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Integrating operations research into green logistics: A review

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Abstract Logistical activities have a significant global environmental impact, necessitating the adoption of green logistics practices to mitigate environmental effects. The COVID-19 pandemic has further emphasized the urgency to address the environmental crisis. Operations research provides a means to balance environmental concerns and costs, thereby enhancing the management of logistical activities. This paper presents a comprehensive review of studies integrating operations research into green logistics. A systematic search was conducted in the Web of Science Core Collection database, covering papers published until June 3, 2023. Six keywords (green logistics OR sustainable logistics OR cleaner logistics OR green transportation OR sustainable transportation OR cleaner transportation) were used to identify relevant papers. The reviewed studies were categorized into five main research directions: Green waste logistics, the impact of costs on green logistics, the green routing problem, green transport network design, and emerging challenges in green logistics. The review concludes by outlining suggestions for further research that combines green logistics and operations research, with particular emphasis on investigating the long-term effects of the pandemic on this field.

Keywords green logistics, operations research, environment, literature review

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1 Introduction

Logistics encompasses various activities, such as transportation, storage, and handling, enabling the movement of products within supply chain networks, starting from raw material sources to the final point of sale or consumption (McKinnon et al., 2015). The COVID-19 pandemic has significantly accelerated the growth of global e-commerce, with its share of retail sales rising from 16% to 19% in 2020 (UN, 2021). This surge in e-commerce presents a formidable challenge for last-mile delivery services. Consequently, companies are actively exploring new strategies to enhance their logistics operations. However, these developments have notable environmental implications (van Woensel et al., 2001). In particular, the emission of greenhouse gas (GHG) during logistics activities significantly contributes to the global environmental impact. Currently, carbon dioxide (CO₂) emissions from the transport sector account for approximately 30% of total emissions in developed countries and 23% worldwide (UNECE, 2021). The United Nations Economic Commission for Europe (UNECE) has recently spearheaded a widespread agreement to reduce CO₂ emissions in transportation by at least 50% by 2050 (UNECE, 2021). Consequently, the environmental influence of logistics has gained considerable attention in recent years.

In recent decades, there has been a growing concern among the public and governments regarding the environmental impact of logistical activities, leading to the emergence of green logistics as a proposed solution (McKinnon et al., 2015). In alignment with McKinnon et al. (2015), we define “green logistics” as the comprehensive study of the environmental implications associated with all aspects of transportation, storage, and handling involved in supply chains, encompassing both forward and reverse movements of physical products. Our research encompasses various logistical aspects, including routing, warehousing, and other relevant factors, while focusing on addressing environmental challenges such as

GHG emissions and the adoption of new green technologies. Although green logistics is a relatively nascent field, it is rapidly evolving in response to the increasing need for sustainable practices in the logistics industry.

The application of advanced analytical methods has significantly contributed to making better decisions in various domains (INFORMS, 2021). Operations research (OR) has been extensively utilized in numerous studies, such as Silver (1981), Luss (1982), Cire and van Hoes (2013), Lien et al. (2014), Ata et al. (2019), and Gupta and Radovanović (2020). Effective utilization of OR techniques has proven instrumental in driving the success of companies such as Procter & Gamble (Hines, 2008), Hewlett Packard (Burman et al., 1998), and United Parcel Services (Holland et al., 2017). These techniques have enabled cost savings, inventory reduction, and increased profitability for these organizations. As sustainability gains more prominence in public discourse, OR techniques are also used to address environmental concerns. Dekker et al. (2012) asserted that OR techniques can effectively strike a balance between profitability and environmental costs, optimize resource utilization, and reduce both costs and emissions.

This review is driven by the pressing real-world issue of sustainable development. The transportation industry is experiencing significant growth, resulting in escalating traffic volumes. As highlighted in the *Statistical Pocket-book 2019* (EEA, 2019), an estimated 3046 billion tonne-kilometers of freight cargo were transported within and between European Union countries (EU-28) via road and maritime transport in 2017, resulting in a substantial

release of GHG. While Europe has made commendable progress in reducing overall GHG emissions, the transport sector has not followed this general trend, and its relative contribution to GHG emissions in Europe has become increasingly significant (EEA, 2020). Consequently, the imperative to promote environmental sustainability within the transport sector becomes crucial. OR techniques, particularly mathematical programming, hold great potential in helping achieve goal of accomplishing more with fewer resources, thereby reducing pollution. Therefore, this review primarily focuses on the intersection of green logistics and OR, exploring the application of OR techniques in the context of achieving environmentally sustainable logistics practices.

The primary objective of this review is to provide a comprehensive overview of the current state and potential advancements in green logistics through a meticulous examination of up-to-date research papers. Given the extensive volume of published papers in this field, it is impractical to review them all. Therefore, we begin by summarizing a selection of representative overview papers on green logistics in Table 1. For readers interested in delving deeper into this subject, we recommend consulting other comprehensive papers such as those authored by Kleindorfer et al. (2005), Srivastava (2007), Sbihi and Eglese (2010), Dekker et al. (2012), and McKinnon et al. (2015).

