83	27.25	18.57	25.72	23.06	26.92	27.41	15.67	26.07	25.69		26.35	15.19	25.03	25.63	25.23	25.61	27.21	26.14	25.41	27.60	26.00
C3	27.19	24.21	9.00	25.63	27.28	25.94	15.00	19.05	24.29	25.30	22.84	8.87	24.88	16.78	26.35		15.36	23.68	15.54	24.15	20.79	21.55	25.33	27.33	27.26	18.96
C4	27.56	25.19	16.33	13.90	27.75	26.29	16.03	19.24	12.71	26.36	23.17	6.33	17.28	12.13	15.19	15.36		24.75	16.69	17.26	18.29	19.18	25.56	27.73	27.56	19.21
C5	26.47	11.27	24.04	25.28	27.31	17.09	25.38	27.56	24.87	18.16	16.67	23.43	18.93	25.21	25.03	23.68	24.75		25.32	19.00	16.83	18.14	16.95	26.68	26.62	27.30
C6	25.23	22.05	23.16	25.62	26.22	18.32	11.21	25.28	24.83	25.51	20.98	16.23	26.16	24.67	25.63	15.54	16.69	25.32		18.08	18.51	18.70	25.70	25.14	25.03	25.23
C7	27.31	21.02	24.73	25.34	27.52	16.75	25.09	27.25	25.00	17.81	16.34	16.84	17.28	25.44	25.23	24.15	17.26	19.00	18.08		17.02	16.88	17.98	25.65	27.27	27.26
C8	26.03	17.44	21.05	27.02	26.24	8.80	18.53	26.08	24.68	24.22	8.22	20.66	17.34	24.30	25.61	20.79	18.29	16.83	18.51	17.02		9.35	24.65	26.28	25.99	26.09
C9	26.21	18.58	26.20	25.12	26.42	8.54	18.69	26.24	19.96	23.97	13.52	18.93	17.15	19.45	27.21	21.55	19.18	18.14	18.70	16.88	9.35		23.82	26.85	26.52	26.58
C10	25.44	18.20	26.27	25.97	25.63	23.87	26.09	25.56	25.73	15.90	24.02	25.57	17.56	22.68	26.14	25.33	25.56	16.95	25.70	17.98	24.65	23.82		25.87	25.55	25.72
C11	17.72	27.24	27.38	27.63	6.28	26.22	25.39	21.32	27.42	22.69	26.78	25.62	25.91	27.57	25.41	27.33	27.73	26.68	25.14	25.65	26.28	26.85	25.87		16.56	19.13
C12	17.56	27.14	24.61	19.24	17.67	25.99	25.20	22.73	25.57	25.72	26.47	27.49	27.35	27.46	27.60	27.26	27.56	26.62	25.03	27.27	25.99	26.52	25.55	16.56		22.17
C13	16.33	27.14	27.45	25.91	19.93	26.46	27.73	13.33	25.69	25.85	26.51	19.09	27.34	18.46	26.00	18.96	19.21	27.30	25.23	27.26	26.09	26.58	25.72	19.13	22.17	

Table 17. Speed matrix of instance *US* 13×13 (in meters per second)

