C H A P T E R

7

Green Network Design Problems

Okan Dukkanci[1], Tolga Bektaş[2], Bahar Y. Kara[1]

[1] Department of Industrial Engineering, Bilkent University, Ankara, Turkey;
[2] Centre for Operational Research, Management Science and Information Systems (CORMSIS), Southampton Business School, University of Southampton, Southampton, United Kingdom

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1. INTRODUCTION

Supply chain management entails designing, planning, and coordination activities for movement of products or delivery of services from the supplier to the customer. However, it is known that some of these activities are harmful to the environment. Taking the right steps for the design activities is critical in order that the environmental performance of a supply chains be improved, and these decisions often manifest themselves in the form of network design problems.

Sustainability for systems is a term which is often used in lieu of "improved environmental performance" or to denote the ways in which "reduction of externalities" of the particular system can be achieved, and not necessarily in its literal meaning which has been characterized as the ability of the system to exist permanently provided that the environment around the system allows it do to so (Jaehn, 2016). In this chapter, we do not delve into such discussions and refer the reader to a fuller discussion on the issue by Jaehn (2016), and take "sustainable" systems on face value as it appears in various references. What we will attempt to do, however, is to differentiate the terms "sustainable" and "green," with emphasis being on the latter, through classification of the extant literature. We start by offering a proposed classification for sustainable logistics design problems as shown in Fig. 7.1.
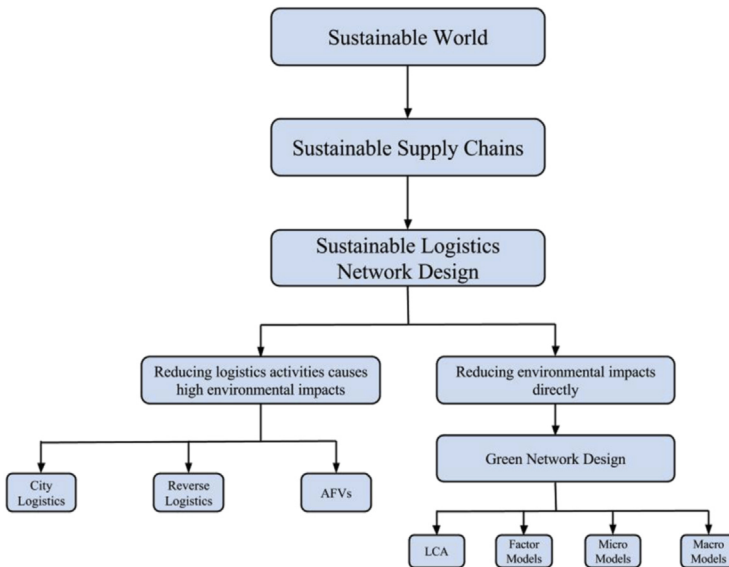

FIGURE 7.1　Classification for the design of the sustainable logistics networks.

Sustainable logistics network design can be separated into two categories, namely those focusing on reducing the type or amount of logistics activities with negative environmental impacts and reducing the negative environmental impact directly (Fig. 7.1). The first category makes use of concepts such as *city logistics*, *reverse logistics*, and *alternate fuel vehicles* (AFVs), which aim to reduce logistics activities that have an environmental impact. In particular, city logistics reduces the environmental impacts of urban freight transportation within city boundaries with due consideration to economical and social impacts. The environmental effects within a city can be reduced by minimizing the number of freight vehicles traveling within the city and by optimizing the usage of these vehicles. City logistics uses two fundamental concepts to achieve this: the consolidation of loads in warehouses and the coordination of freight transportation activities (Crainic et al., 2009). Reverse logistics comprises the reuse, recycling, and disposal of waste products and packaging by arranging transportation activities (McKinnon et al., 2015). Reverse logistics allows companies to reduce emissions by transporting recycled products instead of producing or supplying them. In some studies, both forward and reverse logistics are considered simultaneously, giving rise to what is now known as a closed loop supply chain. Finally, AFVs are vehicles that run on alternative, environmentally friendly sources of fuel such as biodiesel, electricity, hydrogen, methanol, ethanol, and propane, rather than petroleum-based fuels (Davis et al., 2014). AFVs produce lower emissions compared to fuel-based vehicles.

The second main category shown in Fig. 7.1, which we refer to as green network design, is a class of planning problems with the aim of reducing the environmental impacts of logistics activities. One of the prominent environmental impacts of logistics operations is the emission of greenhouse gases (GHGs), due to their detrimental effects on both human health and the environment. GHGs are described as gases that "emit and absorb radiation at specific wave-lengths within the spectrum of thermal infrared radiation emitted by the earth's surface, the atmosphere itself and by clouds" as defined in the Glossary of IPCC's 2007 Synthesis Report (Bernstein et al., 2008). The primary GHGs include carbon dioxide (CO_2) that has been liked to global warming, nitrous oxide (N_2O), methane (CH_4), water vapor (H_2O), and ozone (O_3). Burning fossil fuels such as oil, natural gas, and coal emits GHGs and CO_2 (Bernstein et al., 2008).

Estimating or quantifying emissions of transportation activities is not straightforward. For instance, minimizing the travel distance of a vehicle does not necessarily result in minimizing fuel consumption as the latter depends on other factors, such as speed and load (Demir et al., 2014a). Such environmental factors would therefore have to be explicitly included in the estimation of emissions. Environmental impacts such as emissions have been calculated using different types of principles and models in

the literature. These models include the life cycle assessment (LCA) method, factor models, and macroscopic and microscopic fuel consumption models (Demir et al., 2014a).

LCA is a method used to evaluate the environmental impacts of a product from its raw material form until recycling. Although LCA does not directly model the emissions or the fuel requirements, it proposes a simple and systematic method of calculating the environmental impact of a process such as production, transportation, or disposal. This methodology consists of four stages; goal definition and scoping, inventory analysis, impact assessment, and interpretation. The goal definition and scoping stage entails the definition of the product, process, and activities and the identification of boundaries and environmental impacts. In the second stage, resource usage and environmental releases are characterized. The resource usage and environmental releases that are quantified are assessed during the impact assessment stage. The Eco-indicator 99, a damage-oriented method for life cycle impact assessment, is often used during this stage (Goedkoop and Spriensma, 2000). The final stage evaluates the results obtained during the second and third stages (SAIC and Curran, 2006).

In contrast to the LCA method, the other models focus solely on transportation-related activities. In factor models, the data for travel distance or fuel consumption are collected and multiplied by certain coefficients (e.g., the emission factor), mainly used to estimate the CO_2 emissions. EPA (2016) proposes several such factor models. On the other hand, macroscopic and microscopic models consider other factors that influence fuel consumption and CO_2 emissions, such as vehicle weight, vehicle speed, payload, etc., in order to provide more accurate estimation of fuel consumption, and in turn CO_2 emissions which are directly proportional (Demir et al., 2014a). Macroscopic models estimate fuel consumption and CO_2 emission using average aggregate network parameters, whereas microscopic models include detailed parameters using instantaneous (e.g., second by second) measurements.

Network design problems have been studied with an explicit goal of reducing emissions in the transportation sector using these models, an aspect to which we will refer to as *green*. In this chapter, we present some of these problems by providing definitions, mathematical models, and practical applications. As our focus is on green network design problems, we do not provide a detailed coverage of others that have looked at sustainable network design problems such as AFVs, city logistics, and reverse logistics and closed loop supply chains. However, we do include papers in our survey that relate to both green network design and reverse logistics. For comprehensive surveys on reverse logistics and closed loop supply chains, we refer the reader to Fleischmann et al. (1997), Srivastava (2008), Dekker et al. (2013), and Govindan et al. (2015). In addition to these,

one may refer to Pelletier et al. (2016) and Crainic et al. (2009) for more details on AFVs and city logistics, respectively.