The subsequent sections of this review are structured as follows. Section 2 elucidates the methodology employed to identify relevant papers. Section 3 presents a review of studies focused on green waste logistics. The impact of

Table 1 Representative overview papers on green logistics

Papers	Review range	Theme	Studied problems	Topics
Kleindorfer et al. (2005)	First 50 issues of journal <i>Production and Operations Management</i>	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 since 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, and 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 emerging challenges in green logistics

Notes: (1) “SUS”, “GSC” and “GL” denote sustainability, green supply chain, and green logistics, respectively; (2) the en-dash means that the reviewed paper does not introduce this aspect.

costs on green logistics is explored in Section 4. Section 5 provides an overview of the literature on the green routing problem. Section 6 concentrates on papers addressing green transport network design. Section 7 addresses the challenges associated with green logistics. Finally, Section 8 offers our concluding remarks summarizing the key findings of this review.

2 Literature search methodology

To identify relevant papers for this review, we conducted a search in the Web of Science Core Collection database using six keywords within the 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 excluded articles containing specific irrelevant words related to other disciplines or areas of research, such as chemistry, agriculture, fish, fishery, electronic, pressure, tourism, geography, medicine, psychology, biology, materials science multidisciplinary, surgery, finance, biochemistry, nuclear, ecology, chemical, mechanics, education, and public environmental occupational health.

We further refined the search by selecting English-language documents and limiting the document type to articles only, excluding materials such as editorial materials, notes, or letters. The initial search yielded a broad range of thematic areas beyond the scope of this review. To narrow down the results, we ruled out papers from irrelevant thematic areas, including 1) physics and related areas, 2) geography and related areas, 3) chemistry and related areas, 4) medicine, biology, and related areas, and 5) electronic or mechanical engineering and related areas. After several iterations, the search resulted in a total of 8542 articles published until June 3, 2023. Since our review specifically focuses on the integration of green logistics with OR, we further refined the selection by excluding papers that utilized other methodologies, resulting in a final selection of 670 relevant articles. The paper selection process is summarized in Table 2.

Figure 1 illustrates the distribution of the number of papers published each year. From 1997 to 2020, the number of papers published annually fluctuated but displayed an overall upward trend, with some years showing nearly a doubling of publications. This trend may be attributed to the growing environmental awareness among governments, enterprises, and the general public during this period. However, the outbreak of the COVID-19 epidemic in 2020 has attracted many scholars to study epidemic-related problems, resulting in a decrease in the number of green logistics-related papers published in 2021. After 2021, the number of published papers continued to increase. The initial set of 670 articles was categorized into five broad problem contexts, namely, green waste logistics, the impact of costs on green logistics, the green routing problem, green transport network design, and emerging challenges in green logistics. Subsequently, each of these categories was further organized into smaller subcategories, and the relevant papers were reviewed in the following five sections. It is important to note that logistics encompasses both transportation and storage. However, for this review, we focused exclusively on transportation-related papers. Actually, green storage has been extensively covered in existing review 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;

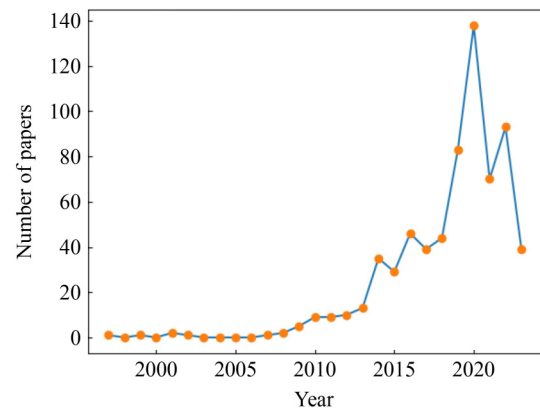


Fig. 1 Number of papers published annually.

Table 2 Four steps of collecting papers

Step	Process
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
Step 3	Exclude irrelevant areas physics and related areas; geography and related areas; chemistry and related areas; medicine, biology and related areas; electronic, mechanical engineering and related areas
Step 4	Manual reading and identification of articles

Custodio and Machado, 2020; Kumar et al., 2021; Zhen and Li, 2022). Therefore, we did not review green storage papers in this particular review, focusing solely on transportation-related aspects.

3 Green waste logistics

Rising environmental concerns and the escalating production of waste have prompted a greater focus on finding environmentally friendly waste management solutions (Sbihi and Eglese, 2010). According to the World Bank (WB, 2018), the global generation of municipal solid waste amounts to 2.01 billion tonnes annually, with projections estimating an increase to 3.4 billion tonnes by 2050. Adopting sustainable transportation practices necessitates addressing waste management in an environmentally conscious manner, leading many researchers to investigate the problem of green waste logistics. Scholars have proposed various approaches, including material and product reuse, to capture surplus value, which involves the implementation of reverse logistics. The COVID-19 pandemic has further emphasized the urgency of establishing efficient and sustainable waste management systems, particularly with the surge in demand for food delivery and similar services (Sumagaysay, 2020). This section of the review first examines studies focused on waste management, followed by an exploration of papers related to reverse logistics in the context of green waste logistics.

3.1 Waste management

In 1987, the Brundtland Commission, a suborganization of the United Nations, defined “sustainable development” as the simultaneous achievement of human development goals while ensuring the preservation of natural systems’ ability to provide resources and ecosystem services on which the economy and society depend (BC, 1987). Proper waste management has since become increasingly vital in achieving sustainable development.

