NETWORK STRUCTURES IN HAZARDOUS WASTE MANAGEMENT SYSTEMS: ADVANCES, CHARACTERISTICS AND CHALLENGES

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ABSTRACT

In recent years, progressive industrial and technological development has increased the amount of hazardous waste generated on the planet. The improper management of these wastes adversely affects human health and the environment due to their corrosive, reactive, ignitable, and toxic characteristics. Consequently, the activities associated with the collection, transport, treatment, recycling, and disposal of hazardous waste increase the related risks producing crucial economic and social impacts. For this reason, hazardous waste management attracts researchers' attention who through the formulation of optimization models have proposed in the literature the hazardous waste location-routing problem (HWLRP). In this regard, this paper studies the evolution of network structures in HWLRP existing in the literature. The main focus of this paper is to provide a review of the most relevant frameworks for the design of a hazardous waste management system and to analyze advances, characteristics, and challenges for future research. This study may help to define assumptions, concepts, and some insights into the design of the subsequent location and routing models applied to hazardous waste management to minimize the economic, social, and environmental impact that these wastes generate.

Keywords: waste management systems, hazardous waste, network structures, location and routing.

1 INTRODUCTION

Hazardous wastes have characteristics such as corrosivity, reactivity, flammability, and toxicity [1]. These wastes are mainly generated by different sources, from large industries, such as chemical factories and oil refineries [2], and small businesses, homes, or hospitals [3]. Industrial and technological development worldwide in recent years, together with population and economic growth, have considerably increased the generation of hazardous waste, that is, there is a direct relationship between the level of development of the country and the quality of life of people concerning the amount of waste produced [4]. Taking into account its characteristics, hazardous waste represents a potential risk to human health and the environment, therefore, it requires strict control from its collection to its final disposal. For this reason, hazardous waste management systems (HWMS) have been created, which are responsible for the collection, distribution, treatment, reuse, and disposal of this waste efficiently and safely [5].

The design of a hazardous waste management system involves various strategic, tactical, and operational decisions, such as the location of recycling or treatment centers and disposal facilities, and the distribution of the routes that collect the waste from the generation nodes [6]. These decisions have been extensively studied in the literature through the application of optimization models in three categories: facility location problem (FLP), vehicle routing problem (VRP), and the combination of these models known as the hazardous waste location-routing problem (HWLRP), which is considered the problem of greatest interest to researchers because it jointly solves the most important decisions for the design of a hazardous waste management system. In these systems, the selection of waste collection routes depends considerably on the location of the treatment, recycling, and disposal centers. According to this, the location of the facilities affects the distribution of the routes for the

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transport of waste, therefore, these decisions are connected, and considering the problem separately can generate an increase in costs and risks [7].

Unlike the traditional location and routing problem, which mainly seeks to minimize total costs, hazardous waste management models have been addressed with different objectives. The selection of the safest routes for waste collection is an important objective, but this minimization of risk can result in increased costs. Whereas, if the main decision is to reduce costs, the risk to society or the environment may be increased. For this reason, most of the existing models in the literature use multi-objective optimization to make the system more efficient and give a different solution alternative to the decision-maker. Cost minimization and risk minimization are the main objectives studied by researchers [3].

An important feature in the design of a hazardous waste management system is the network structure for the location of facilities and the transport of waste between these facilities. The evolution of location and routing models for hazardous waste over the years has presented different frameworks for the network structure with different characteristics, taking into account the need to bring the system closer to real-world conditions. The purpose of this article is to carry out an analysis of the evolution of the main frameworks presented in the literature for the hazardous waste location-routing problem, emphasizing the advances and characteristics of each one of them. In this way, a general framework of the system is proposed so that it serves as a reference for subsequent studies applied to hazardous waste management.

The rest of this article is organized as follows: Section 2 describes a literature review on the HWLRP, and Section 3 presents the advances in network structures for hazardous waste management systems and their characteristics. Section 4 presents the discussion, design of the framework, and challenges for future research, and finally, Section 5 describe the conclusions.