The rest of the chapter is presented as follows. Section 2 presents previous survey papers on green network design. Section 3 provides an extensive literature review on green network design problems and describes applications where relevant. The last section points out some future research directions.

2. PREVIOUS SURVEY PAPERS

The sudden rise of the popularity of sustainable and green supply chain design problems has led to several review articles being published in the literature (Table 7.1). One of the earlier such review papers on green supply chain management is by Srivastava (2007), who classifies the literature as those discussing the importance of the green supply chain management, those on green design, and those on green operations. The survey covers the papers until 2006, a period of time during which the relevant research focused more on reverse logistics. Sbihi and Eglese (2010) introduce green logistics as a concept and combine it with some combinatorial optimization problems, in particular reverse logistics, waste management, and vehicle routing and scheduling problems. Dekker et al. (2012) present a comprehensive review on green logistics problems within operations research, classified into those relevant to transportation, product (inventory), and facility location. Hassini et al. (2012) present a literature review on sustainable supply chain management and performance measures, with a particular focus on the latter. Lin et al. (2014) present a survey on green vehicle routing problems (VRPs) by first classifying the classical VRP, then by categorizing green VRPs, pollution-routing problems (PRPs) and those arising in reverse logistics. The authors describe green VRPs as problems that minimize energy consumption and PRPs as those that minimize GHG (particularly CO_2) emissions. The review by Demir et al. (2014a) is exclusively on green road freight transportation, where the authors identify and explain the factors that affect fuel consumption, and review the relevant fuel consumption models. They specifically focus on routing problems but also mention papers related to location problems. Brandenburg et al. (2014) provide a literature review on sustainable supply chain management, which also covers studies that deal with network design. However, they do not consider routing problems with environmental concerns. The review paper by Eskandarpour et al. (2015) is one on sustainable supply chain network design, with a particular focus on optimization problems arising within this area. The authors review various studies relating to the

TABLE 7.1 Features of Existing Survey Papers

Reference	Sustainability Tool				Decision		Number of Common References
	CL	RL	AFVs	GND	Location	Routing	
Srivastava (2007)	×	●	×	○	○	×	1
Sbihi and Eglese (2010)	×	●	×	○	×	○	0
Dekker et al. (2012)	×	○	×	○	○	○	13
Hassini et al. (2012)	×	○	×	○	○	×	3
Lin et al. (2014)	×	●	○	○	×	●	12
Demir et al. (2014a)	×	×	×	●	○	●	30
Brandenburg et al. (2014)	×	○	×	○	○	×	3
Eskandarpour et al. (2015)	×	○	×	●	●	×	19
Our study	×	○	×	●	●	●	—

CL, city logistics; *GND*, green network design; *RL*, reverse logistics.
×, not covered, ○, partially covered, ●, fully covered.

economical, environmental, or social impacts. The authors do not consider the papers that include any routing decisions.

As Table 7.1 shows, there does not seem to be a review that fully covers the green network design literature where *both* location and routing decisions are included, which is the aim of this chapter. Here, we review 107 articles in detail. The last column of Table 7.1 reports the number of common references cited in the reviews above and in this review. Demir et al. (2014a) and Eskandarpour et al. (2015) are the two reviews that have the highest number of shared references with our study, 30 and 19, respectively. However, Demir et al. (2014a) mainly focus on routing problems, whereas Eskandarpour et al. (2015) only review problems that include location decisions.

3. GREEN NETWORK DESIGN PROBLEMS

The ensuing review is based on a categorization of the relevant studies based on the three classical levels of decision-making, namely operational, tactical, and strategic, as depicted in Fig. 7.2, along with the number of references in each category. Operational decisions are mainly those related to routing. Tactical decisions consist of location-routing and allocation problems. Strategic decisions include studies that look at location-allocation problems. We present the relevant studies in the three main sections below.

3.1 Operational Decision Making

Most papers in this category consider routing decisions. The energy minimizing vehicle routing problem (EMVRP) by Kara et al. (2007) and the pollution-routing problem (PRP) by Bektaş and Laporte (2011) are the
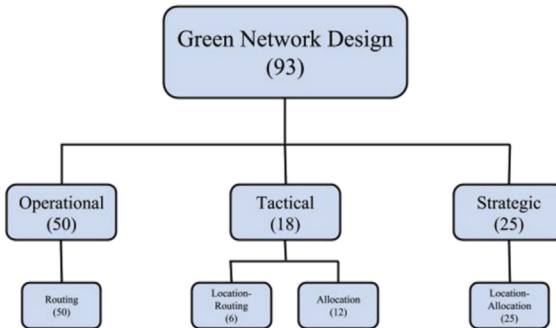

FIGURE 7.2 Categorization of green network design problems.

two pioneering works that consider the minimization of fuel consumption in vehicle routing problems. In the following sections, we describe these two problems with the proposed mathematical formulations and those studies that extend these two problems.

3.1.1 The Energy Minimizing Vehicle Routing Problem

Kara et al. (2007) introduce the EMVRP as an extension of the classical VRP, where the objective is to minimize a distance-weighted load function in order to minimize the total energy consumption. The EMVRP is defined on a network $G = (N, A)$ where $N = \{0, 1, 2, \ldots, n\}$ is the set of nodes and node 0 is the depot. The customer set is denoted by $N_0 = \{1, 2, \ldots, n\}$ and $A = \{(i, j): i, j \in N, i \neq j\}$ denotes the set of arcs. The distance on arc $(i, j) \in A$ is denoted by d_{ij}. A fleet of m vehicles, each with a carrying capacity Q and a tare weight Q_0 is available to serve customers, each of which has a non-negative weight (demand) q_i, $i \in N$. The problem is to find a set of routes for the vehicles that all start from and end at the depot, such that the total energy as modeled by the distance-weighted load function is minimized. The integer programming formulation proposed by Kara et al. (2007) to solve the EMVRP uses a binary variable x_{ij} that equals 1 if a vehicle travels on arc $(i, j) \in A$, and 0 otherwise. A continuous non-negative variable y_{ij} represents the total weight of the vehicle (including tare weight) on arc $(i, j) \in A$. The proposed mathematical model is as follows:

$$\text{Minimize} \sum_{i \in N} \sum_{j \in N \setminus \{i\}} d_{ij} y_{ij} \tag{7.1}$$

subject to

$$\sum_{i \in N_0} x_{0i} = m \tag{7.2}$$

$$\sum_{i \in N_0} x_{i0} = m \tag{7.3}$$

$$\sum_{i \in N} x_{ij} = 1 \quad \forall j \in N_0 \tag{7.4}$$

$$\sum_{j \in N} x_{ij} = 1 \quad \forall i \in N_0 \tag{7.5}$$

$$\sum_{j \in N} y_{ij} - \sum_{j \in N} y_{ji} = q_i \quad \forall i \in N_0 \tag{7.6}$$

$$y_{0i} = Q_0 x_{0i} \quad \forall i \in N_0 \tag{7.7}$$

$$y_{ij} \leq (Q + Q_0 - q_j) x_{ij} \quad \forall (i, j) \in A \tag{7.8}$$

$$y_{ij} \geq (Q_0 + q_i)x_{ij} \quad \forall\, (i,j) \in A \tag{7.9}$$

$$x_{ij} \in \{0,1\} \quad \forall\, (i,j) \in A. \tag{7.10}$$

The objective function (7.1) minimizes a cost function that depends on the total weight of the vehicle and the total distance traversed. Constraints (7.2) and (7.3) set the number of vehicles to m. Constraints (7.4) and (7.5) ensure that a vehicle arrives and leaves each node. Constraint (7.6) is the flow conservation between nodes. Constraint (7.7) ensures that the weight of the vehicle while leaving the depot equals the tare weight. Constraint (7.8) sets an upper bound on the flows and serves as the vehicle capacity constraints. Similarly, constraint (7.9) sets a lower bound on the weight variable.