Many papers in waste management research focus on solid waste management, with the problem often modeled as a variant of the vehicle routing problem (VRP). Ramos et al. (2014a) proposed two multi-product and multi-depot VRP models to optimize recyclable waste collection systems, targeting distance and CO₂ emissions reduction, respectively. Their results demonstrated reductions of up to 22% in distance and 27% in CO₂ emissions. Asefi et al. (2019) developed an integrated framework that combines the VRP and the fleet size problem to solve a cost-effective integrated solid waste management problem. They formulated a bi-objective mixed integer linear programming (MILP) model to simultaneously minimize transportation costs and deviation from fair load allocation to transfer stations. Babae Tirkolae and Aydın (2021)

presented a bi-objective MILP model for capacitated VRP to optimize transportation planning for municipal waste management, considering outsourcing during a pandemic.

Plastic waste management is a significant focus area in waste management research. Bing et al. (2013) proposed an MILP model for designing a plastic recycling network, highlighting that transportation costs account for approximately 7% of the total costs and that multi-modal transport can reduce transportation costs by nearly 20%. Bing et al. (2014) modeled a plastic waste collection problem as a VRP and utilized a tabu search algorithm to improve the routes.

The recycling of the waste of electrical and electronic equipment (WEEE) is another prominent research topic. Ayvaz et al. (2015) developed a multi-echelon, multi-product, capacitated two-stage stochastic programming model for a third-party WEEE recycling company. Their model considered uncertainties in return quantity, sorting ratio, and transportation costs, aiming to maximize total revenue. Safdar et al. (2020) presented a multi-objective model to maximize total profit and social benefits while minimizing environmental impacts in WEEE management design.

Scholars have also investigated recycling-specific items. Dehghanian and Mansour (2009) proposed a three-objective mathematical programming model for maximizing social and economic benefits while minimizing negative environmental impacts in scrap tire recycling, employing a genetic algorithm (GA) to find Pareto-optimal solutions. Zhou and Zhou (2015) developed a nonlinear integer programming (IP) model for determining the locations and quantities of recycling stations and plants in a case study on office paper recycling in Beijing (China), aiming to minimize total costs. Shah et al. (2018) emphasized the value recovery from trash bins, employing a stochastic optimization model with embedded chance constraints to minimize total transportation costs. Furthermore, agricultural residue management has been explored by scholars. Parker et al. (2010) presented a mixed-integer nonlinear programming (MINLP) model for finding the most efficient and economical network to generate hydrogen from agricultural residues. Li and Huang (2018) proposed a mixed-integer programming (MIP) model for constructing reverse logistic networks for pesticide wastes, determining optimal collection locations and flow allocation between recycling and treatment centers.

3.2 Reverse logistics

Remanufacturing end-of-life products offers numerous economic, environmental, and social advantages (El Korchi and Millet, 2011). However, effective remanufacturing requires the establishment of environmentally and economically feasible reverse logistics systems to transport

reusable components back to factories. Manufacturers face pressure from various stakeholders, including customers, suppliers, competitors, and government agencies, to implement reverse logistics practices (Govindan and Bouzon, 2018; Plaza-Úbeda et al., 2021). Our review of papers on reverse logistics revealed a significant increase in publications since 2015. Moreover, there is often an integration of reverse and forward logistics into an integrated logistics network. The combination of reverse logistics with the VRP is also a popular research direction.

One major research direction in reverse logistics is the study of integrated logistics networks that incorporate both reverse and forward logistics. Zarbakhshnia et al. (2020) examined a multi-product, multi-stage, multi-period system that incorporated both forward and reverse logistics under demand uncertainty. They developed a probabilistic MILP model to optimize the flows in both chains, determine the location of established centers, and devise an optimal transportation strategy while considering the impact of CO₂ emissions. Boronoos et al. (2021) proposed a multi-objective MINLP model for a forward and reverse logistics system involving multiple manufacturing centers, warehouses, customer zones, disassembling centers, and remanufacturing centers. Their model determined the optimal facility locations and capacities, quantities of produced/remanufactured and disassembled products, and product flows while minimizing total costs, total CO₂ emissions, and robustness costs in both forward and reverse logistics.

The integration of reverse logistics with the VRP is another prominent research direction. Kumar et al. (2017) proposed an IP model for a multi-period, multi-echelon VRP in a forward–reverse logistics system, aiming to optimize flow allocation and vehicle routing decisions. 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 developed a bi-objective MILP model to determine the optimal two-echelon vehicle routing and the appropriate distribution of total cost savings among participating facilities. Solano et al. (2021) combined reverse logistics with the VRP, focusing on simultaneous pickup and delivery within time windows. Using an MILP model, they determined the optimal vehicle routing for the collection and distribution of bottles and the optimal dispatch quantities.

Scholars have also integrated reverse logistics into location problems to study how to achieve product recovery. Duque et al. (2010) developed an MILP model to design a recovery network structure for a sludge recovery network, optimizing transport and transformation schedules. Govindan et al. (2016) proposed a multi-objective MIP model to investigate product recovery in the electrical

manufacturing industry, aiming to maximize profit by determining the optimal location for a hybrid recovery facility and the optimal flow of products, recovered parts, and materials in the system.

Due to the rise of online shopping and the impact of COVID-19, there has been a surge in returned goods, making the proper management of reverse logistics for these goods a significant research topic. Nenes and Nikolaidis (2012) developed an MILP model for a multi-period used-product returns network, optimizing procurement, remanufacturing, stocking, and salvaging decisions to maximize total network profit. Dutta et al. (2020) studied the reverse logistics problem of an online Indian clothing retailer using a multi-objective IP model, aiming to minimize costs and environmental impacts, maximize social responsibility, and determine optimal technology adoption for incineration centers and fulfillment centers, as well as optimal locations for delivery hubs, landfills, and recycling centers.