2 REVIEW OF HAZARDOUS WASTE LOCATION-ROUTING PROBLEM

The design of hazardous waste management systems has been mostly addressed in the literature as location and routing problems, therefore, this review presents the most relevant research on this topic. The first studies on the HWLRP began in the late 1980s when Zografos and Samara [8] designed for the first time a multi-objective hazardous waste management distribution network that simultaneously considered the minimization of site risk, transport risk, and travel time, for a single type of waste. Later, ReVelle and Jared [9] developed a model to minimize transportation costs and risk for the location of storage and transportation facilities in a problem applied to waste from the nuclear sector. That same year, List and Mirchandani [10] were the first to propose a model with different types of hazardous waste and multiple types of treatment technologies, considering the minimization of the total risk (transport risk and site risk), transport costs, and risk equity maximization. This last objective was also presented by Current and Ratick [11]. Giannikos [7] formulated a problem for the location of disposal facilities and the transportation of hazardous waste with four objectives: minimize costs, total risk, risk equity, and equitable distribution of the disutility caused by the operation of the treatment facilities. A new model is proposed by Nema and Gupta [12] who formulated waste–technology compatibility constraints, taking into account that hazardous waste cannot be treated together unless they are compatible with each other.

At the beginning of the new century, one of the most important studies was presented. Alumur and Kara [2] formulated a model for a real case in the central region of Anatolia, Turkey, to determine the location of treatment centers, disposal facilities, and the transportation of different types of waste according to compatibility constraints to minimize risks and costs. In the same year, Caballero et al. [13] addressed the location of incineration plants for the disposal of solid animal waste and designed routes to serve the generation nodes. Another outstanding study was presented by Samanlioglu [1] who proposed a new design for the network structure, which includes: waste generation nodes, treatment centers, recycling centers, disposal facilities, and the routes between them to minimize total costs, transportation risk, and site risk. Zhao and Verter [14] carried out an application to the used oil waste management, where the routes were formulated for the first time as a tour. Zhao et al. [15] incorporated into their model, the capacity and operation constraints, and risk tolerance measures between routes. An important contribution to the literature on hazardous waste was presented by Yilmaz et al. [5] who made a taxonomy of hazardous waste, establishing seven classifications in total with their respective treatment processes.

In 2018, Rabbani et al. [3] developed for the first time a model with a heterogeneous fleet of vehicles, considering waste–waste compatibility because hazardous waste should not be collected in the same vehicle. In addition to this, the design of the network structure considered transportation as a vehicle routing problem for collection at generation nodes, a condition that had not been previously studied. Zhao and Huang [16] addressed a gap not considered in the literature, since they considered a multi-period planning horizon for location decisions in their model, while Rabbani et al. [17] formulated a multi-objective model with multiple periods for vehicle routing and transportation decisions between facilities. Farrokhi-Asl et al. [18] considered environmental decisions as one of the study objectives of their model. Previous studies optimized costs and risks mainly. Later, Delfani et al. [19] proposed the concept of green location-routing problem (GLRP) applied to hazardous waste, with minimization of CO_2 emissions within its objectives.

Rabbani et al. [20] developed an extension of the models presented in previous studies, including a new optimization objective: workload balance and time windows for the vehicle routing problem. Finally, Tirkolaee et al. [21] addressed a location and routing model with time windows for medical waste management, as a problem that has increased due to the COVID-19 pandemic. The review carried out allows us to recognize the different hazardous waste location-routing models existing in the literature and their main characteristics as evidence of the importance of the research topic. The following section highlights the most important network structures for a hazardous waste management system that have been implemented to solve these models and their evolution according to the findings of the literature review carried out.