Different versions of the EMVRP have been studied in the literature, as shown in Table 7.2, the first column of which shows the reference and the following four columns indicate the general features of the problem studied, namely the network type (single or multiechelon), the number of objectives (single or multiple), solution methods (exact "E" or heuristic "H") and whether an application is presented or not. The next four columns represent the specifications of the proposed models, namely time window (TW), time-dependency (TD), simultaneous pickup and delivery (P&D), and uncertainty (U), respectively. The last four columns are relevant to fuel consumption, the first of which shows the type of emission model (factor, macroscopic, or microscopic) used. The remaining three columns shows whether distance (Dis), load (Loa), and Speed (Spe) are considered as a parameter "P" or decision "D" within the respective models.

Some of the problems shown in Table 7.2 are very similar to the EMVRP. For example, Xiao et al. (2012) consider minimizing fuel consumption in the capacitated vehicle routing problem where the fuel consumption rate is load-dependent, but the way in which it is calculated is more complex. Similarly, Fukasawa et al. (2015) model the cost over each arc as the product of the arc length and the weight of the vehicle including payload and curb weight. The authors presented two new mixed-integer programming formulations, namely an arc-load formulation and a set partitioning formulation, where the latter is solved by a branch-cut-and-price algorithm.

Incorporating backhauling or simultaneous pick-up and delivery options in vehicle routing may provide further reductions in the environmental impacts of vehicle routing, given the flexibility afforded by such options in eliminating some of the transportation activities that cause CO_2 emissions. One such study is by Zachariadis et al. (2015), who studied a load-dependent vehicle routing problem similar to the EMVRP but extended to take into account simultaneous pick-up and delivery. This is

TABLE 7.2 Studies Related to the EMVRP

References	General				Model Specifications				Fuel Consumption			
	Net.	Obj.	Sol. A.	Case	TW	TD	P&D	U	Emission	Dis	Loa	Spe
Kara et al. (2007)	Single	Single	E						Factor	P	D	—
Xiao et al. (2012)	Single	Single	E & H						Factor	P	D	—
Fukasawa et al. (2015)	Single	Single	E						Factor	P	D	—
Zachariadis et al. (2015)	Single	Single	H				✔		Factor	P	D	—
Pradenas et al. (2013)	Single	Single	H		✔		✔		Micro	P	D	P
Tajik et al. (2014)	Single	Single	E		✔		✔	✔	Micro	P	D	P
Kwon et al. (2013)	Single	Single	H						Factor	P	D	—
Kopfer et al. (2014)	Single	Single	E						Factor	P	D	—
Xiao and Konak (2016a)	Single	Single	E & H		✔	✔			Micro & Macro	P, D	D	—
Xiao and Konak (2016b)	Single	Single	H			✔			Macro	P, D	D	—
Androutsopoulos and Zografos (2017)	Single	Multi	H		✔	✔			Micro	P	D	P
Huang et al. (2017)	Single	Single	E & H			✔		✔	Micro	P	D	P
Suzuki (2011)	Single	Single	E		✔				Factor	P	P	P
Cinar et al. (2014)	Single	Single	E & H						Factor	P	D	—
Ubeda et al. (2011)	Single	Single	H	✔			✔		Factor	P	P	—
Treitl et al. (2014)	Single	Single	H	✔					Micro	P	D	P
Li et al. (2016)	Multi	Single	H	✔	✔				Factor	P	D	P
Suzuki (2016)	Single	Multi	H						Factor	P	D	—

modeled by assuming, for each customer $i \in N$, a delivery request d_i and pick-up request p_i. Two non-negative continuous variables D_{ij} and P_{ij} are defined to represent the delivery and pickup load carried on arc $(i, j) \in A$. The model of this problem follows that of the EMVRP, where constraints (7.6)−(7.9) are replaced by the following:

$$\sum_{j \in N} P_{ij} - \sum_{j \in N} P_{ji} = p_i \quad \forall i \in N_0 \tag{7.11}$$

$$\sum_{j \in N} D_{ij} - \sum_{j \in N} D_{ji} = d_i \quad \forall i \in N_0 \tag{7.12}$$

$$d_j x_{ij} \leq D_{ij} \leq (Q - d_i) x_{ij} \quad \forall (i, j) \in A \tag{7.13}$$

$$p_i x_{ij} \leq P_{ij} \leq (Q - p_j) x_{ij} \quad \forall (i, j) \in A \tag{7.14}$$

$$D_{ij} + P_{ij} \leq (Q - \max\{0, p_j - d_j, p_i - d_i\}) x_{ij} \quad \forall (i, j) \in A \tag{7.15}$$

Constraints (7.11) and (7.12) model flow conservation for both pick-up and delivery. Constraints (7.13)−(7.15) provide stronger lower and upper bounds on the flow variables to satisfy vehicle capacity constraints. Zachariadis et al. (2015) describe local search algorithms and a branch-and-cut method for the problem. Other relevant studies are by Pradenas et al. (2013) and Tajik et al. (2014), who consider a VRP with backhauling or simultaneous pick-up and delivery options.

The references mentioned above all assume the use of a homogeneous fleet of vehicles, i.e., all vehicles are identical. In contrast, one can assume a heterogeneous set of vehicles with varying characteristics. Kwon et al. (2013), for example, is one such study that looks at the use of a carbon trading mechanism within the problem. Kopfer et al. (2014) studied a similar problem, namely the emission minimization vehicle routing problem with vehicle categories, but without the use of a carbon trading mechanism.

The studies mentioned above also assume that vehicles travel at constant speed whilst traversing an arc, which may not be a realistic assumption, given that traffic conditions such as congestion are known to affect vehicle speed. One way to tackle this would be to assume that vehicle speeds vary with time, giving rise to routing problems where travel times are time-dependent. One such study is by Xiao and Konak (2016a), who extend the green vehicle routing and scheduling problem (GVRSP) proposed by Xiao and Konak (2015) with the inclusion of time-dependent travel times, time window constraints, the effect of weight on fuel consumption, and a heterogeneous fleet of vehicles. They also allow vehicles to stop on arcs at any time, which breaks away from similar studies that consider time-varying congestion. To solve the problem, the authors propose a hybrid algorithm that uses partial-mixed integer

programming and iterated neighborhood search. The same authors study a heterogeneous fleet GVRSP with a tardiness objective for which they propose a hybrid algorithm that combines a genetic algorithm and the exact dynamic programming solution technique (Xiao and Konak, 2016b). The other two studies that consider time-dependent travel times are Androutsopoulos and Zografos (2017) and Huang et al. (2017). Some variants of the EMVRP incorporate additional time-related constraints such as time windows (Suzuki, 2011) or a limit on tour length (Cinar et al., 2015).

One applications of the EMVRP can be found in the paper by Ubeda et al. (2011), who present a case study for Eroski, a food distribution company, operating in the Navarre region of northern Spain. The distribution network consists of one depot, 15 customers, and 25 suppliers. Backhauling is used to fill stocks from the suppliers after serving the customers. The authors describe a nearest-neighbor insertion algorithm to solve the case study. The results indicate a saving of 14.9% in CO_2 emissions for a week of distribution activities. Treitl et al. (2014) describe one application of the inventory routing problem for a petrochemical company operating in south-eastern Europe. The company operates on a network that consists of one depot, and seven regions including 45 filling stations (customers) in 27 cities. A mathematical formulation for the problem is described, which, when solved with a single objective function that only minimizes economical impacts, a 15.97% saving is achieved over a year. When environmental impacts are included in the objective function, an additional saving of 1.35% is achieved. Li et al. (2016) propose a two-echelon time-constrained vehicle routing problem. The authors developed a two-stage heuristic algorithm and present a real-life application for two trucking companies operated in Shandong province of China, one with 23 city distribution centers serving 1008 customers, and the other with 10 city distribution centers serving 818 customers. The paper by Suzuki (2016) does not present a real-life problem, but considers users' viewpoints while calculating fuel consumption for a routing problem called a practical PRP.