Nodes	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
F1														3	5	4	3	6	6	3	6	6	6	6	6	6
F2														6	5	6	6	4	5	5	5	6	6	6	5	5
F3														5	6	6	6	6	4	5	6	6	6	5	6	6
F4														6	5	5	6	5	5	6	6	4	6	6	6	6
F5														3	4	4	4	5	6	4	6	6	6	5	6	4
F6														6	6	6	6	5	6	6	2	4	6	6	6	6
F7														5	6	5	6	5	6	6	6	6	6	6	6	6
F8														5	6	5	5	4	6	5	6	6	6	5	6	3
F9														6	4	6	6	6	6	6	6	5	6	6	6	6
F10														4	4	6	6	5	6	6	6	6	6	6	6	6
F11														6	6	6	6	6	6	6	4	5	6	6	5	5
F12														6	6	6	3	6	5	6	3	3	6	5	5	5
F13														3	4	6	6	4	6	5	6	6	6	6	6	6
C1	3	6	5	6	3	6	5	5	6	4	6	6	3		5	5	6	4	3	4	6	4	5	6	6	5
C2	5	5	6	5	4	6	6	6	4	4	6	6	4	5		3	6	5	5	4	6	4	5	6	6	5
C3	4	6	6	5	4	6	5	5	6	6	6	6	6	5	3		6	6	5	5	4	2	5	4	4	5
C4	3	6	6	6	4	6	6	5	6	6	6	3	6	6	6	6		6	5	6	3	3	6	5	5	5
C5	6	4	6	5	5	5	5	4	6	5	6	6	4	4	5	6	6		5	6	6	6	6	6	6	6
C6	6	5	4	5	6	6	6	6	6	6	6	5	6	3	5	5	5	5		6	5	6	6	6	6	6
C7	3	5	5	6	4	6	6	5	6	6	6	6	5	4	4	5	6	6	6		6	6	6	6	6	6
C8	6	5	6	6	6	2	6	6	6	6	4	3	6	6	6	4	3	6	5	6		6	6	6	6	6
C9	6	6	6	4	6	4	6	6	5	6	5	3	6	4	4	2	3	6	6	6	6		6	6	6	6
C10	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	6	6	6	6	6	6		5	6	6
C11	6	6	5	6	5	6	6	5	6	6	6	5	6	6	6	4	5	6	6	6	6	6	5		6	6
C12	6	5	6	6	6	6	6	6	6	6	5	5	6	6	6	4	5	6	6	6	6	6	6	6		5
C13	6	5	6	6	4	6	6	3	6	6	5	5	6	5	5	5	5	6	6	6	6	6	6	6	5	

Table 18. Alternative paths matrix of instance *US* 13×13

Instances *Ireland* 6×2 and *Ireland* 22×6 were adapted from the case of a dairy processing industry supply chain presented in the paper of Validi et al. (2020). In instance ***Ireland* 6×2** processing plants are potential facilities, and distribution centers are customers. Thus, the capacity of distribution centers indicated in the original instance was treated as demand (the values were divided by 1,000) (Table 19). The capacity of each facility was defined as the sum of the total demand, to avoid restricting the location decision (Table 20). The opening costs indicated in the original instance were multiplied by 1,000 (Table 20) and the fixed cost of vehicles was set to be 200,000 (Table 21). It was assumed that the capacity of each vehicle was 4,000 demand units, and that each demand unit had a mass of 3.5 kilograms (Table 21).

Customer	C1	C2	C3	C4	C5	C6
Demand (demand units)	800	1,000	1,000	1,000	700	1,000

Table 19. Demand of customers in instance *Ireland* 6×2

Facility	F1	F2
Capacity (demand units)	5,500	5,500
Opening cost (monetary units)	1,500,000	2,000,000

Table 20. Capacity and opening cost of facilities in instance *Ireland* 6×2

Available fleet (number of homogeneous vehicles)	4
Capacity of each vehicle (demand units)	4,000
Fixed cost of each vehicle (monetary units)	200,000

Table 21. Data related to the fleet of instance *Ireland* 6×2

Table 22, 23 and 24 correspond, respectively, to the matrices of distances, speed, and alternative paths of instance *Ireland* 6×2.

Nodes	F1	F2	C1	C2	C3	C4	C5	C6
F1			38.8	7.2	47.0	110.0	73.0	205.0
F2			136.0	98.9	60.6	61.0	70.5	99.9
C1	38.8	136.0		35.9	80.5	131.0	111.0	236.0
C2	7.2	98.9	35.9		45.2	106.0	72.8	201.0
C3	47.0	60.6	80.5	45.2		92.2	28.5	159.0
C4	110.0	61.0	131.0	106.0	92.2		114.0	133.0
C5	73.0	70.5	111.0	72.8	28.5	114.0		148.0
C6	205.0	99.9	236.0	201.0	159.0	133.0	148.0	

Table 22. Distances matrix of instance *Ireland* 6×2 (in kilometers)

Nodes	F1	F2	C1	C2	C3	C4	C5	C6
F1			12.93	6.67	10.44	15.28	7.16	13.67
F2			16.19	12.68	9.18	14.52	14.69	15.14
C1	12.93	16.19		17.10	10.32	16.79	8.81	14.05
C2	6.67	12.68	17.10		10.76	14.72	6.39	13.96
C3	10.44	9.18	10.32	10.76		15.37	5.94	13.25
C4	15.28	14.52	16.79	14.72	15.37		11.88	14.78
C5	7.16	14.69	8.81	6.39	5.94	11.88		14.51
C6	13.67	15.14	14.05	13.96	13.25	14.78	14.51	

