Integrating operations research into green logistics: A review

Abstract: Logistical activities have a perceptible global environmental impact. Against the background of increasing public and government concern for the environment, green logistics is proposed to reduce the environmental effects of logistical activities. As the world deals with the ongoing COVID-19 pandemic, the environmental crisis has not gone away but requires more attention because the challenges are greater. Operations research is typically used to balance the trade-off between environmental concerns and costs, and therefore it can improve the operations management of logistical activities. This paper is a review of studies that integrate operations research into green logistics. To access relevant papers, we searched the papers published until June 2, 2021, in Web of Science Core Collection database using six keywords (green logistics OR sustainable logistics OR cleaner logistics OR green transportation OR sustainable transportation OR cleaner transportation) in topic. We then divided the papers into five broad categories according to their research directions: green waste logistics, the impact of costs on green logistics, the green routing problem, green transport network design, and new challenges in green logistics. Suggestions for further research that combines green logistics and operations research, especially research that considers the long-term effects of the pandemic, are summarized at the end of this review.

Keywords: Green logistics; operations research; environment; literature review

1 Introduction

Logistics involves the transport, storage, and handling of products as they move through supply chain networks from raw material sources to the final point of sale or consumption (McKinnon et al., 2015). Fuelled by COVID-19, global e-commerce showed a rise in its share of all retail sales from 16% to 19% in 2020 (UN, 2021), which definitely poses a huge challenge for last mile delivery services. Hence, companies are investigating new strategies to steadily improve logistics activities. However, such developments have environmental impacts (Van Woensel et al., 2001). Specifically, the release of greenhouse gases (GHG) into the atmosphere has a perceptible global impact on the environment. Currently, carbon dioxide (CO_2) emissions in the transport sector are about 30% of total emissions in developed countries and about 23% of total emissions worldwide (UNECE, 2021). The United Nations Economic Commission for Europe (UNECE) (2021) announced a widespread agreement to reduce CO_2 emissions in transport by at least 50% by 2050. Hence, the influence of logistics on the environment has become a popular topic in recent years.

In recent decades, against the background of increasing public and government concern for the environment, green logistics has been proposed to reduce the environmental effects of logistical activities (McKinnon et al., 2015). Like McKinnon et al. (2015), we define "green logistics" as the study of the environmental influences of all activities involved in the transport, storage, and handling of physical products as they move in both directions in supply chains. We consider all logistical issues, such as routing and warehousing, and study the related environmental problems, such as GHG emissions and the use of new green technologies. Although green logistics is relatively new, it is rapidly evolving.

As advanced analytical methods lead to better decisions (INFORMS, 2021), operations research (OR) has been used in many studies (Silver, 1981; Luss, 1982; Cire and Van Hoeve, 2013; Lien et al., 2014; Ata et al., 2019; Gupta and Radovanović, 2020). When used effectively, OR techniques drive the success of companies, such as Procter & Gamble (CBS News, 2008), Hewlett Packard (Burman et al., 1998), and United Parcel Services (Holland et al., 2017), by saving costs, reducing inventory, and increasing profits. With more public focus on sustainability, OR techniques are also used to address environmental concerns. Dekker et al. (2012) stated that OR techniques can help balance the trade-off between profits and environmental costs, efficiently utilize resources, reducing costs and emissions.

This review was motivated by the real-world problem of sustainable development. The transportation industry is flourishing, and traffic volumes continue to increase. For instance, according to the Statistical Pocketbook 2019 (EEA, 2019), an estimated 3,046 billion tonne-kilometers of freight cargo were transported within and between European Union countries (EU-28) by road and maritime transport in 2017, releasing a tremendous volume of GHG. Recently, Europe has steadily reduced its overall GHG emissions. However, the transport sector has not been part of this general trend, and its relative contribution to GHG emissions in Europe has thus become more significant

(EEA, 2020). Therefore, making the transport sector green is particularly important. In addition, OR techniques, especially mathematical programming, can help achieve the goal of doing more with less resources (less pollution). Hence, this review focuses on green logistics, and especially the application of OR to green logistics.

Our purpose is to provide an overview of the current situation and potential developments in green logistics by reviewing up-to-date papers. As thousands of papers have been published, we cannot review them all. Hence, we first summarize some rep-

Table 1: Representative overview papers on green logistics

Papers	Review range	Theme	Studied problems	Topics
Kleindorfer et al. (2005)	First 50 issues of journal *POM*	SUS	Problems related to environmental, health, and safety concerns with green-product design, lean and green operations, closed-loop supply chains, and other sustainability themes	Environmental management, closed-loop supply chains, and a broad perspective on triple-bottom-line thinking, integrating profit, people, and the planet into the culture, strategy, and operations of companies.
Srivastava (2007)	Books, edited volumes, and journal articles published from 1990	GSC	Problems related to keywords including green supply chain, remanufacturing, green purchasing, green design, industrial ecology, industrial ecosystems, reverse logistics, remanufacturing, and waste management	Importance of green supply-chain management, green design, and green operations
Sbihi and Eglese (2010)	–	GL	Problems which can be formulated as combinatorial optimization problems	Reverse logistics, waste management, vehicle routing and scheduling
Dekker et al. (2012)	–	GL+GSC	Problems solved by OR	Design, planning and control in a supply chain for transportation, inventory of products and facility decisions
McKinnon et al. (2015)	–	GL	Problems aimed at improving the environmental sustainability of logistics	Assessing the environmental effects of logistics, and strategic, operational, as well as public policy perspectives on green logistics.
This paper	Journal articles published between 1990 and June 3, 2023	GL	Problems solved by OR	Green waste logistics, impact of costs on green logistics, green routing problem, green transport network design, and new challenges in green logistics

Notes: (1) “POM”, “SUS”, “GSC”, “GL”, and “OR” denote the journal *Production and Operations Management*; sustainability, green supply chain, green logistics, and operations research, respectively (2) the en-dash means that the reviewed paper does not introduce this aspect.

resentative overview papers on green logistics in Table 1. Readers who are interested in this area should also refer to other papers (Kleindorfer et al., 2005; Srivastava, 2007; Sbihi and Eglese, 2010; Dekker et al., 2012; McKinnon et al., 2015) for a comprehensive overview of green logistics.