3 NETWORK STRUCTURES IN HAZARDOUS WASTE MANAGEMENT SYSTEMS

The planning of a hazardous waste management system begins with the design of the network structure that allows determining the required facilities and the flow of activities that are part of the system. To guarantee the efficient collection, distribution, treatment, reuse, and disposal of hazardous waste, the network structure must be made up of a set of facilities such as recycling centers, treatment centers, and disposal sites, and to define how the transporting process is carried out. Table 1 shows how the different existing frameworks in the literature for the design of network structures in hazardous waste management are made up.

As shown in Table 1, the first studies describe a structure made up only of waste generation nodes and disposal facilities where the waste is sent for disposal. Most studies focused on the collection of a single waste and a single treatment technology. However, in List and Mirchandani [10] these conditions were changed to model the collection of various types of waste. Later, other important facilities were included in the network structure, such as hazardous waste treatment centers with their different treatment technologies, and later, recycling centers, because part of this waste can be recovered both in generation nodes and in treatment centers.

Table 1: System framework on the hazardous waste network design.

Author	Year	Ref	System framework						
			O	G	R	T	D	W	Q
Zografos and Samara	1989	[8]		✓			✓	S	S
ReVelle and Jared	1991	[9]		✓			✓	S	S
List and Mirchandani	1991	[10]		✓			✓	M	M
Current and Ratick	1995	[11]		✓			✓	S	S
Giannikos	1998	[7]		✓			✓	S	S
Nema and Gupta	1999	[12]		✓		✓	✓	M	M
Alumur and Kara	2007	[2]		✓		✓	✓	M	M
Caballero et al.	2007	[13]		✓			✓	S	–
Samanlioglu	2013	[1]		✓	✓	✓	✓	M	M
Zhao and Verter	2015	[14]		✓			✓	S	–
Zhao et al.	2016	[15]		✓	✓	✓	✓	M	M
Yilmaz et al.	2017	[5]		✓	✓	✓	✓	M	M
Rabbani et al.	2018	[3]	✓	✓	✓	✓	✓	M	M
Zhao and Huang	2019	[16]		✓	✓	✓	✓	M	M
Rabbani et al.	2019	[17]	✓	✓	✓	✓	✓	M	M
Farrokhi-Asl et al.	2020	[18]	✓	✓	✓	✓	✓	M	M
Delfani et al.	2020	[19]		✓	✓	✓	✓	M	M
Rabbani et al.	2021	[20]	✓	✓	✓	✓	✓	M	M
Tirkolaee et al.	2021	[21]		✓			✓	S	–

Note: O = depot/origin, G = generation node, R = recycling center, T = treatment center, D = disposal facility, W = waste, Q = treatment technology, S = single waste or technology, M = multiple waste or technology.

Finally, recent studies model waste collection between generation nodes as a vehicle routing problem, which includes depots where vehicles are located. Next, the characteristics of the most relevant frameworks in the literature are described to recognize the advances over the years in the design of network structures for hazardous waste management.

3.1 Generation nodes and disposal facilities

In this network structure, two decisions must be resolved: the location of the disposal facilities and the transport of waste from the generation nodes to the previously located sites, as shown in Fig. 1. Each generation node sends the collected waste (a single type of waste) to a single disposal facility, that is, the transport flow is direct between the nodes (origin–destination). Studies with this framework were developed by Giannikos [7], Zografos and Samara [8], ReVelle and Jared [9], List and Mirchandani [11], and Caballero et al. [13].

Advantages

- Location and routing models with this network structure are less complex to solve.
- These studies are considered the point of departure for subsequent research on hazardous waste management.

Disadvantages

- Considering a single type of waste is far from the real conditions regarding hazardous waste.
- Recycling is not taken into account within hazardous waste management Desventajas.

Figure 1: G+D framework.

3.2 Generation nodes, treatment centers, and disposal facilities

In this network structure, initially proposed in Nema and Gupta [12] and improved and implemented in a real case study years later by Alumur and Kara [2], some nodes generate hazardous waste which can be recycled or sent to a treatment center for its processing. In the treatment centers, part of hazardous waste is recycled and the waste residue is produced, which is transported to the disposal facilities for its elimination (Fig. 2). In this hazardous waste management system, treatment centers and disposal facilities are located within a set of previously defined potential sites and the amount of waste that is transported between the selected facilities is determined.