Table 23. Speed matrix of instance *Ireland* 6×2 (in meters per second)

Nodes	F1	F2	C1	C2	C3	C4	C5	C6
F1			4	3	5	5	5	6
F2			5	5	4	4	6	6
C1	4	5		5	5	5	6	4
C2	3	5	5		5	4	6	6
C3	5	4	5	5		6	4	5
C4	5	4	5	4	6		6	6
C5	5	6	6	6	4	6		6
C6	6	6	4	6	5	6	6	

Table 24. Alternative paths matrix of instance *Ireland* 6×2

In instance *Ireland* 22×6 distribution centers correspond to potential facilities, and retailers to customers. The original values for the demand of each retailer corresponds to two thirds of the total population at the respective location (Validi, 2014), and were divided by 100 (Table 25). The capacity of facilities was considered proportional to the capacity originally defined for distribution centers (the values were divided by 100) (Table 26). The opening costs indicated in the original instance were multiplied by 1,000 (Table 26) and the fixed cost of vehicles was set to be 20,000 (Table 27). It was assumed that the capacity of each vehicle was 3,800 demand units, and that each demand unit had a mass of 3.5 kilograms (Table 27).

Customer	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
Demand (demand units)	250	250	190	90	140	145	100	90	210	90	70	110	120	350	70	160	130	70	3,500	1,380	1,820	1,770

Table 25. Demand of customers in instance *Ireland* 22×6

Facility	F1	F2	F3	F4	F5	F6
Capacity (demand units)	8,000	10,000	10,000	10,000	7,000	10,000
Opening cost (monetary units)	200,000	250,000	250,000	250,000	100,000	250,000

Table 26. Capacity and opening cost of facilities in instance *Ireland* 22×6

Available fleet (number of homogeneous vehicles)	12
Capacity of each vehicle (demand units)	3,800
Fixed cost of each vehicle (monetary units)	20,000

Table 27. Data related to the fleet of instance *Ireland* 22×6

Table 28, 29 and 30 correspond, respectively, to the matrices of distances, speed, and alternative paths of instance *Ireland* 22×6.