The remainder of this study is organized as follows. The search methodology used to identify relevant papers is explained in Section 2. Section 3 presents a review of studies on green waste logistics. The impact of costs on green logistics is studied in Section 4. An overview of the literature on the green routing problem is introduced in Section 5. Section 6 focuses on papers about green transport network design. Section 7 discusses some of the challenges related to green logistics. Our conclusions are presented in Section 8.

2 Literature search methodology

To access relevant papers, we searched the Web of Science Core Collection database using six keywords in topic (i.e., title, abstract, author keywords, and keywords plus). The six keywords were "green logistics OR sustainable logistics OR cleaner logistics OR green transportation OR sustainable transportation OR cleaner transportation". We input these keywords, ruled out articles that contained irrelevant words, including "chemistry OR agriculture OR fish OR fishery OR electronic OR pressure OR tourism OR geography OR medicine OR psychology OR biology OR materials science multidisciplinary OR surgery OR finance OR biochemistry OR nuclear OR ecology OR chemical OR mechanics OR education OR public environmental occupational health". Then, we selected English-language documents only, and set the document type to articles only, excluding other document types such as editorial materials, notes, or letters. The search returned a wide range of thematic areas beyond the scope of this review. Hence, we also refined papers by Web of Science Category Operations Research Management Science, which ruled out papers from irrelevant thematic areas, such as physics and related areas; geography and related areas; chemistry and related areas; medicine, biology, and related areas; electronic, mechanical engineering, and related areas; engineering civil, architecture, and related areas; business finance; and social sciences, development studies, and related areas. After several attempts, the search resulted in 1,058 articles published until June 3, 2023.

As this review focuses on green logistics combined with OR, we ruled out papers using other methodologies, refining the number of relevant articles to 816. Table 1 presents the paper selection process. According to our review, Figure 1 illustrates the number of papers published each year. From 1997 to 2016, the number of papers published each year fluctuated, but the overall trend was upward. From 2017 to 2022, the number of papers published each year continued to increase, nearly doubling in some years, which may have been caused by the increasing environmental awareness of governments, enterprises, and the public.

Table 1: Four steps of collecting papers

Step 1	Search Keywords green logistics OR sustainable logistics OR cleaner logistics OR green transportation OR sustainable transportation OR cleaner transportation
Step 2	Exclude Keywords chemistry OR agriculture OR fish OR fishery OR electronic OR pressure OR tourism OR geography OR medicine OR psychology OR materials science multidisciplinary OR surgery OR finance OR biochemistry OR biology OR nuclear OR ecology OR chemical OR mechanics OR education OR public environmental occupational health
Step 3	Choose Web of Science Category operations research management science
Step 4	Manual reading and identification of articles

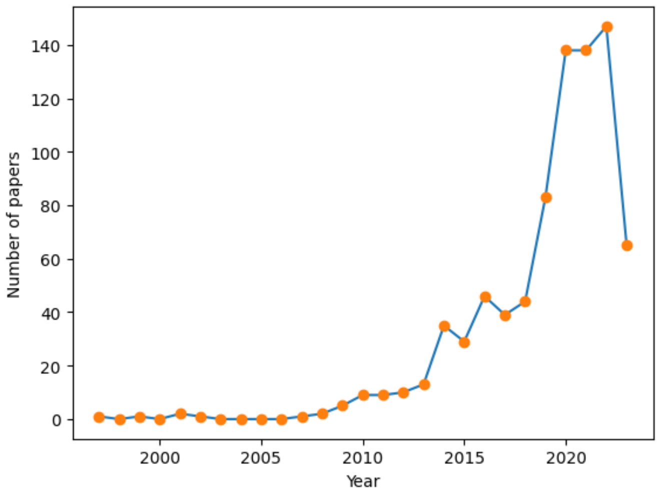

Figure 1: The number of papers published annually

We first divided the 816 articles into five broad categories based on the problem context: green waste logistics, the impact of costs on green logistics, the green routing problem, green transport network design, and new challenges in green logistics. These five broad categories were then organized into smaller categories, and the relevant papers are reviewed in the following five sections. Here, notice that logistics contains transportation and storage. But we didn't review green storage because there are already many review papers on green storage papers (de Koster et al., 2007; Gu et al., 2007, 2010; Gong and de Koster, 2011; Staudt et al., 2015; Shah and Khanzode, 2017; Azadeh et al., 2019; Yener and Yazgan, 2019; Custodio and Machado, 2020; Kumar et al., 2021;

Zhen and Li, 2022).Hence, we only reviewed transportation-related papers.

3 Green waste logistics

Increasing environmental concerns and increased waste production have caused people to think about how to deal with waste in a green way (Sbihi and Eglese, 2010). According to the World Bank (WB, 2018), the world generates 2.01 billion tonnes of municipal solid waste annually, and that is expected to increase to 3.4 billion tonnes by 2050. Dealing with waste in a green way is essential for sustainable transportation; therefore, many scholars have chosen to study the green waste logistics problem. Scholars have proposed the reuse of materials and products to capture surplus value, which involves reverse logistics. Recently, the COVID-19 pandemic has made the need for green waste management systems even more urgent because of the resulting boom in food delivery and similar services (Sumagaysay, 2020). This section first examines the studies on waste management and then discusses the papers related to reverse logistics.

3.1 Waste management

In 1987, as a sub-organization of the United Nations, the Brundtland Commission (formerly the World Commission on Environment and Development) defined "sustainable development" as "meeting human development goals while simultaneously sustaining the ability of natural systems to provide natural resources and ecosystem services on which the economy and society depend" (BC, 1987). Properly dealing with waste has since become increasingly important.

Most papers related to waste management focus on solid waste management (SWM). Many scholars have modeled the SWM problem as a variant of the vehicle routing problem (VRP). Ramos et al. (2014a) modeled a recyclable waste collection system as two multi-product and multi-depot VRP models to minimize distance and CO_2 emissions, respectively. Their results showed reductions of up to 22% for distance and 27% for CO_2 emissions. Asefi et al. (2019) proposed an integrated framework combining the VRP and the fleet size problem to solve a cost-effective integrated SWM problem. They developed a bi-objective mixed integer linear programming (MILP) model to simultaneously minimize transportation costs and deviation from the fair load allocation to transfer stations. Recently, Babaee-Tirkolaee and Aydın (2021) proposed a bi-objective MILP model for a capacitated VRP to optimize transportation planning for municipal waste management during a pandemic with consideration of outsourcing.