3.1.2 The Pollution-Routing Problem

The second main study that considers environmental impacts in the VRP is the PRP proposed by Bektaş and Laporte (2011), where the objective function minimizes the total cost including the driver cost and the fuel consumption and CO_2 emissions cost. The fuel consumption is estimated using CMEM as the emission model, in which all parameters on a given segment of road (e.g., arc) are assumed to be constant except for load and speed, which are considered as decision variables in order to calculate emissions more accurately. One of the assumptions in this work is that vehicles travel with a speed of at least 40 km/h that is typically

applicable to intercity routes, i.e., urban areas and congestion speeds are not considered.

The PRP is defined on the same graph $G = (N, A)$ as the EMVRP, where, additionally, there are time windows $[a_i, b_i]$ for each customer $i \in N_0$, with the service time at this customer denoted by t_i. Also, α_{ij} is an arc specific constant and β is a vehicle specific constant. Bektaş and Laporte (2011) describe an integer linear programming formulation for the PRP, where the main routing variable x_{ij} is the same as the one defined for the EMVRP. In addition, the continuous non-negative variables f_{ij} and v_{ij} represent the total weight of the vehicle (excluding tare weight) and speed of the vehicle on arc $(i, j) \in A$, respectively. The start time of service at node $j \in N_0$ is denoted by y_j. The total time spent on a route in which node $j \in N_0$ is the last visited node is denoted by s_j. As the speed variables v_{ij} result in a nonlinear term in the objective function and the constraints, Bektaş and Laporte (2011) discretize the speed into a set of levels $R = \{0, 1, 2, \ldots, r\}$ and v^r represents the average vehicle speed for a speed level $r \in R$. A new binary variable z^r_{ij} is defined which equals 1 if a vehicle travels with a speed level $r \in R$ on arc $(i, j) \in A$, and 0 otherwise. The corresponding mathematical formulation is as follows:

$$Minimize \sum_{(i, j) \in A} (c_f + e)\alpha_{ij}d_{ij}wx_{ij} \tag{7.16}$$

$$+ \sum_{(i, j) \in A} (c_f + e)\alpha_{ij}f_{ij}d_{ij} \tag{7.17}$$

$$+ \sum_{(i, j) \in A} (c_f + e)d_{ij}\beta \left(\sum_{r \in R} (v^r)^2 z^r_{ij} \right) \tag{7.18}$$

$$+ \sum_{j \in N_0} ps_j \tag{7.19}$$

subject to (7.2), (7.4), (7.5), and (7.10)

$$\sum_{j \in N} f_{ji} - \sum_{j \in N} f_{ij} = q_i \quad \forall i \in N_0 \tag{7.20}$$

$$q_j x_{ij} \leq f_{ij} \leq (Q - q_i)x_{ij} \quad \forall (i,j) \in A \tag{7.21}$$

$$y_i - y_j + t_i + \sum_{r \in R}(d_{ij}/v^r)\Big/z^r_{ij} \leq M_{ij}(1 - x_{ij}) \quad \forall i \in N, j \in N_0, i \neq j \tag{7.22}$$

$$a_i \leq y_i \leq b_i \quad \forall i \in N_0 \tag{7.23}$$

$$y_j + t_j - s_j + \sum_{r \in R}(d_{j0}/v^r)\Big/z^r_{j0} \leq L(1 - x_{j0}) \quad \forall j \in N_0 \tag{7.24}$$

$$\sum_{r \in R} z_{ij}^r = x_{ij} \quad \forall (i,j) \in A \tag{7.25}$$

$$f_{ij} \geq 0 \quad \forall (i,j) \in A \tag{7.26}$$

$$z_{ij}^r \in \{0,1\} \quad \forall (i,j) \in A, r \in R \tag{7.27}$$

The objective function consists of two components, the first of which is the cost of fuel consumption and CO_2 emission represented by (7.15), and the second is the cost of drivers shown by (7.19). Constraint (7.20) ensures flow conservation between nodes. Constraint (7.21) imposes lower and upper bounds on the flow variables and serves as a vehicle capacity constraint. Constraint (7.22) computes the service start time for each node. The time window restrictions for each customer are modeled through constraint (7.23). The total time spent on each route is calculated by constraint (7.24). Finally, constraint (7.25) ensures that only one level of speed is chosen on each arc of the graph that is traversed by a vehicle.

We now present a review of studies that are in the spirit of the PRP. These studies are summarized in Table 7.3. Initially, we focus on the studies that focus on the original version of the PRP. Demir et al. (2012) study the PRP where the vehicles were allowed to travel slower than 40 km/h. They develop a heuristic algorithm in which the VRP with time windows is solved by an adaptive large neighborhood search, following which a speed optimization algorithm finds the optimal speed for each arc of route identified for each vehicle. Demir et al. (2014b) study the biobjective variant of the PRP, where the two (conflicting) objectives are to minimize fuel and minimize fuel consumption. Pareto solutions are identified by using the heuristic as a search engine, in conjunction with four a posteriori methods, namely a weighting method, a weighting method with normalization, the ε-constraint method, and a new hybrid method that combines the adaptive weighting and the ε-constraint method. The results indicated that the hybrid one outperforms the others. One other metaheuristic for the PRP is described by Kramer et al. (2015), which combines iterated local search with speed optimization procedures and integer programming optimization over a set partitioning formulation.

As for the exact methods on the PRP, Fukasawa et al. (2016) use disjunctive convex programming to develop two mixed-integer convex optimization models where the speed is kept as a continuous variable. They also develop a set of valid inequalities. Dabia et al. (2017) describe a branch-and-price algorithm to solve a variant of the PRP where the speed along all arcs of a given route is assumed to be constant. In the algorithm, the master problem is of a set-partitioning type, and where the pricing is performed through solving a speed and start-time elementary shortest path problem with resource constraints using a tailored labeling algorithm.

TABLE 7.3   Studies Related to the PRP

References	General				Model Specifications				Fuel Consumption			
	Net.	Obj.	Sol. A.	Case	TW	TD	P&D	Unc	Emis. M.	Dis	Loa	Spe
Bektaş and Laporte (2011)	Single	Single	E		✔				Micro	P	D	D
Demir et al. (2012)	Single	Single	E & H		✔				Micro	P	D	D
Demir et al. (2014b)	Single	Multi	H		✔				Micro	P	D	D
Kramer et al. (2015)	Single	Single	H		✔				Micro	P	D	D
Fukasawa et al. (2016)	Single	Single	E		✔				Micro	P	D	D
Dabia et al. (2017)	Single	Single	E		✔				Micro	P	D	D
Franceschetti et al. (2013)	Single	Single	E		✔	✔			Micro	P	D	D
Ehmke et al. (2016b)	Single	Single	H			✔		✔	Micro	P	D	P
Franceschetti et al. (2017)	Single	Single	H		✔	✔			Micro	P	D	D
Koç et al. (2014)	Single	Single	H		✔				Micro	P	D	D
Saka et al. (2017)	Single	Single	H		✔				Micro	P	D	D
Kumar et al. (2016)	Single	Multi	H		✔				Micro	P	D	D
Eshtehadi et al. (2017)	Single	Single	E		✔			✔	Micro	P	D	D
Majidi et al. (2017)	Single	Single	H		✔		✔		Micro	P	D	D
Soysal et al. (2015a)	Single	Single	E	✔				✔	Micro	P	D	P
Soysal et al. (2015b)	Multi	Single	E	✔		✔			Micro	P	D	P
Soysal et al. (2016)	Single	Single	E	✔				✔	Micro	P	D	P
Alinaghian and Naderipour (2016)	Single	Single	H	✔		✔			Macro	P	D	D

Fuel consumption is known to be affected by congestion, particularly with the low speeds that vehicles travel at under heavy traffic conditions. Franceschetti et al. (2013) incorporate such considerations within the PRP, in particular time-dependent travel times, where it is assumed that there is an initial period of congestion followed by free-flow traffic conditions, and look at optimal policies around departure time. They also advocate for idle waiting both before and after service to avoid congestion. The mathematical formulation they describe without any congestion is also valid for the PRP, which is shown to perform better than that of Bektaş and Laporte (2011). The authors also study a special case where there is only one vehicle and a fixed sequence of customers and proposed a specified algorithm for this problem. An adaptive large neighborhood search for this problem can be found in Franceschetti et al. (2017). In urban areas, the conditions around vehicle speeds are different to those of intercity travel. One way to calculate vehicle speed on a path between two customers is an arc-averaging method described by Ehmke et al. (2016a). A time-dependent vehicle routing problem in urban areas is described and solved in Ehmke et al. (2016b).