Nodes	F1	F2	F3	F4	F5	F6	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
F1							32.9	2.6	51.3	125.0	107.0	117.0	79.5	142.0	106.0	165.0	133.0	109.0	229.0	237.0	248.0	190.0	218.0	203.0	87.5	99.3	62.1	93.7
F2							3.4	36.8	24.9	104.0	70.1	80.8	45.0	115.0	68.4	131.0	99.0	74.8	202.0	202.0	212.0	157.0	190.0	158.0	49.7	61.1	29.3	55.9
F3							47.4	81.1	45.6	92.4	31.8	44.8	16.4	87.9	24.9	80.1	54.7	31.2	164.0	159.0	170.0	114.0	139.0	118.0	5.0	16.5	20.7	16.4
F4							108.0	131.0	82.0	2.2	62.0	53.1	77.0	33.2	114.0	118.0	119.0	122.0	119.0	134.0	145.0	81.7	144.0	122.0	94.8	105.0	103.0	81.0
F5							72.6	111.0	72.2	113.0	48.0	61.1	39.2	102.0	2.8	47.8	26.1	6.8	170.0	149.0	165.0	119.0	113.0	95.1	28.8	12.5	45.7	30.4
F6							199.0	238.0	188.0	133.0	126.0	122.0	152.0	100.0	150.0	99.1	125.0	146.0	47.6	0.8	11.9	50.9	57.5	53.6	160.0	158.0	181.0	143.0
C1	32.9	3.4	47.4	108.0	72.6	199.0		33.6	27.2	107.0	74.0	83.5	47.7	118.0	69.5	135.0	102.0	76.1	205.0	201.0	212.0	156.0	192.0	161.0	52.0	62.5	29.2	58.6
C2	2.6	36.8	81.1	131.0	111.0	238.0	33.6		51.6	125.0	109.0	119.0	80.0	142.0	107.0	166.0	136.0	114.0	229.0	238.0	249.0	189.0	220.0	197.0	88.3	100.0	62.6	94.9
C3	51.3	24.9	45.6	82.0	72.2	188.0	27.2	51.6		79.6	59.1	69.5	42.4	91.5	70.7	127.0	104.0	86.0	178.0	188.0	199.0	139.0	177.0	154.0	50.8	63.7	41.4	53.3
C4	125.0	104.0	92.4	2.2	113.0	133.0	107.0	125.0	79.6		63.8	55.5	77.2	33.7	115.0	121.0	121.0	122.0	119.0	134.0	145.0	82.2	145.0	122.0	96.5	105.0	102.0	82.7
C5	107.0	70.1	31.8	62.0	48.0	126.0	74.0	109.0	59.1	63.8		12.0	25.3	51.1	48.4	71.9	63.4	57.3	132.0	127.0	138.0	82.1	115.0	92.8	33.5	39.9	53.8	18.6
C6	117.0	80.8	44.8	53.1	61.1	122.0	83.5	119.0	69.5	55.5	12.0		38.0	40.6	60.8	73.9	68.4	69.6	127.0	121.0	132.0	76.4	110.0	87.2	46.6	52.4	65.5	31.0
C7	79.5	45.0	16.4	77.0	39.2	152.0	47.7	80.0	42.4	77.2	25.3	38.0		73.8	36.8	86.6	64.9	43.2	158.0	153.0	163.0	108.0	141.0	118.0	18.5	28.3	28.2	14.7
C8	142.0	115.0	87.9	33.2	102.0	100.0	118.0	142.0	91.5	33.7	51.1	40.6	73.8		100.0	92.9	103.0	108.0	88.4	101.0	112.0	48.9	112.0	89.4	89.3	91.8	100.0	70.4
C9	106.0	68.4	24.9	114.0	2.8	150.0	69.5	107.0	70.7	115.0	48.4	60.8	36.8	100.0		50.1	27.8	6.4	172.0	152.0	167.0	121.0	115.0	98.9	25.8	10.4	42.2	31.6
C10	165.0	131.0	80.1	118.0	47.8	99.1	135.0	166.0	127.0	121.0	71.9	73.9	86.6	92.9	50.1		26.0	45.2	139.0	101.0	116.0	88.0	60.0	47.0	79.0	59.6	91.4	77.6
C11	133.0	99.0	54.7	119.0	26.1	125.0	102.0	136.0	104.0	121.0	63.4	68.4	64.9	103.0	27.8	26.0		21.5	155.0	127.0	142.0	108.0	86.9	73.2	53.7	37.9	69.8	53.7

Nodes	F1	F2	F3	F4	F5	F6	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
C12	109.0	74.8	31.2	122.0	6.8	146.0	76.1	114.0	86.0	122.0	57.3	69.6	43.2	108.0	6.4	45.2	21.5		170.0	147.0	162.0	119.0	107.0	93.3	32.2	19.1	49.1	37.0
C13	229.0	202.0	164.0	119.0	170.0	47.6	205.0	229.0	178.0	119.0	132.0	127.0	158.0	88.4	172.0	139.0	155.0	170.0		48.4	53.0	53.1	98.5	88.5	169.0	171.0	188.0	154.0
C14	237.0	202.0	159.0	134.0	149.0	0.8	201.0	238.0	188.0	134.0	127.0	121.0	153.0	101.0	152.0	101.0	127.0	147.0	48.4		12.6	50.6	57.2	53.3	159.0	158.0	181.0	143.0
C15	248.0	212.0	170.0	145.0	165.0	11.9	212.0	249.0	199.0	145.0	138.0	132.0	163.0	112.0	167.0	116.0	142.0	162.0	53.0	12.6		62.4	57.3	69.7	171.0	170.0	193.0	155.0
C16	190.0	157.0	114.0	81.7	119.0	50.9	156.0	189.0	139.0	82.2	82.1	76.4	108.0	48.9	121.0	88.0	108.0	119.0	53.1	50.6	62.4		75.9	57.1	115.0	120.0	137.0	100.0
C17	218.0	190.0	139.0	144.0	113.0	57.5	192.0	220.0	177.0	145.0	115.0	110.0	141.0	112.0	115.0	60.0	86.9	107.0	98.5	57.2	57.3	75.9		23.9	138.0	124.0	165.0	126.0
C18	203.0	158.0	118.0	122.0	95.1	53.6	161.0	197.0	154.0	122.0	92.8	87.2	118.0	89.4	98.9	47.0	73.2	93.3	88.5	53.3	69.7	57.1	23.9		120.0	109.0	142.0	103.0
C19	87.5	49.7	5.0	94.8	28.8	160.0	52.0	88.3	50.8	96.5	33.5	46.6	18.5	89.3	25.8	79.0	53.7	32.2	169.0	159.0	171.0	115.0	138.0	120.0		17.2	23.8	16.2
C20	99.3	61.1	16.5	105.0	12.5	158.0	62.5	100.0	63.7	105.0	39.9	52.4	28.3	91.8	10.4	59.6	37.9	19.1	171.0	158.0	170.0	120.0	124.0	109.0	17.2		34.9	20.9
C21	62.1	29.3	20.7	103.0	45.7	181.0	29.2	62.6	41.4	102.0	53.8	65.5	28.2	100.0	42.2	91.4	69.8	49.1	188.0	181.0	193.0	137.0	165.0	142.0	23.8	34.9		35.1
C22	93.7	55.9	16.4	81.0	30.4	143.0	58.6	94.9	53.3	82.7	18.6	31.0	14.7	70.4	31.6	77.6	53.7	37.0	154.0	143.0	155.0	100.0	126.0	103.0	16.2	20.9	35.1	