Plastic waste management is a particularly hot topic in waste management research. Bing et al. (2013) proposed a MILP model to design a plastic recycling network. The computational results indicated that transportation costs account for about 7% of the total costs and that multimodal transport can reduce the transportation costs by nearly 20%. Bing et al. (2014) also modeled a plastic waste collection problem as a VRP and used a tabu search algorithm to improve the routes.

How to recycle the waste of electrical and electronic equipment (WEEE) is another hot research topic. Ayvaz et al. (2015) proposed a multi-echelon, multi-product, capacitated two-stage stochastic programming model for a third-party WEEE recycling company. The model considers return quantity, sorting ratio, and transportation cost uncertainties and aims to maximize total revenue. Safdar et al. (2020) developed a multi-objective model to maximize total profit and social benefits and minimize environmental impacts in WEEE management design.

Scholars have also studied how to recycle specific items. For scrap tires, Dehghanian and Mansour (2009) proposed a three-objective mathematical programming model to maximize social and economic benefits and simultaneously minimize negative environmental impacts. They used a genetic algorithm to find pareto-optimal solutions. Zhou and Zhou (2015) developed a nonlinear integer programming (IP) model to determine the locations and number of recycling stations and plants to minimize the total cost in a case study of office paper recycling in Beijing (China). Shah et al. (2018) discussed the importance of value recovery from trash bins by using a stochastic optimization model with embedded chance constraints to minimize total transportation cost.

Some scholars have studied how to manage agricultural residues. Parker et al. (2010) developed a mixed integer nonlinear programming (MINLP) model to find the most efficient and economical network for generating hydrogen from agricultural residues. Constructing a set of reverse logistic networks for pesticide wastes, Li and Huang (2018) proposed a mixed integer programming (MIP) model to determine the optimal locations for collecting pesticide wastes and the flow allocation between recycling and treatment centers.

3.2 Reverse logistics

Remanufacturing end-of-life products has many economic, environmental, and social advantages (Millet, 2011). However, remanufacturing these products first requires environmentally and economically feasible reverse logistics to transport reusable used components to factories. In addition, customers, suppliers, competitors, and government agencies pressure manufacturers to implement reverse logistics (Govindan and Bouzon, 2018; Plaza-Úbeda et al., 2021). After reviewing all of the collected papers on reverse logistics, we found that the number of papers published on reverse logistics has exploded since 2015. Moreover, reverse and forward logistics are often combined into an integrated logistics network. Reverse logistics is also studied in conjunction with the VRP.

One of the major research directions in reverse logistics is the study of integrated logistics networks that combine reverse and forward logistics. Considering the impact of CO_2 emissions, Zarbakhshnia et al. (2020) studied a multi-product, multi-stage, multi-period, forward and reverse logistics system under demand uncertainty. They developed a probabilistic MILP model to determine the flows of both the forward and reverse chains, the location of active established centers in the forward and reverse chains, and an optimal transportation strategy. Boronoos et al. (2021) proposed a multi-objective MINLP model for a forward and reverse logistics system with multiple manufacturing centers, warehouses, customer zones, disassembling centers, and remanufacturing centers. They determined the optimal location and capacity of facilities, quantity of produced/remanufactured and disassembled products, and the flow of products in the system while minimizing total costs, total CO_2 emissions, and robustness costs in both the forward and reverse logistics.

The combination of reverse logistics and the VRP is another popular research direction. Kumar et al. (2017) proposed an IP model for a multi-period, multi-echelon VRP in a forward-reverse logistics system to find the optimal flow allocation and make vehicle routing decisions. To minimize the total cost and number of vehicles, Wang et al. (2018) investigated a cooperation problem for recycling vehicle route optimization in a two-echelon reverse logistics network with semitrailers and vehicle sharing. They proposed a bi-objective MILP model to determine the optimal two-echelon vehicle routing and the proper distribution among participating facilities of the total cost savings. Solano et al. (2021) combined reverse logistics and the VRP with simultaneous pickup and delivery within a time window. Using a MILP model, they found the optimal vehicle routing for the collection and distribution of bottles and the optimal quantity to dispatch.

Scholars have often integrated reverse logistics into the location problem to study how to achieve product recovery. Studying a sludge recovery network, Duque et al. (2010) developed a MILP model to design a recovery network structure and found the optimal transport and transformation schedules. Govindan et al. (2016) proposed a multi-objective MIP model to investigate product recovery in the electrical manufacturing industry. With the aim of maximizing profit, they determined the best location for a hybrid recovery facility and the optimal flow of products, recovered parts, and material in the system.

Because of COVID-19 and the convenience of online shopping, an increasing number of customers are shopping online. The online shopping boom has inevitably led to many returned goods. How to properly manage the logistics of returned goods has become a hot research topic. Nenes and Nikolaidis (2012) proposed a MILP model for a multi-period used-product returns network to determine the optimal procurement, remanufacturing, stocking, and salvaging decisions while maximizing the network's total profit. Developing a multi-objective IP model, Dutta et al. (2020) studied the reverse logistics problem of an online Indian cloth retailer to determine the optimal technology adoption for incineration centers and fulfillment centers and the optimal locations of delivery hubs, landfills, and recycling centers to minimize costs and environmental impacts and maximize social responsibility.

4 Impact of costs on green logistics

Green logistics balances environmental, economic, and social benefits. Companies and individuals are often required by the government to reduce emissions. Toll roads are an example of this phenomenon[1]. Governments often use subsidies to encourage companies and individuals to upgrade old high-emission equipment and taxation to punish them for emitting pollutants. Hence, this section reviews the papers that study the impact of costs on green logistics.

As an economic method for controlling externalities, environmental charges have become a preferred method of encouraging the sustainable development of transportation (Lu and Morrell, 2001). Alkhayyal et al. (2019) proposed a single-period MILP model based on the market price of CO_2 emissions for a reverse supply chain to find the optimal flow of components between remanufacturing facilities that minimizes

[1] Although the main purpose of road tolls is reducing congestion, they also greatly reduce pollutant emissions.