4 Impact of costs on green logistics

Green logistics involves striking a balance among environmental, economic, and social benefits. Government regulations often require companies and individuals to reduce emissions, and toll roads are one example of such measures¹⁾. Governments commonly employ subsidies to incentivize the upgrading of old, high-emission equipment, while taxation serves as a deterrent for emitting pollutants. This section reviews papers that explore the impact of costs on green logistics.

Environmental charges have emerged as an effective economic approach for controlling externalities and promoting sustainable transportation (Lu and Morrell, 2001). Alkhayyal (2019) proposed a single-period MILP model for a reverse supply chain that considers the market price of CO₂ emissions. Their model optimizes the flow of components between remanufacturing facilities, aiming to minimize CO₂ emissions, product recovery, transportation, energy use, rent costs, and labor.

Road toll design is a popular topic within the realm of charging problems in green logistics. Lv et al. (2020) developed an inexact bilevel programming model that accounts for stochastic and fuzzy uncertainties to design a road toll system considering vehicle emissions. Rodriguez-Roman and Ritchie (2020) introduced a transportation network paradox highlighting the unintended effects of reducing traffic emissions. They proposed multi-objective models for optimizing toll designs to minimize air pollutants inhaled by humans and address environmental inequality.

To achieve green logistics goals, companies often need

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

to make substantial equipment investments, and government subsidies play a crucial role in incentivizing such upgrades. Wu and Wang (2020) investigated a shore-power deployment problem to reduce in-port emissions by enabling berthed ships to connect to the shore electrical network. They proposed an IP model to develop 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 concerning leftover pharmaceuticals. Their model considers the interplay among a third-party logistics company, the producer, and the government to balance environmental, economic, and social benefits.

Taxation policies are also a perspective of study in the field. Li et al. (2019) proposed an intermodal transportation network planning model that minimizes overall transportation costs, handling costs, and CO₂ emission costs. The computational results revealed that carbon taxes have a limited influence on intermodal transport networks, with unloading and loading costs exerting a far greater impact on the total cost than CO₂ emissions. Chen et al. (2020) determined the optimal joint taxation-subsidy emissions reduction policy for the government to minimize additional investments in the coastal transportation system.

5 Green routing problem

Since the introduction of the classic VRP by Dantzig and Ramser (1959), VRPs have been a highly active and rapidly growing research area (Vidal et al., 2020). With the rapid expansion of last mile logistics, the negative impacts of transportation, such as noise, air pollution, and land use, have received considerable attention (Marrekchi et al., 2021). Among these, pollutant emissions from transportation activities are recognized as a major threat to the environment (Suzuki and Kabir, 2015). Consequently, OR scholars have directed their focus toward studying the green routing problem.

The energy minimization VRP was first proposed by Kara et al. (2007) by combining the VRP with environmental protection concerns. Subsequently, Bektaş and Laporte (2011) introduced the pollution-routing problem (PRP), and Erdoğan and Miller-Hooks (2012) presented the concept of the green VRP. Although these concepts exhibit some differences in their formulation, their underlying nature is not substantially distinct. Marrekchi et al. (2021) stated that in the PRP, the vehicle speed on each arc is optimized to minimize fuel consumption, emissions, or driver costs. A specific characteristic of the PRP is the variation in load and speed among different arcs while keeping other parameters constant. This implies that the PRP requires determining the optimal speed or load for vehicles on each arc, while the green VRP does not

impose such a requirement (i.e., the speed of vehicles on all arcs may remain constant). Therefore, this section first reviews papers on the green VRP and PRP and subsequently examines papers related to the production and transportation routing problem, with additional discussion of other relevant issues in the final subsection.

5.1 Green vehicle routing problems

Over the course of 60 years since its introduction, numerous variants of the VRP have been proposed and studied. One widely examined variant is the capacitated vehicle routing problem (CVRP), which incorporates limited vehicle capacity to align with real-world scenarios. The CVRP has been a topic of extensive research due to its practical relevance. Typically, the objective of the CVRP is to minimize the total travel distance or travel time. To address environmental concerns, emissions have been introduced into the CVRP.

Fukasawa et al. (2016) presented two MILP models, namely, the arc-load model and the set partitioning model, for energy minimization in the CVRP. Notably, the path with the least energy consumption does not always correspond to the shortest distance, as factors such as idle driving, rapid acceleration, and sudden braking impact fuel consumption. The authors employed branch-and-cut and branch-cut-and-price algorithms to solve the arc-load and set partitioning models, respectively, with the latter algorithm yielding significant improvements. Gupta et al. (2022) approached a multi-objective CVRP with fuzzy time distances and demand split into bags.

The VRP with time windows has gained increasing importance, as customers often require customized service times in distribution systems. Küçükoğlu et al. (2015) developed an MILP model to plan vehicle routes with time windows, aiming to minimize total fuel consumption and subsequently reduce CO₂ emissions. Niu et al. (2018) proposed an MIP model for an open VRP with time windows from an environmental perspective, wherein vehicles do not return to the depot after completing their tasks. This approach minimizes total costs, including fuel consumption, CO₂ emissions, and driver wages. Some studies have also considered soft time windows that incur penalty costs if violated. Lee and Prabhu (2016) optimally assigned customer deliveries to vehicles based on fuel performance metrics and just-in-time delivery, which are correlated with vehicle cruising speeds. They developed an algorithm to determine vehicle routes and cruising speeds.