The choice of vehicles in the fleet also impacts fuel consumption, as each type of vehicle has its own specific parameters such as curb weight, engine friction factor, engine speed, etc. Koç et al. (2014) study the extent to which the fleet choice matters by introducing and solving the fleet size and mix PRP, where a heterogeneous vehicle fleet is used. Saka et al. (2017) study the PRP with a heterogeneous fleet of vehicles. Instead of time windows, however, the proposed problem assumes that there are deadlines associated with each customer request.

Several studies apply different variants of the PRP to real or realistic problem instances. For instance, Soysal et al. (2015a) present an application based on distribution of fresh tomato for a company operating in western Turkey, where the distribution network has one distribution center and 11 supermarkets (customers). The authors solve an inventory routing problem for perishable items by considering environmental factors and demand uncertainty. The results show that using consideration of perishability of items and fuel consumption reduces the total amount of emissions by 2%, but this leads to a 25.2% increase in the total cost. Soysal et al. (2015b) conduct a case study for the distribution network of a supermarket chain operating in the Netherlands, where the distribution network consists of one depot, two satellites, and 16 customers. For this application, the authors extend the problem setting of Bektaş and Laporte (2011) to a time-dependent, two-echelon CVRP formulation with environmental considerations. The results indicate that using a fuel-minimizing objective function provides an average reduction of 2.5% on fuel consumption, but this comes at the expense of a 10.8% increase on cost. Soysal et al. (2016) extend the study of Soysal et al. (2015a) by

considering multiple products and multiple suppliers where horizontal collaboration is assumed between suppliers. They present a practical application for two suppliers, one of which distributes figs and the other cherries to five wholesale market halls (customers) using a 3PL company. The numerical evidence suggests that through horizontal collaboration a reduction of 17.1% and 29.3% can be achieved, on the total cost and the total amount of emissions, respectively. The final application we present here is by Alinaghian and Naderipour (2016) that is for a distribution operation of dairy products in the city of Esfahan in Iran, which includes one depot, 28 customers, and three vehicles. The case study is then formulated as a time-dependent vehicle routing problem with the objective of reducing fuel consumption. The authors present numerical results suggesting that savings of around 21% can be reaped on fuel consumption.

3.1.3 Other Routing Problems

This section discusses other types of routing problems that explicitly incorporate environmental considerations. A list of the studies reviewed in this section is provided in Table 7.4.

One of the first studies that addresses CO_2 emissions within the VRP is Palmer (2007), who investigates the effects of congestion on CO_2 emissions. Kuo (2010) studies a VRP with time-dependent travel times for which the author develops a method to calculate fuel consumption and solves the problem using a simulated annealing algorithm. Figliozzi (2010) describes an emissions-minimizing VRP, which incorporates time-dependent travel speeds and time windows, for which a single objective and hierarchical multiobjective formulations are presented. The author describes heuristic algorithms for both versions of the problem. Along similar lines, Jabali et al. (2012) describe a time-dependent VRP that minimizes emissions. A tabu search method using a nearest-neighbor heuristic as a construction algorithm is described to solve the problem. Mirzapour Al-e-hashem and Rekik, 2014 present a multiproduct multiperiod inventory routing problem with a heterogeneous fleet of vehicles where greenhouse gas emissions are limited by a constraint. The authors propose a mixed-integer linear programming formulation to solve the proposed problem. Xiao and Konak (2015) introduce the green vehicle routing and scheduling problem with time-dependent travel times and time window constraints. The authors develop an MILP formulation of the problem and a three-stage solution approach for the solution with hierarchical objectives. They also describe a simulated annealing algorithm to solve large-size problem instances. Ehmke et al. (2016a) investigate the effects of speed variability in relation to minimizing emissions on paths in urban areas. They assume that vehicles travel at traffic speed, using which they develop two data-driven approaches to find the shortest

TABLE 7.4 Other Green Routing Problems

References	General				Model Specifications				Fuel Consumption			
	Net.	Obj.	Sol. A.	Case	TW	TD	P&D	Unc	Emis. M.	Dis	Loa	Spe
Palmer (2007)	Single	Single	H		✔	✔			Micro	P	P	D
Kuo (2010)	Single	Single	H			✔			Factor	P	P	P
Figliozzi (2010)	Single	Multi	E & H		✔	✔			Macro	P	—	P
Jabali et al. (2012)	Single	Single	H			✔			Macro	P	—	D
Mirzapour Al-e-hashem and Rekik, 2014	Single	Single	H						Factor	P	—	—
Xiao and Konak (2015)	Single	Multi	E & H		✔	✔			Factor	P	—	—
Ehmke et al. (2016a)	Single	Single	H			✔		✔	Macro	P	P	P
Çimen and Soysal (2017)	Single	Single	H			✔		✔	Macro	P	—	P
Maden et al. (2010)	Single	Single	H	✔	✔	✔			Macro	P	—	P
Figliozzi (2011)	Single	Multi	H	✔	✔	✔			Macro	P	—	D
Qian and Eglese (2014)	Single	Single	H	✔	✔	✔			Macro	P	—	D
Soysal and Çimen (2017)	Single	Single	H	✔		✔			Macro	P	—	P
Aranda et al. (2012)	Single	Single	H	✔					LCA	—	—	—
Oberscheider et al. (2013)	Single	Single	E & H	✔	✔		✔		Factor	—	—	P

paths that minimize fuel consumption, namely path and arc-averaging methods. Çimen and Soysal (2017) study a similar problem by considering stochastic vehicle speeds and a different macroscopic emission model.

Other applications reported for routing problems with an explicit consideration to minimize negative environmental impacts are as follows. Maden et al. (2010) describe a case study for the distribution system of an electric goods wholesaler operated in the southwest of the United Kingdom, for deliveries made over 9 days and where the number of customers visited ranges between 40 and 64 each day. A heuristic algorithm based on tabu search is used to solve the problem. Through a computational study, the authors report around 7% savings on CO_2 emissions. Figliozzi (2011) studies the same problem introduced in an earlier study (Figliozzi, 2010) by analyzing CO_2 emissions for different levels of congestion and time-definite customer demands. The author also carries out a case study in Portland, United States. An algorithm that consists of a route construction and a route improvement phase is described to solve the problem, using which the author analyzes the impact of different speed levels and different depot locations on emissions. Qian and Eglese (2014) focus on a problem that finds paths with the least fuel consumption, where vehicle speeds are time-dependent. The authors also conduct a case study with 14 customers and one depot located in Bristol, United Kingdom. The authors describe a time-increment-based dynamic programming algorithm and a new heuristic method consisting of a route selection and a speed adjustment stage. The application of the algorithms leads to about 6%—7% savings in emissions. Soysal and Çimen (2017) concern a distribution system operating over a pharmaceutical warehouse and 15 pharmacies in Ankara, Turkey. The application of a simulation-based restricted dynamic programming approach as a solution approach indicates that if the vehicles avoid heavily congested periods in serving the pharmacies, then savings of 2.3% can be achieved on the total amount of emissions. Other application-based studies are Aranda et al. (2012) and Oberscheider et al. (2013).