CO_2 emissions, product recovery, transportation, energy use, rent costs, and labor.

Among the numerous charging problems in green logistics, road toll design is the most popular. Lv et al. (2020) developed an inexact bilevel programming model with stochastic and fuzzy uncertainties to design a road toll that considers vehicle emissions. To reduce the air pollutants inhaled by humans and minimize environmental inequality, Rodriguez-Rodriguez-Roman and Ritchie (2020) introduced a transportation network paradox that showed the unintended effects of reducing traffic emissions and then proposed multi-objective models for a surrogate-based toll design optimization problem.

To achieve the goal of green logistics, companies typically must make a significant investment in equipment, and the government must provide subsidies to encourage them to upgrade their equipment. Considering the relationships between the government, container ports, and shipping lines, Wu and Wang (2020) investigated a shore-power deployment problem to reduce in-port emissions by having berthed ships plug into the shore electrical network. They proposed an IP model to create a government subsidy policy that maximizes the reduction of in-port ship emissions. Liu et al. (2020b) developed an integrated nonlinear bilevel programming model for a reverse logistics problem for leftover pharmaceuticals. They jointly considered a third-party logistics company, the producer, and the government to balance the environmental, economic, and social benefits.

Some scholars have studied the problem from the taxation policy perspective. Li et al. (2019) proposed an intermodal transportation network planning model to minimize overall transportation costs, handling costs, and CO_2 emission costs. The computational results showed that carbon taxes do not significantly influence intermodal transport networks, and the influence of unloading and loading costs on the total cost was far greater than that of CO_2 emissions. Chen et al. (2020) determined the optimal government joint taxation-subsidy emissions reduction policy to minimize additional government investment in the coastal transportation system.

5 Green routing problem

Since the classic VRP was introduced by Dantzig and Ramser (1959), VRPs have been an intensive and fast-growing research topic (Vidal et al., 2020). Because of the rapid development of last mile logistics, the negative effects of transportation, such as noise, air pollution, and land use have been widely studied (Marrekchi et al., 2021). In particular, the pollutant emissions from transportation activities are regarded as the greatest threat to the environment (Suzuki and Kabir, 2015). Hence, OR scholars have studied the green routing problem.

Kara et al. (2007) combined the VRP and environmental protection concerns and first proposed the energy minimization VRP. Bektaş and Laporte (2011) introduced the pollution-routing problem (PRP). Erdoğan and Miller-Hooks (2012) then put forward the concept of a green VRP. Although these concepts differ in their formulation, they are not very different in their nature. Marrekchi et al. (2021) stated that in the PRP, the vehicle speed on each arc was optimized to minimize fuel, emissions, or driver costs. A specific characteristic of the PRP is that the load and speed vary from one arc to another while the other parameters remain the same. This means that the PRP requires that the vehicles on each arc have an optimal speed or load, whereas the green VRP does not have such a requirement (i.e., the speed of vehicles on all of the arcs may be constant). This section, therefore, first reviews the papers on green VRP and PRP, and then reviews the papers on the production and transportation routing problem, and other related issues are mentioned in the last subsection.

5.1 Green vehicle routing problems

During the 60 years since its introduction, many variants of the VRP have been raised and studied. A VRP with limited vehicle capacity is defined as a capacitated vehicle routing problem (CVRP), which is more in line with reality. Because of its practical relevance, the CVRP has been widely studied for several decades. Generally, the objective of the CVRP is to minimize either total travel distance or travel time. To consider environmental issues, emissions are introduced into the CVRP. Fukasawa et al. (2016) proposed two MILP models (an arc-load model and a set partitioning model) for an energy minimization CVRP. It is important to note that the path with the least consumed energy is not always the path with the shortest distance because vehicle energy consumption is not determined solely by distance. Idle driving, rapid acceleration, sudden braking, and other factors also affect fuel consumption. Fukasawa et al. (2016) used a branch-and-cut algorithm and a branch-cut-and-price algorithm to solve the arc-load model and the set partitioning model, respectively. Their computational results showed a significant improvement with the latter algorithm. Gupta et al. (2021) addressed a multi-objective CVRP with fuzzy time-distances and demand split into bags.

The VRP with time windows is becoming increasingly important because customers prefer customized service times in distribution systems. Küçükoğlu et al. (2015) developed a MILP model to plan vehicle routes with time windows to minimize total fuel consumption and thereby minimize CO_2 emissions. Proposing a MIP model, Niu et al. (2018) investigated an open VRP with time windows from an environmental perspective, which means that vehicles do not return to the depot after finishing their tasks. This minimizes total costs such as fuel consumption, CO_2 emissions, and driver wages. Some papers have also considered soft time windows that can be violated with penalty costs. Lee and Prabhu (2016) optimally assigned customer deliveries to vehicles on the basis of fuel performance metrics and just-in-time delivery, both of which are related to the cruising speed of vehicles. They developed an algorithm to determine vehicle routes and cruising speeds.

As another variant of the VRP, the multi-depot VRP, has attracted considerable attention from scholars and practitioners (Zhang et al., 2020a). The multi-depot VRP requires that vehicles serve customers from several depots and then return to a pre-assigned depot. Ramos et al. (2014b) modeled a multi-objective, multi-depot, and periodic VRP as a set partitioning formulation to balance the costs associated with social and environmental concerns related to drivers' maximum working hours in a period and the level of CO_2 emissions. To address socio-environmental concerns, Jabir et al. (2017) proposed an integer linear programming (ILP) model to integrate economic costs and emissions reduction for a capacitated multi-depot VRP problem.

The classical VRP usually assumes that each vehicle performs only one trip. In reality, the high cost of additional vehicles means that vehicles may perform multiple trips. Cinar et al. (2015) proposed a MIP model for a cumulative multi-trip VRP with limited duration and considering the reduction of CO_2 emissions. They also developed a simulated annealing algorithm to solve the model to minimize fuel consumption. Tirkolaee et al. (2018) designed a hybrid genetic algorithm for a multi-trip capacitated VRP to minimize total costs including the costs of CO_2 emissions, vehicle usage, and routing.

Scholars have also investigated other types of VRPs from an environmental perspective, such as the split-delivery VRP (Eydi and Alavi, 2019), time-dependent VRP (Xiao and Konak, 2017; Kazemian et al., 2018), and heterogeneous VRP (Behnke and Kirschstein, 2017; Behnke et al., 2021).