Figure 2: G+T+D framework.

Advantages

- The network structure considers different types of waste and different treatment technologies (one type of technology in each treatment center).
- The proposed models consider waste–technology compatibility constraints.
- Recycling is allowed both in the waste generation nodes and in the treatment centers.
- Mass balance constraints are considered for waste transportation between treatment centers and disposal facilities, that is, hazardous waste that cannot be treated or recycled is sent to final disposal facilities for elimination.

Disadvantages

- The system with this network structure does not take into account the location of recycling centers.

3.3 Generation nodes, treatment centers, recycling centers, and disposal facilities

The location of recycling centers in the system is included for the first time in Samanlioglu [1]. The design implemented by this author is considered one of the most complete available in the literature for hazardous waste management [18]. The network structure consists of some waste generation nodes and three types of facilities: treatment, recycling, and disposal. As shown in Fig. 3(a), after storing the different types of hazardous waste in the generation nodes, two activities are carried out: sending non-recyclable waste to a compatible treatment

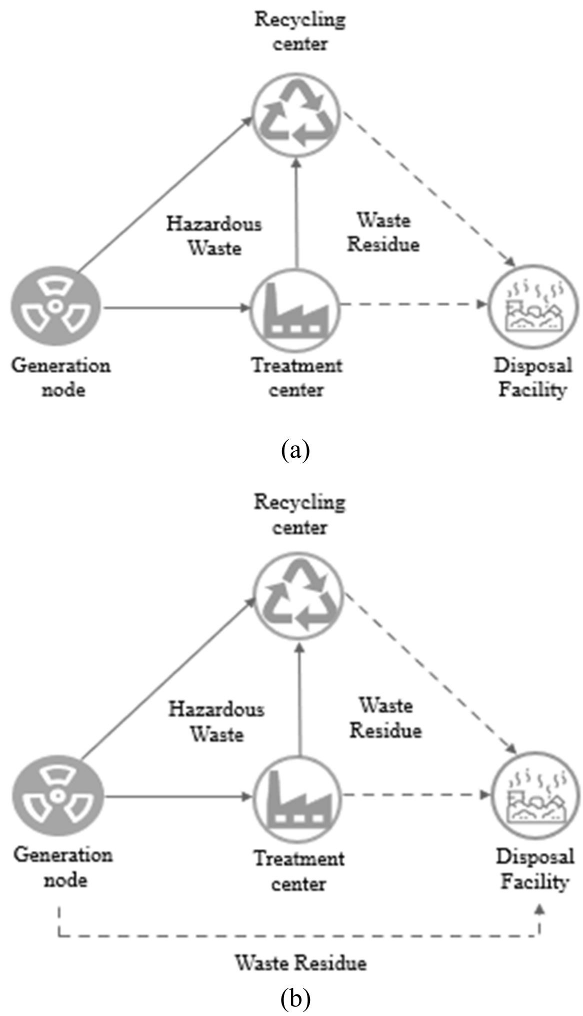

Figure 3: G+T+R+D framework. (a) Without G to D transport; and (b) With G to D transport.

center and sending recyclable waste to a recycling center. In a treatment center, after carrying out the transformation processes, waste is generated that is transported to a recycling center or sent to a disposal facility. In the same way, in the recycling centers, waste that cannot be reused is discarded and sent to the disposal facility. In this system, there is no direct flow of waste from the generation nodes to the disposal facilities.

Fig. 3(b) presents a network structure that allows waste transportation from the generation nodes to the disposal facilities. In this design proposed in Zhao et al. [15] and Zhao and Huang [16], hazardous waste is classified according to its generation source: treatable, recyclable, and disposable. In this way, disposable waste is sent directly for disposal in landfills.