Another prominent variant, the multi-depot VRP, has attracted considerable attention from both researchers and practitioners. The multi-depot VRP involves vehicles serving customers from multiple depots and returning to preassigned depots. Ramos et al. (2014b) formulated a multi-objective, multi-depot, and periodic VRP as a set partitioning problem to balance costs associated with

social and environmental concerns, including drivers' maximum working hours and CO₂ emissions. Jabir et al. (2017) proposed an integer linear programming model that integrates economic costs and emissions reduction for a capacitated multi-depot VRP problem, considering socioenvironmental considerations.

In reality, vehicles may perform multiple trips to minimize additional vehicle costs. The cumulative multi-trip VRP addresses this by allowing vehicles to make multiple trips within a limited duration while considering CO₂ emissions reduction. Cinar et al. (2015) developed an MIP model for this variant and used a simulated annealing algorithm to minimize fuel consumption. Tirkolaei et al. (2018) designed a hybrid GA for a multi-trip capacitated VRP, aiming to minimize total costs encompassing CO₂ emissions, vehicle usage, and routing.

Scholars have also explored other environmentally focused VRP types, 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

One important branch of the classical green routing problem is the PRP, which aims to determine optimal routes and speeds to minimize operational and environmental costs. Bektaş and Laporte (2011) introduced the PRP as a variant of the VRP with time windows. Over the years, several variants of the PRP have been developed by incorporating additional constraints such as time windows, simultaneous pickup and delivery, congestion periods, and uncertainty of parameters (Marrekchi et al., 2021).

PRP with time windows plays a crucial role in freight transportation planning. Due to its complexity, most solution methods for this problem are based on heuristics. Dabia et al. (2017) proposed an exact solution based on a branch-and-price algorithm for the PRP with time windows. Saka et al. (2017) investigated a PRP with customer deadlines and multiple vehicle types, focusing on speed optimization along given vehicle routes. They developed an MIP model to minimize total costs, including fuel consumption, emissions, and driver costs.

PRP with simultaneous pickup and delivery is another important variant in green routing problems. In this problem, customer orders need to be transported from multiple origins to multiple destinations without intermediate transshipments. Bravo et al. (2019) solved a multi-objective pickup and delivery PRP with time windows, aiming 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 significant issue, particularly in urban areas, as it contributes to increased CO₂ emissions.

Franceschetti et al. (2017) proposed a metaheuristic approach for the time-dependent PRP, determining optimal vehicle routing and speed for each route to minimize driver wages and CO₂ emissions. Their approach also considered traffic congestion, which restricts vehicle speed and leads to increased emissions.

Addressing uncertainty is another important aspect of the PRP. Eshtehadi et al. (2017) obtained robust solutions for a PRP with demand and travel time uncertainty using an integer linear programming model combined with robust optimization techniques, such as the soft worst case, hard worst case, and chance constraints. Tajik et al. (2014) applied robust optimization theory and proposed an MILP model for a PRP with pickups and deliveries under uncertainties related to service time, travel time, fuel consumption, and CO₂ emissions. The objective function of their model aimed to minimize travel distance, the number of available vehicles, fuel consumption, and CO₂ emissions.

5.3 Production and transportation routing problem

Sustainability in logistics network design goes beyond optimizing operations to encompass the entire production system and postproduction management, taking into account the carbon emissions generated throughout the supply chain (Lee et al., 2010). Transportation, in particular, is a highly visible aspect of the supply chain that contributes significantly to GHG emissions (Dekker et al., 2012). Many companies have adopted environmentally friendly vehicles, equipment, and facilities and have adjusted their operations to reduce CO₂ emissions (Hua et al., 2011). This subsection focuses on the combination of transportation routing problems and production problems, which has been a subject of extensive research for decades.

The traditional inventory and routing problem aims to determine the optimal joint strategy for inventory and transportation. Rahimi et al. (2017) addressed this problem by proposing a multi-objective stochastic model considering fuzzy demand distributions and transportation costs. Their model aimed to balance economic performance, service levels, such as delivery and shortage delays, and the environmental footprint.

To ensure the best possible food quality for customers, Chan et al. (2020) developed a four-objective MILP model for constructing intelligent food logistics. The model aimed to fulfill customer demands quickly while minimizing total system costs, maximizing average food quality, reducing CO₂ emissions during production and transportation, and minimizing the total weighted delivery lead time.

Given the increasing average distance between locations in distribution networks due to globalization, location and routing decisions have become critical for the success of many companies (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 in a perishable food supply network. Schiffer and Walther (2018) developed a robust location-routing approach for an electric logistics fleet planning problem considering uncertain customer patterns. Wang et al. (2020b) considered a two-echelon location and routing problem with eco-packages, addressing both large-scale eco-package transport and small-scale eco-package pickups and deliveries.

The integration of location, routing, and inventory management is crucial for optimizing logistics networks. Zhalechian et al. (2016) introduced a location-routing-inventory model under mixed uncertainty, considering CO₂ emissions, fuel consumption, wasted energy, and social influences. They used a stochastic-possibilistic programming approach to tackle the uncertainty. Biuki et al. (2020) studied an integrated location-routing-inventory problem for designing a logistics network in a sustainable supply chain for perishable products. They formulated the problem as a multi-objective MIP model and applied hybrid metaheuristics, combining GA and particle swarm optimization (PSO) algorithm, to solve the model.

5.4 Other related issues

Due to space limitations, we cannot provide an in-depth discussion of all the problems identified. Other related issues include the location-allocation-inventory problem (Tirkolaee et al., 2020), last mile problem (Letnik et al., 2020; Zhang et al., 2022), 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., 2021).