5.2 Pollution-routing problem

An especially important branch of the classical green routing problem is the PRP that aims to determine a set of routes and speeds to minimize total operational and environmental costs. Bektaş and Laporte (2011) introduced the PRP as a successive application in the green routing problem, and they considered it a variant of the VRP with time windows. Other variants have been developed by combining various constraints such as time windows, simultaneous pickup and delivery, congestion periods, and the uncertainty of some parameters (Marrekchi et al., 2021).

The PRP with time windows is important for freight transportation planning. Because of the complexity of the PRP with time windows, nearly all known solution methods are based on heuristics. Dabia et al. (2017) first introduced an exact solution based on a branch-and-price algorithm for a PRP with time windows. Saka et al. (2017) investigated a PRP with customer deadlines and multiple vehicle types and focused on speed optimization for a given vehicle route. They proposed a MIP model to minimize total costs, including fuel, emissions, and driver costs.

The PRP with simultaneous pickup and delivery is an important green routing problem in which customer orders must be transported from multiple origins to multiple destinations without intermediate transshipment. Bravo et al. (2019) solved a multi-objective pickup and delivery PRP with time windows to minimize fuel consumption, traveling time, and service quality. They developed an evolutionary algorithm to find a set of routes for product pickups and deliveries during a planning period.

Congestion is a major problem, especially in big cities, that increases CO_2 emissions and should be considered when investigating routing problems. Franceschetti et al. (2017) proposed a metaheuristic for a time-dependent PRP that determines the optimal vehicle routing and speed for each route to minimize driver wages and CO_2 emissions. They also considered traffic congestion, which restricts vehicle speed and increases emissions.

In terms of uncertainty, Eshtehadi et al. (2017) obtained robust solutions for a PRP with demand and travel time uncertainty from their proposed ILP model with several robust optimization techniques, soft worst case, hard worst case, and chance constraints. Applying recent robust optimization theory, Tajik et al. (2014) proposed a MILP model for a PRP with pickups and deliveries under uncertainties related to service time, travel time, fuel consumption, and CO_2 emissions. The objective function of the model was to minimize travel distance, the number of available vehicles, fuel consumption, and

CO_2 emissions.

5.3 Production and transportation routing problem

Sustainability extends the concept of logistics network design to optimize operations from a broader perspective that includes the entire production system and postproduction management (Lee et al., 2010). Specifically, although supply chain activities all generate carbon emissions, transportation is the most visible part of the supply chain that releases a tremendous amount of GHG (Dekker et al., 2012). Hua et al. (2011) stated that many companies use some environmentally friendly vehicles, equipment, and facilities and adjust their operations to reduce their CO_2 emissions. Hence, this subsection focuses on combining transportation routing problems and production problems, which has been widely studied for decades.

The traditional inventory and routing problem seeks the best joint strategy in terms of inventory and transportation. Considering fuzzy demand distributions and transportation costs, Rahimi et al. (2017) proposed a multi-objective stochastic model to balance economic performance, service levels such as delivery and shortage delays, and the environmental footprint. To provide customers with the best food quality possible, Chan et al. (2020) developed a four-objective MILP model to construct intelligent food logistics and ensure that customer demands are fulfilled as quickly as possible while considering the environmental impact. The four objectives are to minimize total system costs, maximize average food quality, minimize CO_2 emissions during production and transportation, and minimize the total weighted delivery lead time.

With continuous globalization, the average distance between two locations in distribution networks has greatly increased. Therefore, the success of many companies depends on location and routing decisions (Elhedhli and Merrick, 2012). Govindan et al. (2014) proposed a multi-objective MIP model for a two-echelon location and routing problem with time windows to achieve economic and environmental aims in a perishable food supply network. Schiffer and Walther (2018) developed a robust location-routing approach for an electric logistics fleet planning problem with the consideration of uncertain customer patterns. Wang et al. (2020b) considered a two-echelon location and routing problem with eco-packages, which is also a pickup and delivery problem with time windows. They solved the large eco-package transport problem and small eco-package pickups and deliveries in the first and second echelons, respectively.

Three key problems in optimizing a logistics network are the location, routing, and inventory problems. Specifically, facility location, vehicle routing, and inventory management are closely interrelated problems in logistics network design. Zhalechian et al. (2016) introduced a new location-routing-inventory model under mixed uncertainty and considering CO_2 emissions, fuel consumption, wasted energy, and the social influences of creating jobs and economic development. They used a stochastic-possibilistic programming method to tackle the uncertainty. Biuki et al. (2020) studied an integrated location-routing-inventory problem to design a logistics network for perishable products in a sustainable supply chain. They formulated the problem as a multi-objective MIP model and used two hybrid meta-heuristics as series and parallel combinations of a genetic algorithm (GA) and particle swarm optimization (PSO) to solve the model.

5.4 Other related issues

We cannot describe all of the problems we found because of space limits. Other related issues include the location-allocation-inventory problem (Tirkolaee et al., 2020), last mile problem (Letnik et al., 2020; Zhang et al., 2020b), speed-routing problem (Psaraftis and Kontovas, 2014; Zhao et al., 2019), traveling salesman problem (Roberti and Wen, 2016; Wang et al., 2020a), and traveling purchaser problem (Cheaitou et al., 2020).

6 Green transport network design

Logistics activities often cover a region in the form of a network. The need for appropriate transport network design is critical because of the growing problems caused by increased road traffic and the problems related to emissions. Different from the VRP, transport network design tends to be a problem for larger transportation areas, such as intermodal transportation between continents, and can involve multiple modes of transportation rather than just vehicles. Hence, companies or governments must carefully design transport networks to ensure effective transportation and mitigate the associated problems. This section reviews the papers from several research directions, i.e., intermodal transportation, green passenger transport networks, aviation and marine logistics network design, and other related issues.

6.1 Intermodal transportation

The growing concern about global warming is stimulating the development of more sustainable transportation modes. Among them, intermodal transportation is already considered one of the most effective ways to reduce GHG (Ji and Luo, 2017). Specifically, intermodal transportation allows the combination of different transportation modes to exploit each mode's advantages to the fullest to better cope with the growing demand for transportation while saving energy and reducing emissions. With intermodal transportation, cargo can be transported by several transportation modes (e.g., road, rail, maritime, and air) between its origin and destination.