Advantages

- In addition to the advantages associated with the structure presented in the previous section, this system takes into account the importance of recycling, therefore, it allows the location of recycling centers and the transport of waste between treatment centers to recycling centers and between recycling centers to disposal facilities.

Disadvantages

- The system does not consider the vehicle routing problem for waste collection between generation nodes. Although most of the previous studies define hazardous waste management as a location and routing problem, they do not explicitly deal with the classic problem proposed by Nagy and Salhi [22]. In these cases, routing is associated with waste transportation between facilities and generation nodes.

3.4 Depot, generation nodes, treatment centers, recycling centers, and disposal facilities

To address the disadvantage presented in the previous section, a network structure that considers the vehicle routing problem is presented in Rabbani et al. [3]. Although the facilities to be located are the same as those presented by Samanlioglu [1], for this structure exists a central depot where the vehicles are parked. The vehicles start their route at the depot, collect the hazardous wastes at the generation nodes, drop off their load at a recycling center or a treatment center compatible with the waste they transport, and finally return to the depot. In addition to this, the waste transport processes between facilities mentioned in the previous structures are carried out (Fig. 4).

Studies with this type of network structure have also been presented in Rabbani et al. [17], [20]. According to Farrokhi-Asl et al. [18] additionally allows the location of different depots within a set of potential sites.

Advantages

- As in the previous structure, the implementation of different types of waste, different treatment technologies, location of treatment centers, recycling, and disposal facilities are considered an advantage.
- Implementation of the vehicle routing problem for the collection of hazardous waste.
- Waste–waste compatibility constraints are formulated, taking into account that hazardous waste cannot be transported together.
- For this, a system is designed for the first time that proposes the use of a heterogeneous fleet of vehicles for the collection of the waste generated.

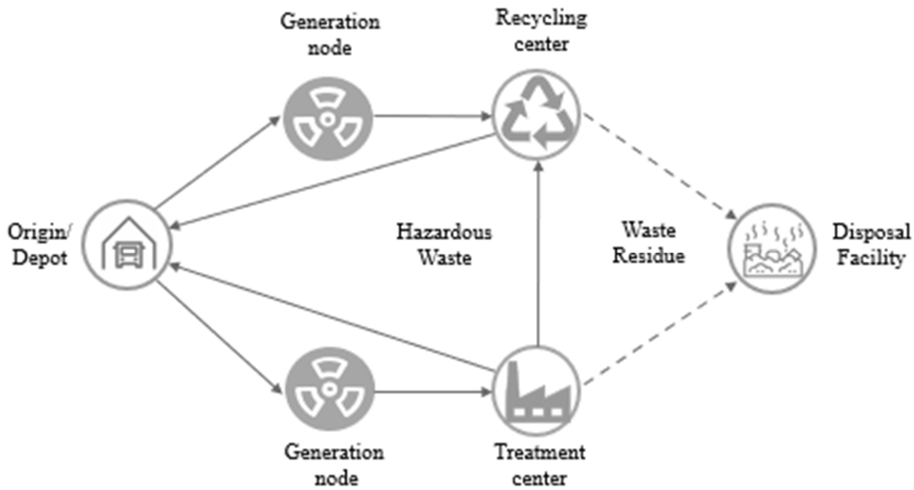

Figure 4: O+G+T+R+D framework.

Disadvantages

- The network structure increases the complexity of the hazardous waste management system, which represents the need to implement more robust solution methods for the multi-objective location and routing problem.

4 DISCUSSION: FRAMEWORK AND CHALLENGES

The evolution of network structures for the design of a hazardous waste management system allows us to recognize the importance of this research topic over the years. The planning of these systems implies the selection of different facilities, the collection of waste at the generation points, and the transport of waste residue between the selected facilities [12]. All of the above is an integrated process that can be solved by formulating multi-objective location and routing mathematical models. Studies developed in the literature have particular characteristics to adapt their models to conditions closer to real life. Although the first studies did not take into account any of these conditions, technological advances and the development of new solution strategies for highly complex mathematical models have allowed problems to be formulated that demand greater computational efforts but that contemplate a more complete design. Thus, an effective hazardous waste management system should achieve the following:

- Establishing the routes of the vehicles that are responsible for the collection of hazardous waste in each of the generation nodes.
- Determining the location of the system facilities: treatment centers, recycling centers, and disposal facilities.
- Determining the type of technology to be implemented in each localized treatment center.
- Establishing the transport process for recyclable waste and waste residue to be disposed of between the selected facilities.