6 Green transport network design

Logistics activities often encompass a broad region, forming a network that facilitates the movement of goods and services. With the surge in road traffic and concerns regarding emissions, it has become imperative to devise appropriate transport network designs. Unlike the VRP, which primarily focuses on optimizing vehicle routes, transport network design addresses larger transportation areas, such as intermodal connections between continents. Moreover, it incorporates multiple modes of transportation, including not only vehicles but also air and marine transport. Consequently, it is essential for companies and governments to meticulously plan transport networks to ensure efficient transportation while mitigating associated challenges. This section provides an overview of research papers across various areas, including intermodal transportation, sustainable passenger transport networks,

aviation and marine logistics network design, as well as other pertinent issues.

6.1 Intermodal transportation

The increasing concern about global warming has spurred the development of more sustainable transportation modes. Intermodal transportation, in particular, is recognized as one of the most effective ways to reduce GHG emissions (Ji and Luo, 2017). Intermodal transportation involves combining different modes of transportation to leverage the advantages of each mode, thereby addressing the growing demand for transportation while saving energy and reducing emissions. It enables the movement of cargo using various transportation modes, such as road, rail, maritime, and air, between their points of origin and destination.

In practice, road transportation is extensively utilized and offers highly flexible services, while rail transportation provides lower shipping costs and better reliability. By combining road and rail modes, it is possible to benefit from the accessibility 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 CO₂ emissions constraints to study a hazardous materials routing problem in the road–rail intermodal transportation network. They developed a three-stage exact algorithm that combined fuzzy credibilistic chance constraints, linearization methods, and a normalized weighting approach to solve the model. Liu et al. (2019) aimed to achieve a sustainable transport network with centralized freight decisions and proposed a nonlinear, nonconvex, and discontinuous MIP model for a road–rail intermodal transportation network design problem involving freight consolidation. They employed GA and PSO algorithms with a batch strategy to solve the model.

Combining land and water transport is feasible and effective, particularly for coastal areas, to enhance the green efficiency of transport systems (Chen et al., 2020). Initiatives such as the Marine Highway Program in the United States and the Motorways of the Sea Program in the EU have been proposed to promote the development of intermodal transport by integrating water transport. In China, several ministries and commissions, including the Ministry of Transport, have jointly issued a notice to encourage the further development of intermodal transport (SCIO, 2016). The most common combinations of land and water transport are sea–road and sea–rail intermodal transport. Among them, the sea–truck problem has received significant attention.

To strike a balance between economic and environmental benefits, Dong et al. (2020) developed an MIP model for a sea–truck intermodal distribution network. The model optimizes the selection of ship types, their sailing routes

and speeds, and the network cargo flows involving land and water transport. Two objective functions are considered: 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 in a sea-rail intermodal transportation network, considering CO₂ emissions and stochastic demand and supply. They proposed a chance-constrained nonlinear IP model to minimize the expected value of the total weighted sum of CO₂ emissions-related costs and repositioning costs.

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

6.2 Green passenger transport network

The construction of transportation infrastructure for public transport has wide-ranging impacts on economic growth, social progress, and environmental pollution. In recent times, sustainability has garnered significant attention from decision-makers in the public transport sector due to its potential to substantially reduce fuel consumption and pollutant emissions compared to private car transport. Therefore, this subsection examines various research streams concerning passenger transport networks.

With the rise in urban populations, there is a growing interest worldwide in planning and design problems related to railways (Kang et al., 2014). Rail planning and design play a crucial role, as trains offer efficient transportation of passengers and cargo in an economically viable and environmentally friendly manner, making railways a part of green logistics. Kang et al. (2014) proposed a rail transit route optimization model to design a sustainable and cost-effective rail infrastructure. Their model aimed to minimize the initial construction cost, life-cycle cost, and penalty cost for violating design constraints. Wang et al. (2019b) developed an IP model to determine the optimal train-set circulation plan for passenger railway transportation hubs. They utilized a GA heuristic to solve the model and demonstrated that efficient train-set circulation plans can be achieved by dispatching train sets between stations in transportation hubs. For more studies on railway optimization, interested readers can refer to Zhou et al. (2019a) (passenger train-booking optimization) and Wang et al. (2021) (train

timetable optimization).

As urbanization accelerates, particularly in China, the increasing number of cars has made the urban traffic problem more prominent. Consequently, the development of public transport has become vital for sustainable development (Zhou et al., 2019b). Jiménez and Román (2016) addressed the allocation problem of an urban bus fleet to fixed routes, considering factors such as new propulsion technologies and variations between routes and bus types. They formulated an MILP model to minimize the weighted sum of various emissions. Chen et al. (2019) investigated the problem of bus route headway allocation, considering passenger demand elasticity, travel time randomness between stops, and abandoned passenger flow as sources of uncertainty. Their computational results indicated that their model could contribute to sustainable public transport by reducing passenger waiting time and attracting more passengers to bus travel. Many scholars have examined the bus scheduling problem, considering aspects such as air pollution reduction (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. (2020) also explored a new method for prioritizing signalized corridors for trams that typically operate on dedicated lanes in urban streets.