Table 28. Distances matrix of instance *Ireland* 22×6 (in kilometers)

Nodes	F1	F2	F3	F4	F5	F6	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
F1							13.71	7.22	13.15	16.03	13.72	13.93	12.05	14.79	8.03	16.18	9.24	7.90	15.27	14.11	14.25	15.08	12.98	14.71	10.42	7.88	12.94	14.20
F2							5.67	17.52	11.86	15.76	9.74	10.36	10.00	13.69	6.33	14.56	7.86	6.23	15.30	13.47	13.59	13.77	14.39	12.54	8.28	8.49	13.95	8.47
F3							10.53	11.26	12.67	15.40	9.64	9.96	11.39	12.21	4.15	9.54	8.29	4.73	14.39	13.25	13.49	13.57	11.58	13.11	5.95	3.67	8.63	6.07
F4							13.85	16.79	16.08	6.11	14.76	14.75	14.26	13.83	14.62	15.13	14.17	14.52	16.53	13.96	14.22	15.13	15.00	15.64	12.15	13.46	14.31	22.50
F5							7.56	9.25	8.02	12.56	10.67	10.18	8.71	21.25	9.33	19.92	18.13	11.33	15.74	14.61	16.18	14.17	14.49	14.41	5.65	13.02	6.35	8.44
F6							13.82	15.26	15.67	14.78	15.00	14.52	14.90	15.15	14.71	15.02	14.88	14.31	14.42	3.13	12.40	15.42	15.97	16.24	13.33	14.63	13.71	14.90
C1	13.71	5.67	10.53	13.85	7.56	13.82		16.00	12.95	14.86	9.49	10.71	9.94	14.05	6.44	16.07	7.73	7.05	15.53	12.41	12.62	11.82	14.55	12.20	8.67	6.51	12.17	8.14
C2	7.22	17.52	11.26	16.79	9.25	15.26	16.00		15.64	16.03	12.98	13.22	13.33	14.79	8.11	17.29	9.07	8.26	15.27	14.17	14.31	15.00	13.10	13.13	13.38	7.94	13.04	10.54
C3	13.15	11.86	12.67	16.08	8.02	15.67	12.95	15.64		15.61	13.13	13.63	11.78	13.86	6.93	17.64	9.12	8.96	14.83	13.62	15.08	14.48	14.75	15.10	9.96	7.08	12.55	9.87
C4	16.03	15.76	15.40	6.11	12.56	14.78	14.86	16.03	15.61		14.18	15.42	12.87	14.04	10.65	14.40	14.40	13.56	16.53	13.96	14.22	15.22	15.10	15.64	12.37	10.94	14.17	12.53
C5	13.72	9.74	9.64	14.76	10.67	15.00	9.49	12.98	13.13	14.18		10.00	9.37	13.10	13.44	14.98	14.09	13.64	15.71	15.12	15.33	16.10	15.97	17.19	7.44	11.08	11.21	10.33
C6	13.93	10.36	9.96	14.75	10.18	14.52	10.71	13.22	13.63	15.42	10.00		10.56	13.53	12.67	13.69	13.41	11.60	16.28	14.40	14.67	15.92	16.67	17.10	7.06	10.92	7.80	11.48
C7	12.05	10.00	11.39	14.26	8.71	14.90	9.94	13.33	11.78	12.87	9.37	10.56		12.30	5.11	19.24	18.03	5.54	15.49	14.17	14.30	15.00	14.69	15.13	8.81	6.74	10.44	8.17
C8	14.79	13.69	12.21	13.83	21.25	15.15	14.05	14.79	13.86	14.04	13.10	13.53	12.30		15.15	15.48	14.31	15.00	17.33	14.03	14.36	16.30	15.56	16.56	9.92	15.30	12.82	15.64