3.2 Tactical Decision Making

This section reviews studies concerning tactical decisions such as location-routing and allocation problems.

3.2.1 *Location-Routing Problems*

The first class of problems we review here is those that consider a joint treatment of location and routing decisions. The literature on such problems is still in its infancy when an explicit consideration of

environmental performance of the transportation activities is concerned. Table 7.5 provides a summary of the existing papers.

The first two of the studies listed in Table 7.5 address the location and routing decisions as part of a green network design problem. In particular, Cachon (2014) looks at a retail store supply chain problem by considering CO_2 emissions, where the objective is to minimize the transportation cost, which includes costs relevant to operating vehicles, fuel consumption and emissions, and space (store) cost. A two-echelon network is considered with a warehouse, retailers, and customers. To replenish the inventories, retailers travel to warehouses, which formulated as a traveling salesman problem, whereas the distribution problem for the customer modeled as a continuous version of a p-median problem, to which inventory decisions are linked. The problem compares small local shops and big retailers with regards to this objective. The second study is by Govindan et al. (2014), who describe a two-echelon location-routing problem with time windows for a perishable food supply chain network with manufacturers, distribution centers, and retailers. The model consists of two objective functions; to minimize the total cost and minimize the total environmental impact. The authors describe a multiobjective hybrid approach to solve a problem that combines two multiobjective algorithms, namely a multi-objective particle swarm optimization and a multiobjective variable neighborhood search.

Koç et al. (2016) analyze the impact of location, fleet composition, and routing on emissions in urban freight transportation. In this study, speed is not considered to be a decision variable in this problem but rather determined on the basis of different speed zones that cities are assumed to be divided into. The authors describe a location-routing problem with a heterogeneous fleet of vehicles in a city logistics concept. The problem is solved by means of an adaptive large neighborhood search algorithm. On the basis of randomly generated but structured instances, the findings suggest that the depot locations are generally selected to be farther away from city centers even if this increases the distance, mainly due to being able to drive faster than the slow speeds assumed in city centers. Toro et al. (2017) present a biobjective green capacitated location-routing problem where the two objective functions minimize the operational cost and fuel consumption and CO_2 emission, respectively. The ε-constraint method is used to solve the corresponding biobjective mathematical model.

Zhalechian et al. (2016) study a real-life application that is based on a supply chain of LCD and LED televisions assuming a two-echelon network. The network consists of 20 cities in Iran, each of which is a demand point, seven candidate depot locations, and two suppliers. For this application, the authors introduce a sustainable closed-loop location-routing inventory problem under mixed uncertainty where the objectives

TABLE 7.5 Tabulated Summary of Location-Routing Problems Incorporating Environmental Concerns

	General				Model Specifications				Fuel Consumption			
References	**Net.**	**Obj.**	**Sol. A.**	**Case**	**TW**	**TD**	**P&D**	**Unc**	**Emis. M.**	**Dis**	**Loa**	**Spe**
Cachon (2014)	Multi	Single	E						Factor	P	—	—
Govindan et al. (2014)	Multi	Multi	H		✔				Factor	—	—	—
Koç et al. (2016)	Single	Single	E & H						Micro	P	D	P
Toro et al. (2017)	Single	Multi	E						Macro	P	D	P
Zhalechian et al. (2016)	Multi	Multi	H	✔				✔	Micro	P	D	—
Tricoire and Parragh (2017)	Single	Multi	E & H	✔					Factor	P	D	—

are to: (1) minimize the total cost; (2) minimize the environmental impact of CO_2 emissions, fuel consumption, and wasted energy; and (3) maximize the social impact of the closed-loop supply chain. The authors present a stochastic-possibilistic programming formulation of the problem that treats some of the uncertainty through the use of fuzzy parameters, and propose a new hybrid two-stage solution algorithm. The last study we review in this section is the one by Tricoire and Parragh (2017), who describe a green city hub location-routing problem which is an extension of the location-routing problem with a heterogeneous fleet with two objectives; to minimize the total cost and minimize CO_2 emissions. Solutions are obtained by decomposition that first generates vehicle routes which are fed into a set covering model solved using a biobjective branch-and-bound algorithm. The authors test their algorithm on instances obtained from industrial partners in Austria that include 22 hubs, 898 or 1635 customers, and two or seven vehicle types. The authors conclude by suggesting that investing in facilities reduces pollution by showing trade-offs with cost.

3.2.2 Allocation Problems

Problems arising at a tactical level of decision making also include those of allocation, in which decisions concern the assignment of customers to facilities (or depots) at given locations. In multiechelon networks, allocation decisions are made at each echelon. For example, in a two-echelon network with suppliers, distribution centers, and retailers, the allocation decisions include the assignment of distribution centers to the suppliers and the retailers to the distribution centers. Table 7.6 presents an overview of the studies of such problems with an explicit aim of reducing negative environmental impacts of transportation activities.

Each study shown in Table 7.6 gives rise to a different formulation of the relevant problem. Rather than presenting the individual formulations, we provide below a general representative model that serves as a framework of allocation problems where environmental indicators are represented in a minimizing objective function using cost measures. The problem is defined on a directed graph where N is the set of nodes consisting of a set of suppliers, distribution centers, and retailers denoted, with the corresponding nodes denoted by the sets S, D, R, respectively. Each distribution center $j \in D$ has a storage capacity C_j and each retailer $k \in R$ has demand D_k. The unit transportation and CO_2 emissions cost per a unit distance are denoted by c_t and c_{co}, respectively, where d_{ij} represents the distances between two different nodes i and j. The decision variables of the formulation are defined as follows: Non-negative continuous variables f_{ij} and g_{ij} represent the amount of commodity carried between a supplier $i \in S$ and a distribution center $j \in D$, and a distribution center $j \in$

TABLE 7.6 Allocation Problems With Environmental Concerns

References	General				Model Specifications				Fuel Consumption			
	Net.	Obj.	Sol. A.	Case	TW	TD	P&D	Unc	Emis. M.	Dis	Loa	Spe
Paksoy and Özceylan (2014)	Multi	Single	E						Macro	P	—	D
Soysal et al. (2014)	Multi	Multi	E	✔					Factor	P	D	—
Neto et al. (2008)	Multi	Multi	E	✔					LCA	—	D	—
Neto et al. (2009)	Multi	Multi	H	✔					LCA	—	D	—
Bing et al. (2014)	Multi	Single	E	✔					Factor	P	D	—
Kim et al. (2009)	Single	Multi	H	✔					Macro	P	D	P
Bauer et al. (2010)	Single	Single	E	✔					Macro	P	D	P
Pan et al. (2013)	Multi	Single	E	✔					Macro	P	D	P
Qu et al. (2016)	Single	Single	E	✔					Factor	P	D	—
Demir et al. (2016)	Single	Single	E & H	✔	✔			✔	Micro	—	D	—
Nagurney et al. (2007)	Multi	Multi	E						Factor	—	D	—
Cruz and Matsypura (2009)	Multi	Multi	E						Factor	—	D	—

D and a retailer $k \in R$, respectively. A generic formulation for a basic allocation problem is as follows:

$$Minimize \sum_{i \in P} \sum_{j \in D} f_{ij} d_{ij} (c_{co} + c_t) + \sum_{j \in D} \sum_{k \in C} g_{jk} d_{jk} (c_{co} + c_t) \qquad (7.28)$$

subject to

$$\sum_{i \in P} f_{ij} \leq C_j \quad \forall j \in D \qquad (7.29)$$

$$\sum_{j \in D} g_{jk} = D_k \quad \forall k \in R \qquad (7.30)$$

$$\sum_{i \in P} f_{ij} - \sum_{k \in R} g_{jk} = 0 \quad \forall j \in D \qquad (7.31)$$

$$f_{ij} \geq 0 \quad \forall i \in P, j \in D \qquad (7.32)$$

$$g_{jk} \geq 0 \quad \forall j \in D, k \in R \qquad (7.33)$$

The objective function (7.28) minimizes the total transportation and CO_2 emissions cost. Constraint (7.29) imposes capacity limits on the distribution centers. Constraint (7.30) ensures that the demand of each customer is fully met. Constraint (7.31) guarantees that all demand sent to a distribution center will be distributed to the customers allocated to that distribution center. Constraints (7.32) and (7.33) are the non-negativity restrictions on the decision variables.