In reality, road transportation is widely used and can provide highly flexible transportation services, whereas rail transportation can offer cheaper shipping costs with better reliability. The combination of road and rail transportation modes can take advantage of the accessibility advantage of road transportation for short- and medium-distance logistics and the economic and reliability advantages of rail transportation for long-distance logistics (Verma and Verter, 2010). Sun et al. (2019) proposed a bi-objective fuzzy MINLP model with CO_2 emissions constraints to investigate a hazardous materials routing problem in the road-rail intermodal transportation network. They designed a three-stage exact algorithm combining fuzzy credibilistic chance constraints, linearization methods, and a normalized weighting method to solve the model. To achieve a sustainable transport network with centralized freight decisions, Liu et al. (2019) proposed a nonlinear, nonconvex, and discontinuous MIP model that considers distance economies of scale, volume economies of scale, and vehicle size economies of scale for a road-rail intermodal transportation network design problem involving freight consolidation. They used a GA and PSO algorithm with a batch strategy to solve the model.

To improve the green efficiency of transport systems, combining land and water transport is feasible and effective for coastal areas (Chen et al., 2020). The United States has proposed the Marine Highway Program to promote the development of intermodal transport (USDoT, 2021). The European Union has similarly proposed the Motorways of the Sea Program to enhance the utilization of water transport (EU, 2021). Eighteen ministries and commissions in China, including the Ministry of Transport, jointly issued a notice on further encouraging the development of intermodal transport (SCIO, 2016). Two categories of intermodal transport (i.e., sea-road and sea-rail) are the most common combinations of land and water transport. In terms of the sea-road transportation system, the sea-truck problem has been studied the most.

To balance the trade-off between economic and environmental benefits, Dong et al. (2020) proposed a MIP model for a sea-truck intermodal distribution network to optimally determine how many ships of each type to use, their sailing routes and speeds, and the network cargo flows involving land and water transport. The model considers two objective functions (i.e., minimizing transportation costs and emissions). Baykasoğlu and Subulan (2019) also studied the sea-truck/trailer problem. Zhao et al. (2018) investigated a stochastic empty container repositioning problem that considered CO_2 emissions and stochastic demand and supply for a sea-rail intermodal transportation network. They proposed a chance-constrained nonlinear IP model to minimize the expected value of the total weighted sum of the CO_2 emissions-related and repositioning costs.

For large volumes of goods over long distances, road-rail-waterway transportation may be the most flexible and environmentally friendly method. Demir et al. (2016) studied a road-rail-inland waterway intermodal service network design problem with travel time and demand uncertainties. They solved a MILP model to obtain robust transportation plans according to different objectives, such as containing cost, time, and the amount of GHG emissions. Demir et al. (2019) further proposed a bi-objective (i.e., economic and environmental objectives) MILP model for a green sea-rail intermodal transportation network with time-related costs.

6.2 Green passenger transport network

Constructing transportation infrastructure for public transport has significant and broad influences on economic growth, social progress, and environmental pollution. Recently, sustainability has attracted considerable attention from public transport decision makers because public transport can significantly reduce fuel consumption and pollutant emissions compared with private car transport. Hence, this subsection reviews several streams of research on passenger transport networks.

As urban populations increase, interest in planning and design problems related to railways is increasing worldwide, especially in the United States (Kang et al., 2014). Rail planning and design are vital because of the ability of trains to efficiently transport cargo and passengers in an economical and environmentally friendly manner, which makes railways part of green logistics. To design a sustainable and cost-effective rail infrastructure, Kang et al. (2014) proposed a rail transit route optimization model to minimize the initial construction cost, life-cycle cost, and penalty cost for violating design constraints. Wang et al. (2019b) proposed an IP model to find the optimal train-set circulation plan for passenger railway transportation hubs. They applied a GA heuristic to solve the model. Their computational results showed that in a transportation hub, train-sets dispatched between stations can contribute to more efficient train-set circulation plans. Readers interested in more studies on the railway optimization problem should refer to Zhou et al. (2019a) (passenger train-booking optimization) and Wang et al. (2021) (train timetable optimization).

As urbanization accelerates, especially in China, the number of cars is increasing rapidly, which makes the urban traffic problem increasingly salient. Hence, the development of public transport has become important for sustainable development (Zhou et al., 2019b). Jiménez and Román (2016) addressed the problem of allocating an urban bus fleet to a set of fixed routes while considering new propulsion technologies and differences between routes and bus types. They proposed a MILP model to minimize the weighted sum of the various emissions. Chen et al. (2019) investigated a bus route headway allocation problem under the three uncertainties of passenger demand elasticity, the randomness of travel time between stops, and abandoned passenger flow. Their computational results indicated that their model could meet the goal of sustainable public transport by reducing passenger waiting time and attracting more passengers to bus travel. Many scholars have studied the bus scheduling problem and considered aspects such as reducing air pollution (Li and Head, 2009), route determination (Pternea et al., 2015; Ren et al., 2020), and distribution optimization based on passenger flows (Gong et al., 2019). Ji et al. (2019) also investigated a new method for prioritization along signalized corridors for trams that typically run on exclusive lanes in urban streets.

A "bicycling renaissance" has emerged in the last century (Pucher et al., 1999), and governments worldwide have invested in bicycle facilities (Duthie and Unnikrishnan, 2014). To promote bicycling as a green traveling mode, Bagloee et al. (2016) proposed a mathematical method to determine the latent misutilized capacity in congested urban areas for the creation of exclusive bicycle lanes. To minimize total travel time in the context of a congested city, they developed a bilevel programming model whose upper level minimizes the total system cost and the lower level uses a multi-class user equilibrium traffic flow to reflect users' behavior. Apart from bicycle lane priority, some policies, such as electric bicycles, shared bicycles, and the integration of public transport and bicycles, have also been studied by scholars. To improve the competitiveness of bike-and-ride services in inter-zonal areas, Tavassoli and Tamannaei (2020) developed an IP model to maximize the number of modal shifts from private cars to bike-and-ride services.