C9	8.03	6.33	4.15	14.62	9.33	14.71	6.44	8.11	6.93	10.65	13.44	12.67	5.11	15.15		18.56	11.58	10.67	15.09	14.90	15.46	14.40	14.74	14.98	5.06	9.63	8.79	8.10
C10	16.18	14.56	9.54	15.13	19.92	15.02	16.07	17.29	17.64	14.40	14.98	13.69	19.24	15.48	18.56		16.67	16.74	15.44	15.30	16.11	14.67	16.67	15.67	8.23	16.56	10.88	11.76
C11	9.24	7.86	8.29	14.17	18.13	14.88	7.73	9.07	9.12	14.40	14.09	13.41	18.03	14.31	11.58	16.67		10.24	15.20	15.12	15.78	15.00	14.48	15.25	7.46	15.79	9.69	11.19
C12	7.90	6.23	4.73	14.52	11.33	14.31	7.05	8.26	8.96	13.56	13.64	11.60	5.54	15.00	10.67	16.74	10.24		14.91	14.41	15.88	14.17	13.72	14.14	5.37	12.24	5.85	8.81
C13	15.27	15.30	14.39	16.53	15.74	14.42	15.53	15.27	14.83	16.53	15.71	16.28	15.49	17.33	15.09	15.44	15.20	14.91		13.44	16.06	17.70	16.42	14.75	14.08	14.25	14.92	16.04
C14	14.11	13.47	13.25	13.96	14.61	3.13	12.41	14.17	13.62	13.96	15.12	14.40	14.17	14.03	14.90	15.30	15.12	14.41	13.44		11.67	14.06	15.89	14.81	13.25	13.17	13.71	14.90
C15	14.25	13.59	13.49	14.22	16.18	12.40	12.62	14.31	15.08	14.22	15.33	14.67	14.30	14.36	15.46	16.11	15.78	15.88	16.06	11.67		14.86	10.61	17.87	13.57	13.49	13.99	15.20
C16	15.08	13.77	13.57	15.13	14.17	15.42	11.82	15.00	14.48	15.22	16.10	15.92	15.00	16.30	14.40	14.67	15.00	14.17	17.70	14.06	14.86		15.81	15.86	11.98	13.33	12.69	13.89
C17	12.98	14.39	11.58	15.00	14.49	15.97	14.55	13.10	14.75	15.10	15.97	16.67	14.69	15.56	14.74	16.67	14.48	13.72	16.42	15.89	10.61	15.81		15.32	10.95	14.76	13.75	15.00
C18	14.71	12.54	13.11	15.64	14.41	16.24	12.20	13.13	15.10	15.64	17.19	17.10	15.13	16.56	14.98	15.67	15.25	14.14	14.75	14.81	17.87	15.86	15.32		11.76	13.97	13.15	15.61
C19	10.42	8.28	5.95	12.15	5.65	13.33	8.67	13.38	9.96	12.37	7.44	7.06	8.81	9.92	5.06	8.23	7.46	5.37	14.08	13.25	13.57	11.98	10.95	11.76		4.10	8.81	6.75
C20	7.88	8.49	3.67	13.46	13.02	14.63	6.51	7.94	7.08	10.94	11.08	10.92	6.74	15.30	9.63	16.56	15.79	12.24	14.25	13.17	13.49	13.33	14.76	13.97	4.10		8.31	6.97
C21	12.94	13.95	8.63	14.31	6.35	13.71	12.17	13.04	12.55	14.17	11.21	7.80	10.44	12.82	8.79	10.88	9.69	5.85	14.92	13.71	13.99	12.69	13.75	13.15	8.81	8.31		11.70
C22	14.20	8.47	6.07	22.50	8.44	14.90	8.14	10.54	9.87	12.53	10.33	11.48	8.17	15.64	8.10	11.76	11.19	8.81	16.04	14.90	15.20	13.89	15.00	15.61	6.75	6.97	11.70	