Several studies look at allocation problems on variations or extensions of the formulation above. For example, Paksoy and Özceylan (2014) study a supply chain network design problem that minimizes the costs relevant to transportation, noise pollution, CO_2 emissions, and fuel consumption. The authors present an integer nonlinear programming formulation of the problem. Soysal et al. (2014) consider a food logistics network design problem for which they present a multiobjective linear programming model. The objectives are to minimize the total logistics cost and to minimize the total GHG emissions. The authors use the ε-constraint method to identify the Pareto frontier, and present a real-life application for a beef logistics network in Brazil exporting products to the European Union.

Some studies include reverse logistics activities in the green network design problems. In such settings, end-of-life facilities are explicitly represented in the network, at which point the products are recycled and sent onwards to the suppliers. Neto et al. (2008) look at design and evaluation of sustainable logistics network structures using a multiobjective optimization model in which the objectives relate to minimizing cost and environmental impacts. They describe a new technique to evaluate the

efficiency of existing networks that exploits the similarities between data envelopment analysis and multiobjective programming. The European pulp and paper industry is used as a case study. Neto et al. (2009) study a similar problem where they propose a two-phase heuristic algorithm to find an approximation to the Pareto frontier, using a recycling logistics network in Germany as a real-life application of the problem. Bing et al. (2014) describe a sustainable reverse logistic network design problem for a multilevel network with multiple products, using a case study arising in the separation of plastic waste operations in the Netherlands.

Within the context of tactical level planning problems, there are studies that assume the use of different transportation modes on more complex networks where each mode of transportation has its own set of parameters, such as capacity and emissions. For example, Kim et al. (2009) study a biobjective design problem on a multimodal hub and spoke network where the objectives are to minimize transport cost and CO_2 emissions and solved using the ε-constraint method. The authors apply the method to a problem arising in a real-life freight distribution network connecting the ports of Rotterdam in the Netherlands and Gdansk in Poland. One other such study is by Bauer et al. (2010) on designing an intermodal freight network. The authors describe a large-scale integer linear programming formulation of the problem, and apply it on an intermodal network operating over Austria, the Czech Republic, and Poland. Pan et al. (2013), Qu et al. (2016), and Demir et al. (2016) are other studies that consider different transportation modes.

Some studies on these problems apply game theoretic models. Nagurney et al. (2007), for example, look at a transportation network design problem arising in a supply chain with two objectives, one maximizing profit and the other minimizing emissions. The authors derive optimality and equilibrium conditions for the problem. Cruz and Matsypura (2009) study a supply chain network design problem to which corporate social responsibility considerations are incorporated.

3.3 Strategic Decision Making

This section analyzes the studies in which long-term strategic decisions are made, such as those concerning facility location, with explicit environmental concerns in mind. Table 7.7 presents an overview of the relevant studies in this area, which we describe in further detail below.

Ghaddar and Naoum-Sawaya (2012) study a facility location problem with market competition in which market prices and production costs are decided based on economic equilibrium. The authors impose a limit on emissions by considering a carbon trading mechanism. Xifeng et al. (2013) present a multiobjective uncapacitated facility location problem where the

TABLE 7.7   Strategic Location Problems With Environmental Concerns Defined on Single Echelon Networks

References	General				Model Specifications				Fuel Consumption			
	Net.	Obj.	Sol. A.	Case	TW	TD	P&D	Unc	Emis. M.	Dis	Loa	Spe
Ghaddar and Naoum-Sawaya (2012)	Single	Single	E	✔					Factor	—	D	—
Xifeng et al. (2013)	Single	Multi	H						Factor	P	P	—
Treitl and Jammernegg (2014)	Single	Single	E & H	✔					Factor	P	D	—
Harris et al. (2014)	Single	Multi	E & H						Factor	P	—	—
Khoei et al. (2017)	Single	Single	E		✔	✔			Micro	P	P	D
Mohammadi et al. (2014)	Single	Multi	E & H					✔	Micro	P	D	P
Niknamfar and Niaki (2016)	Single	Multi	H		✔				Micro	P	P	D

objective functions are to minimize cost, to minimize CO_2 emissions, and to maximize minimum service reliability. The problem is solved by a heuristic hybrid algorithm that uses the ε-constraint method. Treitl and Jammernegg (2014) study two problems that include location-allocation decisions, namely the p-median and the warehouse location problem, where environmental and economic impacts of transportation activities are minimized. Harris et al. (2014) solve a capacitated facility location-allocation problem using multiobjective optimization where the objective functions are to minimize the total cost and to minimize the CO_2 emissions. Solutions are obtained using a mixed integer linear programming formulation and a heuristic that combines a multiobjective evolutionary algorithm for the location decisions and Lagrangian relaxation for the allocation decisions. Khoei et al. (2017) describe a green Weber problem and time-dependent version of the same, where the decisions concern the location of a single facility, as well as the speeds of the vehicles sent to customers, so that the total amount of CO_2 emissions is minimized. Second-order cone programming formulations are described for both problems.

There are a couple of studies that look at environmental considerations within hub location problems. In particular, Mohammadi et al. (2014) describe a sustainable hub location problem with three objectives, namely to minimize transportation costs, to minimize the total cost of noise pollution, and to minimize the fuel consumption on arcs and at hubs. Niknamfar and Niaki (2016) describe a biobjective hub location problem assuming collaboration between a holding company and multiple carriers. The objective function maximizes the profits for both the company and the carriers. Fuel consumption and CO_2 emissions are modeled as tax for carriers in the objective function.

As for other strategic location(-allocation) problems that appear in the literature on multiechelon networks, we present a summary in Table 7.8 and discuss these references in further detail below.

Hugo and Pistikopoulos (2005) describe a supply chain design network problem with the consideration of LCA principles and using multiple objective functions. The objectives are to maximize the net present value and to minimize the environmental impact. The authors propose a multiobjective mixed integer linear programming formulation and use the ε-constraint method to find the efficient frontier. Wang et al. (2011) consider environmental investment decisions for facilities with two objective functions; to minimize the total cost and minimize CO_2 emissions from facilities and transportation activities. Elhedhli and Merrick (2012) study a two-echelon supply chain network design problem, where the objective is to minimize the costs of installation, handling, transportation, and CO_2 emissions. The solution algorithm combines Lagrangian relaxation with a heuristic. Mallidis et al. (2012) study a

TABLE 7.8 Strategic Location Problems With Environmental Concerns Defined on Multiechelon Networks