6.3 Aviation and marine logistics network design

To properly deal with the rapid increase in environmental impacts caused by air transport, especially pollutant emissions, the goal of the aviation industry in the early twenty-first century is to make air transport greener (Parsa et al., 2019). Parsa et al. (2019) proposed a multi-objective MILP model to optimize the airline hub-and-spoke network, including the location of hub airports, allocation of non-hub airports to hub airports, airplane fleet composition, and allocation of airplanes. The three objectives considered in Parsa et al. (2019) were to minimize the total flow and hub establishment costs, to minimize the amount of GHG and fuel consumption, and to minimize aircraft noise in the network.

With the goal of reducing global sulfur emissions from shipping, the International Maritime Organization (IMO) promulgated Emission Control Area (ECA) regulations in 2015 to reduce the sulfur content of ship emissions worldwide to 0.5% by 2020 (IMO, 2016). Increasingly strict regulations require shipping to go green as soon as possible. Zhen et al. (2020) developed a MINLP model to determine the optimal fleet deployment along routes (including the adoption of green technology), timetables, cargo allocation among routes, sailing speeds on all legs, and berth allocation considering the availability of shore power. To minimize total transportation cost, Du et al. (2016) proposed a MILP model for a liner ship fleet deployment problem with collaborative transportation to achieve sustainable development.

Ports are important marine logistics nodes. Reducing air pollution in container ports is key to the development of green ports. Recently, many ports have begun making efforts to become green ports. Heilig et al. (2017) investigated a multi-objective interterminal truck routing problem that considers truck emissions. The three objective functions considered in the paper were minimizing the cost of hiring trucks, minimizing the route and service specific costs, and minimizing emissions. Yi et al. (2020) investigated the sustainable transportation of prefab products from factories to construction sites by ship. They proposed a large-scale IP model to optimally determine loading plans, i.e., which products to load into each cargo hold, how to pack the products into the holds, and how to minimize the number of holds used.

6.4 Other related issues

We cannot describe all of the problems we found because of space limits. Other related issues include urban passenger traffic structure optimization (Li and Lu, 2021), one-way traffic reconfiguration planning (Karimi et al., 2021), rescue logistics design considering CO_2 emissions (Boostani et al., 2020), urban underground logistics network planning (Hu et al., 2020), and urban freight transportation (Pamučar et al., 2016; Bi et al., 2020).

7 New challenges in green logistics

In addition to the studies on green logistics already introduced, some new challenges that must be addressed have arisen from the rapid development of new technologies and new customer demands. In recent years, with the rise of the sharing economy, shared mobility has become popular, and has attracting much research attention. Technological developments related to new vehicles, such as smart cars, unmanned aerial vehicles (UAVs), and electric vehicles, are frequently emerging. We introduce some related issues at the end of this section.

7.1 Shared mobility

Shared mobility is increasingly attracting the attention of both industry and academia because it can reduce traveling costs and emissions. In an environmentally friendly society, shared mobility has become a powerful force for sustainable development (Wang et al., 2017). Customer sharing, vehicle sharing, depot resource sharing, and even comprehensive resource sharing are common in production operations. Transportation resource sharing has spread to many countries for passenger transport (Wang et al., 2019a).

To reduce the external influences of transportation, sustainable alternatives to individual motorized mobility have been developed over the last few decades. As a sustainable transport system, bicycle sharing, which allows the use of bicycles for short periods of time, is becoming increasingly popular. Frade and Ribeiro (2015) developed a MILP model to maximize demand in a bicycle-sharing system. The proposed model can help find the optimal fleet size, location and capacity of bicycle stations, and number of bicycles at each station under the condition of balancing the annual cost and revenue of the system. Luo et al. (2020) studied a bicycle rebalancing problem which is a multiple traveling salesman problem with pickup and drop-off demands to determine the optimal fleet size and rebalancing strategy. They proposed an IP model to minimize vehicle travel distances and meet the rebalance demands of clusters.

As a sustainable transportation mode, ride-sharing, also known as car-sharing or carpooling, allows drivers to share unoccupied seats with customers. Ride-sharing relieves road congestion and parking pressure and helps reduce fuel consumption by increasing the payload of cars on the road. Over the past decade, developments in the communications field have led to the successful development of ride-sharing, such as Carpooling.com in Europe, Avego, Zimride and Carticipate in the United States, and DiDiPinChe in China. Optimization problems in ride-sharing systems are becoming trickier because of the increasing size of the problem. Naoum-Sawaya et al. (2015) introduced a stochastic MIP model to optimally determine the allocation of shared cars considering the uncertainty of vehicle availability, which is actually a car placement problem in a ride-sharing system. The objective function of the model was to minimize expected travel time. Stiglic et al. (2016) proposed an IP model for a single rider and single driver matching problem to maximize the number of matches to investigate the effects of driver and rider flexibilities. Their computational results showed that slightly increased flexibility in the earliest departure time and maximum detour time can greatly increase the matching rate.

The rapid growth of e-commerce has led to a surge in urban parcel deliveries, putting significant pressure on last-mile delivery providers. As crowdsourced delivery is more flexible and less capital intensive than traditional distribution methods, it currently plays an important role (Zhen et al., 2021). Chen et al. (2018) developed an IP model for a multi-driver multi-task matching problem with time windows that considers task transfers between drivers, drivers' maximum detours, and capacity limits. They developed two heuristic algorithms to solve the model, and the computational results showed that crowdsourced delivery was economical and sustainable.

More problems related to shared mobility have been studied, such as a shared logistics chain with economic and environmental objectives (Mrabti et al., 2020), an on-demand rapid transit system integrating shared goods with passengers (Fatnassi et al., 2015), and the selection of inventory sharing strategies (Liu et al., 2020a).

7.2 New vehicles

Many scholars have applied OR methods to study problems related to using new vehicle technologies, such as smart cars, UAVs, and electric vehicles, instead of manual gasoline vehicles. As these new vehicle types have vastly different features compared with traditional gasoline vehicles, more research has been done on them.