Table 29. Speed matrix of instance *Ireland* 22×6 (in meters per second)

Nodes	F1	F2	F3	F4	F5	F6	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
F1							4	3	5	6	6	5	5	6	3	5	4	6	5	5	6	6	5	5	4	5	5	6
F2							4	5	5	6	6	6	5	4	6	5	6	5	6	6	5	6	4	6	4	6	5	5
F3							5	5	6	6	3	3	5	5	4	4	3	4	6	6	6	5	5	5	1	5	4	6
F4							5	5	4	3	6	6	6	2	6	6	6	6	4	6	6	5	6	4	6	6	6	6
F5							6	6	5	6	5	6	4	6	1	6	5	3	6	6	6	6	4	3	4	4	5	4
F6							5	5	6	6	5	6	6	6	6	6	4	5	3	1	2	4	3	3	6	6	6	6
C1	4	4	5	5	6	5		6	3	6	6	5	5	6	6	5	5	6	5	6	6	6	5	6	4	6	6	5
C2	3	5	5	5	6	5	6		5	6	4	4	6	6	5	6	4	5	5	6	5	6	4	6	4	5	4	4
C3	5	5	6	4	5	6	3	5		6	5	5	5	5	6	6	6	6	6	5	5	6	6	6	6	6	6	5
C4	6	6	6	3	6	6	6	6	6		5	5	6	2	6	5	6	6	5	6	6	5	6	3	6	5	5	6
C5	6	6	3	6	5	5	6	4	5	5		2	5	6	4	5	4	5	5	6	6	5	6	6	4	4	6	4
C6	5	6	3	6	6	6	5	4	5	5	2		6	5	6	4	4	6	5	6	6	5	6	6	5	6	6	6
C7	5	5	5	6	4	6	5	6	5	6	5	6		6	5	5	3	4	6	6	6	5	4	5	5	6	5	5
C8	6	4	5	2	6	6	6	6	5	2	6	5	6		6	4	5	5	5	6	6	4	4	5	6	5	6	4
C9	3	6	4	6	1	6	6	5	6	6	4	6	5	6		5	4	1	6	6	6	6	4	3	5	4	6	4
C10	5	5	4	6	6	6	5	6	6	5	5	4	5	4	5		4	4	6	6	6	6	3	2	3	4	5	4
C11	4	6	3	6	5	4	5	4	6	6	4	4	3	5	4	4		4	6	6	6	6	6	3	4	3	4	4
C12	6	5	4	6	3	5	6	5	6	6	5	6	4	5	1	4	4		6	5	4	6	4	3	5	5	5	4
C13	5	6	6	4	6	3	5	5	6	5	5	5	6	5	6	6	6	6		3	2	2	3	4	5	6	5	5
C14	5	6	6	6	6	1	6	6	5	6	6	6	6	6	6	6	6	5	3		3	5	3	4	5	6	6	6
C15	6	5	6	6	6	2	6	5	5	6	6	6	6	6	6	6	6	4	2	3		4	5	4	5	6	6	6
C16	6	6	5	5	6	4	6	6	6	5	5	5	5	4	6	6	6	6	2	5	4		4	5	5	5	5	4
C17	5	4	5	6	4	3	5	4	6	6	6	6	4	4	4	3	6	4	3	3	5	4		3	5	6	5	5
C18	5	6	5	4	3	3	6	6	6	3	6	6	5	5	3	2	3	3	4	4	4	5	3		5	5	5	5
C19	4	4	1	6	4	6	4	4	6	6	4	5	5	6	5	3	4	5	5	5	5	5	5	5		5	5	6
C20	5	6	5	6	4	6	6	5	6	5	4	6	6	5	4	4	3	5	6	6	6	5	6	5	5		6	4
C21	5	5	4	6	5	6	6	4	6	5	6	6	5	6	6	5	4	5	5	6	6	5	5	5	5	6		6
C22	6	5	6	6	4	6	5	4	5	6	4	6	5	4	4	4	4	4	5	6	6	4	5	5	6	4	6	

Table 30. Alternative paths matrix of instance *Ireland* 22×6