Over the past century, a “bicycling renaissance” has emerged (Pucher et al., 1999), and governments worldwide have invested in bicycle facilities (Duthie and Unnikrishnan, 2014). To promote bicycling as a sustainable mode of transportation, Bagloee et al. (2016) proposed a mathematical method to identify the latent underutilized capacity in congested urban areas for creating exclusive bicycle lanes. They developed a bilevel programming model that minimizes the total system cost at the upper level and employs a multi-class user equilibrium traffic flow at the lower level to capture users’ behavior and minimize total travel time in congested cities. In addition to bicycle lane priority, scholars have also studied policies such as electric bicycles, shared bicycles, and the integration of public transport and bicycles. To enhance the competitiveness of bike-and-ride services in interzonal areas, Tavassoli and Tamannaie (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 address the increasing environmental impacts, particularly pollutant emissions, caused by air transport, the aviation industry’s focus in the early twenty-first century has been to make air travel more environmentally friendly (Parsa et al., 2019). Parsa et al. (2019) proposed a multi-objective MILP model to optimize the airline hub-and-spoke network, considering factors such as the location of hub airports, allocation of non-hub airports to hub

airports, airplane fleet composition, and airplane allocation. The objectives of their model were to minimize total flow and hub establishment costs, reduce GHG emissions and fuel consumption, and minimize aircraft noise within the network.

To reduce global sulfur emissions from shipping, the International Maritime Organization (IMO) implemented Emission Control Area (ECA) regulations in 2015, requiring reduction in the sulfur content of ship emissions worldwide to 0.5% by 2020. With increasingly stringent regulations, the shipping industry is compelled to adopt greener practices. Zhen et al. (2020) developed an MINLP model to optimize fleet deployment, including the adoption of green technology, route selection, cargo allocation, sailing speeds, and berth allocation, while considering the availability of shore power. Du et al. (2016) proposed an MILP model for liner ship fleet deployment with collaborative transportation to minimize total transportation costs and promote sustainable development.

Ports play a crucial role as marine logistics nodes, and reducing air pollution in container ports is pivotal for the development of green ports. Many ports have begun implementing measures to become greener. Heilig et al. (2017) investigated a multi-objective interterminal truck routing problem that considered truck emissions. Their objectives included minimizing the cost of hiring trucks, route and service-specific costs, and emissions. Yi et al. (2020) studied the sustainable transportation of prefabricated products from factories to construction sites via ships. They proposed a large-scale IP model to optimize loading plans, including product allocation, packing arrangements, and minimizing the number of cargo holds used.

6.4 Other related issues

In addition to the aforementioned topics, there are several other related issues in transportation logistics. These include optimizing the structure of urban passenger traffic (Li and Lu, 2021), planning one-way traffic reconfiguration (Karimi et al., 2022), designing rescue logistics while considering CO₂ emissions (Boostani et al., 2021), planning urban underground logistics networks (Hu et al., 2020), and addressing urban freight transportation (Pamučar et al., 2016; Bi et al., 2020). Due to space limitations, it is not possible to provide an exhaustive description of all the identified issues.

7 Emerging challenges in green logistics

In addition to the studies on green logistics already discussed, several new challenges have emerged due to the rapid development of new technologies and changing customer demands. These challenges have garnered significant attention from both industry and academia. In

recent years, shared mobility has gained popularity with the rise of the sharing economy, and it has become a focal point of research. Moreover, advancements in new vehicle technologies, such as smart cars, unmanned aerial vehicles (UAVs), and electric vehicles (EVs), have also sparked extensive research efforts. We introduce some of these related issues in this section.

7.1 Shared mobility

Shared mobility is gaining increasing attention because it offers the potential to reduce travel costs and emissions. It has emerged as a powerful force for sustainable development in environmentally friendly societies (Wang et al., 2017). Various forms of sharing, including customer sharing, vehicle sharing, depot resource sharing, and comprehensive resource sharing, have become common in transportation operations. Shared mobility for passenger transport has gained traction in many countries (Wang et al., 2019a).

Bicycle sharing has become popular as a sustainable mode of transportation for short trips. Frade and Ribeiro (2015) developed an MILP model to maximize demand in a bicycle-sharing system. Their model determines the optimal fleet size, location and capacity of bicycle stations and the number of bicycles at each station while balancing the annual cost and revenue of the system. Luo et al. (2020) addressed the bicycle rebalancing problem, which involves optimizing the fleet size and rebalancing strategy for a multiple traveling salesman problem with pickup and drop-off demands. They proposed an IP model that minimizes vehicle travel distances while meeting the rebalancing demands of clusters.

Ride-sharing, also known as car-sharing or carpooling, allows drivers to share unoccupied seats with customers. Ride-sharing helps alleviate road congestion, reduce parking pressure, and decrease fuel consumption by increasing the occupancy of cars on the road. Optimization problems in ride-sharing systems have become more complex with the growing scale of the problem. Naoum-Sawaya et al. (2015) introduced a stochastic MIP model that optimally determines the allocation of shared cars considering the uncertainty of vehicle availability. Stiglic et al. (2016) proposed an IP model for a single rider and single driver matching problem to maximize the number of matches, investigating the effects of driver and rider flexibilities.

With the rapid growth of e-commerce, urban parcel deliveries have surged, putting significant pressure on last-mile delivery providers. Crowdsourced delivery, which is more flexible and less capital intensive than traditional distribution methods, has played a crucial role (Zhen et al., 2021). Chen et al. (2018) developed an IP model for a multi-driver multi-task matching problem with time windows, considering task transfers between drivers, drivers' maximum detours, and capacity limits.