Smart cars are automobiles with advanced driving assistance systems that provide a more enjoyable driving experience and safety assurances. An autonomous vehicle is a smart car that can sense its environment and move safely with little or no human help. Conceição et al. (2020) proposed a MINLP model for a reversible lane network planning problem to make optimal traffic assignment and reversible lane decisions. They found that reversible lanes can help reduce road congestion, delays, and travel times up to 36%, 22%, and 9%, respectively. Lin et al. (2021) studied a multi-objective optimal planning problem of dedicated connected lanes for autonomous vehicles. They developed a multi-objective bilevel model to minimize the system's total costs including travel cost, lane construction cost, and emission cost in the upper level, and they introduced a multi-class network equilibrium with heterogeneous traffic in the lower level.

UAVs are expected to revolutionize the logistics industry worldwide. Leading logistics and e-commerce companies, such as DHL (Banker, 2013) and JD (JDX, 2017), are testing using UAVs to deliver parcels. Advances in UAV technology have increased the use of UAVs in transportation, which means that traffic associated with the operation of UAVs is a major problem. Eun et al. (2019) introduced a two-phase method to compare UAVs with traditional ground vehicles in terms of their levels of environmental protection. The optimal delivery plans for UAV-alone and ground vehicle-alone systems were determined by solving a VRP model with multi-sharable depots and multi-trips in phase one. In phase two, CO_2 emissions were calculated given the distance of the optimal routes from phase one. Li et al. (2020) proposed a MILP model with vehicle-type and half-side traffic restrictions to investigate the impact of UAV delivery on sustainability and costs. They found that UAV delivery more effectively reduces CO_2 emissions and costs under the vehicle-type restriction than under the half-side traffic restriction.

As the amount of CO_2 emissions is increasing rapidly, many countries are shifting toward electric vehicles. Compared with vehicles that consume fossil fuel, electric vehicles are environmentally friendly, and their operating cost is quite low. Specifically, the operating costs of fossil fuel and electric vehicles are two cents and more than 12 cents per mile, respectively (Abouee-Mehrizi et al., 2021). One of the main research directions regarding electric vehicles is the electric VRP. Compared with the traditional VRP, the electric VRP must consider recharging stations. Assuming that a partially discharged battery can be recharged at any available station, Macrina et al. (2019) proposed a MILP model for a comprehensive energy consumption problem that considers loaded cargo, speed, deceleration, acceleration, mixed vehicle fleet (electric and conventional vehicles), time windows, and road gradients. Goeke (2019) developed a MIP model for a pickup and delivery electric VRP with time windows and capacity limits for energy consumption and cargo. They allowed for vehicles to be recharged when stopped at dedicated stations. Resource distribution in the smart grid for electric vehicles has also been widely studied by scholars. With the aim of minimizing the present value of net electricity and emission costs, Hajimiragha et al. (2011) developed a robust optimization model that considered the limits of the electricity grid and the transport sector to integrate electric vehicles into the electric grid. Reddy et al. (2016) proposed a dual-objective (emissions and operating costs) programming model to solve a distributed resource scheduling problem in the smart grid for electric vehicle deployment.

Other studies on electric vehicles consider the management of traffic congestion with subsidies (Wu et al., 2020), an electric VRP with backhauls (Granada-Echeverri et al., 2020), road pricing for electric and gasoline vehicles (Xi et al., 2020), the allocation of electric vehicles in parking lots (Neyestani et al., 2014), lane expansions for electric vehicles (Cheng et al., 2020), electric vehicle fleet renewal (Kuppusamy et al., 2017), and electric vehicle fleet deployment (Schiffer et al., 2021).

7.3 Other related issues

In addition to these two categories, a number of new research directions have been investigated. To decrease transportation costs, shippers often outsource transportation activities to logistics companies. To further reduce transportation costs, Santos et al. (2021) presented a collaborative collection method to allow orders to be picked up from producers in the backhauling routes of leading retailers or third-party logistics providers. They proposed a multi-objective MIP model to minimize operational costs, fuel consumption, and operational and CO_2 emissions. Their computational results showed that the collaborative collection method can help reduce global fuel consumption and operation costs by 26% and 28%, respectively.

Fleet renewal optimization, especially converting to electric fleets, is another hot research topic. Stasko and Gao (2010) proposed an IP model to study an integrated problem with vehicle purchase, retrofit, and aggregated task assignment decisions to reduce transit fleet emissions. Ahani et al. (2016) proposed an optimization framework based on portfolio theory that considers the risks and costs related to uncertainties in certain input parameters to determine an optimal fleet replacement plan.

8 Conclusions

We conclude this paper by summarizing our main findings and by providing outlooks on future research directions.

8.1 Summary

In this paper, we have conducted an up-to-date review of papers that combine green logistics and operations research. After analyzing 816 papers, this review makes two relevant contributions. First, it provides a comprehensive review of the key topics to advance understanding of the state of research on green logistics. Second, this paper identifies several directions for further research, especially those considering the long-term impacts of the COVID-19 pandemic. However, this study has two potential extensions for the current writing. First, the specific model formulation and algorithm design can be introduced in detail. Second, a chronological overview of the development of research methodologies for a specific problem can be focused in the future.

8.2 Suggestions for further research directions

In recent years, the development of the sharing economy has provided significant energy savings and emissions reductions. The sharing economy, e.g., crowdsourced delivery and bike sharing, allows better use of existing resources. In addition, inventions such as electric vehicles and electric bikes improve the feasibility of green logistics. Hence, planning the use of these new technologies is important.

Proper pricing for externalities, such as the release of GHG and other emissions, is a highly effective strategy to reduce pollution. Determining how to get individuals, companies, or governments to reduce their emissions through reasonable pricing is a very complex research topic. For example, some international organizations use average indicators to assess ship emissions, such as the average emissions per nautical mile, and if the actual emissions of a ship exceed a certain number, the shipping company is fined. However, using these average indicators may result in some ships sailing empty to reduce their average emissions, which actually increases emissions.

Hence, the proper pricing of externalities requires more detailed investigation.

As noted, the long-term impacts of the COVID-19 pandemic need more research attention in relation to green logistics problems. Since the start of the pandemic, some new modes, such as working from home and online meetings, have been widely adopted. How to improve logistics services, especially in a green manner, to meet the demands of these new living and working patterns must be further studied. In addition, global e-commerce showed a dramatic rise, reaching 26.7 trillion US dollars (UN, 2021), which undoubtedly poses a huge challenge for last mile delivery services. How to deal with problems related to the e-commerce boom in a green manner should also be studied.

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