References	General				Model Specifications				Fuel Consumption			
	Net.	Obj.	Sol. A.	Case	TW	TD	P&D	Unc	Emis. M.	Dis	Loa	Spe
Hugo and Pistikopoulos (2005)	Multi	Multi	E	✔					LCA	P	—	—
Wang et al. (2011)	Multi	Multi	E	✔					Factor	P	D	—
Elhedhli and Merrick (2012)	Multi	Single	H						Factor	P	D	P
Mallidis et al. (2012)	Multi	Multi	E	✔					Factor	—	D	—
Kadzinski et al. (2017)	Multi	Multi	E & H	✔					Factor	—	D	—
Varsei and Polyakovskiy (2017)	Multi	Multi	E	✔					Factor	—	D	—
Pishvaee and Razmi (2012)	Multi	Multi	E	✔				✔	LCA	—	D	—
Miranda-Ackerman et al. (2017)	Multi	Multi	E	✔					LCA	—	D	—
Chaabane et al. (2011)	Multi	Multi	E	✔					Factor	P	D	—
Abdallah et al. (2012)	Multi	Single	E	✔					LCA	P	D	—
Chaabane et al. (2012)	Multi	Multi	E						LCA	—	D	—
Shaw et al. (2016)	Multi	Single	E					✔	Factor	—	D	—
Rezaee et al. (2017)	Multi	Single	E	✔				✔	Factor	—	D	—
Guillen-Gosalbez and Grossman (2009)	Multi	Multi	E	✔				✔	LCA	P	D	—
Bojarski et al. (2009)	Multi	Multi	E	✔					LCA	P	—	—
Duque et al. (2010)	Multi	Multi	E	✔					LCA	—	D	—
Pinto-Varela et al. (2011)	Multi	Multi	E	✔					LCA	P	—	—
You et al. (2012)	Multi	Multi	E	✔					LCA	P	D	—

supply chain network design problem in which the decisions concern the selection of the port of entry and transportation mode, and where the authors analyze the impact of using dedicated and shared warehouses on cost and emissions on a real-life application in southeast Europe. Kadzinski et al. (2017) revisit a case study that was looked at by Mallidis et al. (2012), by casting the problem as a multiobjective green supply chain problem. The objectives separately minimize the total cost, total amount of CO_2 emissions, and the total amount of particulate matters emitted. In addition to using exact methods such as the weighted sum and epsilon constraint scalarization, the authors apply two well-known multiobjective evolutionary algorithms, namely SPEA2 and NSGA-II, and devise an interactive solution mechanism that incorporates the indirect preferences of a decision maker. Varsei and Polyakovskiy (2017) study a multi-objective sustainable supply chain network design problem where the objective is to minimize the economical, environmental, and social impacts of the supply chain for a top wine company in Australia. The authors develop a customized model solved by an augmented ε-constraint method. Other similar studies are due to Pishvaee and Razmi (2012) and Miranda-Ackerman et al. (2017).

Similar to those discussed in previous sections, some studies make use of a carbon trading mechanism to minimize emissions. Chaabane et al. (2011) is one such studies, which uses goal programming to solve a biobjective network design problem minimizing total cost and the total amount of CO_2 emissions are minimized. Abdallah et al. (2012) propose a carbon-sensitive supply chain problem using green procurement strategies, where a single objective function minimizes the sum of the fixed costs, distribution costs, procurement costs, and emissions costs related to the carbon trading mechanism. Chaabane et al. (2012) present a biobjective sustainable supply chain network design problem under an emission trading mechanism that includes reverse logistics activities. Other studies that consider a carbon trading mechanism are Shaw et al. (2016) and Rezaee et al. (2017), both of which study green network design problems under uncertainty.

A number of studies have a particular focus on the design chemical supply chains with environmental consideration. For example, Guillen-Gosalbez and Grossman (2009) describe a sustainable chemical supply chain design problem where the objectives are to maximize the net present value and minimize the environmental impacts based on LCA principles. The authors formulated the problem as a bicriterion stochastic mixed integer nonlinear programming model, which is then reformulated as a parametric mixed integer nonlinear programming model. Other similar studies are due to Bojarski et al. (2009), Duque et al. (2010), Pinto-Varela et al. (2011), and You et al. (2012).

3.4 Other Studies

In conducting this review, a number of papers were identified that did not necessarily focus on decision (optimization) problems arising in logistics network planning, but rather provided broader discussions and insights into green applications. For this reason, we review them here separately as opposed to being part of the three-level classification of decision-making. For example, some studies discuss the use of computerized routing and scheduling as well as vehicle telematics for reducing emissions (e.g., Léonardi and Baumgartner, 2004; Baumgartner et al., 2008). Others discuss the need to use geographical information system software in vehicle routing such as GIS, ArcGIS, and GPS (e.g., Ericsson et al., 2006; Apaydin and Gonullu, 2008; Tavares et al., 2009; Jovicic et al., 2010; Zsgraiova et al., 2013; Bandeira et al., 2013). Wu and Dunn (1995) and Aronsson and Huge Brodin (2006) evaluate the effect of innovative ideas, strategies, or structural changes on the environment. Beltran et al. (2009) propose a transit network design problem with green vehicles that produce lower emissions. Since the number of green vehicles is limited, they are only assigned to specific routes.

The use of other types of methods within green network design are discussed in various references, such as simulation (Van Der Vorst et al., 2009), analytic network process (Dou and Sarkis, 2010), constant factor approximation algorithms (Gaur et al., 2013), and fuzzy-based approaches (Cirovic et al., 2014; Jovanovic et al., 2014).

4. CONCLUSIONS AND THOUGHTS ON FURTHER RESEARCH

Given the increasing concerns on impacts of transportation, logistics, and supply chain activities on the environment, the existing body of research is continually developing and expanding at a significant pace. This review has identified most of these studies to be on operational aspects, such as vehicle routing and scheduling, which are short-term plans for such activities. The work on integrating environmental concerns, although growing, is less developed at tactical and strategic levels of decision making, and as such it will be important to understand the implications of longer-term decisions, such as facility location, customer allocation, and transport mode choice, on the environment as well as on the economic viability of the underlying logistics system.

Despite their common and widespread use, the use of the terms "green" and "sustainability" present a certain degree of ambiguity. We do not claim to have offered, or even attempted, a complete clarification between the uses of these terms here as such discussions are beyond the

scope of this review. However, in the way of taking some steps towards such a clarification, at least in the context of green network design, we have assumed "green" design activities to be a class of "sustainable" design activities. We have assumed that green pertains to an explicit goal of reducing emissions in designing logistics networks.

This review has highlighted that a good portion of the relevant OR literature in this field makes use of multiobjective optimization tools in formulating, solving, and analyzing green network design problems. This is not entirely surprising given the ability of multiobjective optimization tools to allow for separate treatment of various objectives that are not all necessarily commensurable (e.g., cost in monetary units vs. emissions in grams). This is all the more important as not all environmental considerations can be measured in monetary units. Such tools also allow identifying the trade-offs between what seem to be conflicting objectives, although in some cases there may be win−win situations.

A common way in dealing with green network design problems seems to be an explicit integration of the environmental factors, such as emissions, noise pollution, carbon trading mechanisms, and energy usage, into the existing models of such problems. This typically manifests itself in the form of an augmented (and often more complicated) objective function(s), where the aim is often to minimize the environmental consequences along with the traditional operational cost measures. The one aspect that comes across clearly from a methodological point of view is that such integrations give rise to problem extensions that are often as challenging, if not more difficult, to solve. Most of the solution algorithms, which have been described for the solution of such problems, seem to be modifications of the existing ones.

The explicit goal of reducing emissions assumes the availability of models that adequately capture the type of factors affecting fuel consumption that is inherently linked to emissions, the degree to which such factors affect fuel usage and the accuracy of estimations. Whilst there is a good body of work on this aspect, offering models that range from macroscopic to microscopic, from factor models and wide-area assessment tools, there is still some room for studies that offer empirical evidence as to the accuracy of such models. These models are generally used for operational activities. The consideration of higher-level design problems such as facility location require a good understanding of the emissions caused by the processes within such entities (e.g., energy use within manufacturing facilities or container ports), which also need further investigation.

Finally, we mention the importance of the choice of transport mode in designing distribution networks, given the unique characteristics and environmental performance of each individual mode of transport. Modal shift, a term that has long been known and discussed within logistics to

reduce the environmental externalities, can be captured at sufficient levels of detail within strategic and tactical decision-making problems discussed above, which would allow for assessing the trade-offs associated with shifting of freight on economic and environmental measures of performance.

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