They devised two heuristic algorithms to solve the model, showing that crowdsourced delivery is both economical and sustainable. Other research on shared mobility includes a shared logistics chain with economic and environmental objectives (Mrabti et al., 2021), 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 new vehicle technologies such as smart cars, UAVs, and EVs, which offer distinct features compared to traditional gasoline vehicles.

Smart cars are equipped with advanced driving assistance systems that enhance driving experience and safety. Autonomous vehicles, a type of smart car, can sense their environment and operate with minimal or no human intervention. Conceição et al. (2020) proposed a MINLP model for reversible lane network planning to optimize traffic assignment and reversible lane decisions. Their findings indicated that reversible lanes can significantly reduce road congestion, delays, and travel times. 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 at the upper level. At the lower level, they introduced a multi-class network equilibrium with heterogeneous traffic.

UAVs are expected to revolutionize the logistics industry globally, with leading logistics and e-commerce companies, such as DHL (Banker, 2013) and JD (JDX, 2017), are testing using UAVs for parcel delivery. The increased use of UAVs in transportation presents challenges related to traffic management. Eun et al. (2019) compared UAVs with traditional ground vehicles in terms of their environmental impact using a two-phase method. They determined optimal delivery plans for UAV-alone and ground vehicle-alone systems by solving a VRP model in phase one and calculated CO₂ emissions in phase two. Li et al. (2020) proposed an MILP model with vehicle-type and half-side traffic restrictions to investigate the impact of UAV delivery on sustainability and costs, demonstrating that UAV delivery effectively reduces CO₂ emissions and costs under certain restrictions.

As CO₂ emissions continue to rise, many countries are transitioning to EVs due to their environmental friendliness and lower operating costs (Abouee-Mehrizi et al., 2021). One of the main research directions regarding EVs is the electric vehicle routing problems (EVRPs). 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 an MILP model for a comprehensive

EVRP considering loaded cargo, speed, deceleration, acceleration, mixed vehicle fleet (electric and conventional vehicles), time windows, and road gradients. Goeke (2019) developed an MIP model for a pickup and delivery EVRP with time windows and capacity limits, allowing vehicles to recharge at dedicated stations. Scholars have also extensively studied resource distribution in the smart grid for EVs. Hajimiragha et al. (2011) developed a robust optimization model to integrate EVs into the electric grid while minimizing net electricity and emission costs. Reddy et al. (2016) proposed a dual-objective (emissions and operating costs) programming model for distributed resource scheduling in the smart grid to facilitate EV deployment.

Other studies on EVs include managing traffic congestion with subsidies (Wu et al., 2022), EVRPs with backhauls (Granada-Echeverri et al., 2020), road pricing for EVs and gasoline vehicles (Xi et al., 2020), allocation of EVs in parking lots (Neyestani et al., 2015), lane expansions for EVs (Cheng et al., 2020), fleet renewal of EVs (Kuppusamy et al., 2017), and EV fleet deployment (Schiffer et al., 2021).

7.3 Other related issues

Apart from the aforementioned categories, several other research directions have been explored. To reduce transportation costs, shippers often outsource transportation activities to logistics companies. Santos et al. (2021) proposed a collaborative collection method that allows orders to be picked up from producers along backhauling routes of leading retailers or third-party logistics providers. They developed a multi-objective MIP model to minimize operational costs, fuel consumption, and CO₂ emissions. Their results indicated that the collaborative collection method can significantly reduce global fuel consumption and operation costs by 26% and 28%, respectively.

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

8 Conclusions

We conclude this paper by summarizing the main findings and providing suggestions for future research directions in the field of green logistics.

8.1 Summary

In this paper, we conducted a comprehensive review of papers that integrate green logistics and OR. Analyzing 670 papers, we made two significant contributions. First, we provided a comprehensive overview of key topics in green logistics, advancing our understanding of the state of research in this field. Second, we identified several research directions for further exploration, particularly in light of the long-term impacts of the COVID-19 pandemic. However, there are two potential extensions that could enhance this review. First, providing detailed explanations of specific model formulations and algorithm designs would be beneficial. Second, a chronological overview of the development of research methodologies for specific problems could be a focus for future studies.

8.2 Suggestions for further research directions

In recent years, the sharing economy has emerged as a significant contributor to energy savings and emissions reduction. Sharing resources, such as crowdsourced delivery and bike sharing, allow for better utilization of existing assets. Furthermore, the adoption of new technologies, such as EVs and electric bikes, has increased the feasibility of green logistics. Therefore, exploring how to effectively plan the utilization of these technologies is crucial.

Proper pricing mechanisms for externalities, such as GHG emissions, can be a highly effective strategy for pollution reduction. However, determining how to incentivize individuals, companies, or governments to reduce emissions through reasonable pricing is a complex research area. For example, the use of average indicators to assess ship emissions may lead to unintended consequences, such as ships sailing empty to lower their emissions average, which can actually increase overall emissions. Therefore, a more detailed investigation into proper pricing mechanisms for externalities is necessary.

The long-term impacts of the COVID-19 pandemic require further research attention in the context of green logistics. Since the onset of the pandemic, new modes of work, such as remote work and online meetings, have become widespread. Studying how to improve logistics services, particularly in a green manner, to accommodate the demands of these new living and working patterns is essential. Additionally, the rapid growth of global e-commerce, which reached 26.7 trillion US dollars (UN, 2021), poses significant challenges for last-mile delivery services. Exploring green solutions to address the issues arising from the e-commerce boom should also be a focus of future research.

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