4.1 General framework

According to the findings of the research carried out, this article presents a general framework that integrates all the previously mentioned decisions and serves as a point of departure for the design of a hazardous waste management system. This allows future research on the hazardous waste location-routing problem to take into account the characteristics of this framework for the network structure. The proposed framework is shown in Fig. 5. First, the generation nodes of hazardous waste are presented, which can be factories, hospitals, homes, and small businesses, among others. In each generation node, the waste is classified as recyclable waste, treatable waste, and disposable waste. Once the waste is stored at the source, a fleet of vehicles carries out the collection process. It must be taken into account that the dangerous conditions of this waste do not allow some of them to be transported together, therefore, a different type of vehicle is available for the collection of each classified waste. In this way the following activities are carried out:

1. Vehicles that collect recyclable hazardous waste send their load to a recycling center.
2. Vehicles that collect treatable hazardous waste send their load to a treatment center considering that each type of waste can only be treated by one type of compatible treatment technology. Hazardous waste treatment is generally carried out using chemical and thermal methods. Among the most used chemical processes are ion exchange, oxidation, and precipitation, while thermal processes are mainly applied through incineration [3].
3. Vehicles that collect disposable hazardous waste send their load directly to a disposal facility.

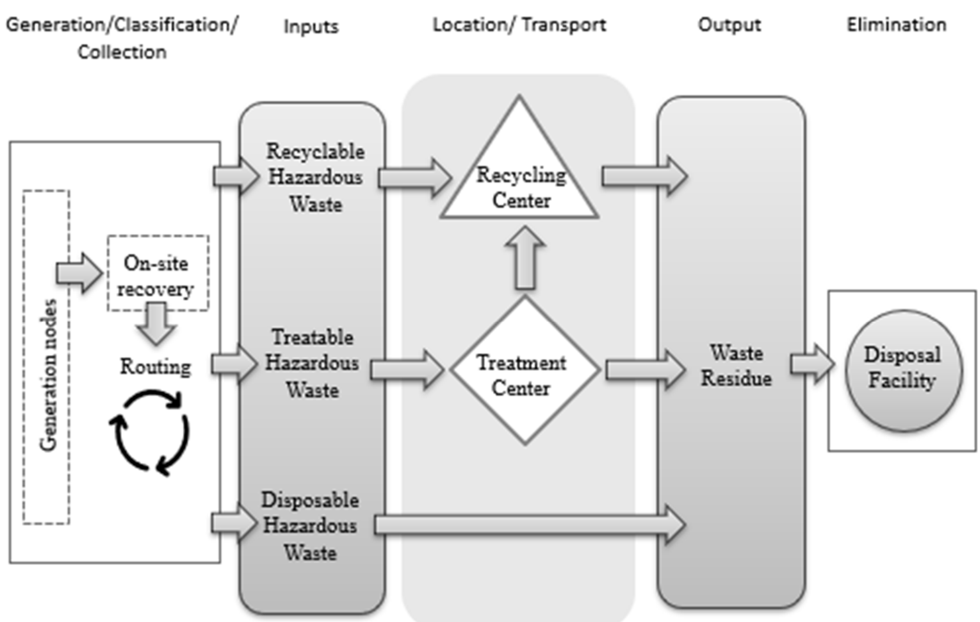

Figure 5: Hazardous waste management system framework.

Subsequently, in the treatment and recycling centers, transformation processes are carried out with the following activities:

1. In the recycling centers, a percentage of the waste is recovered while the waste residue is sent to a disposal facility.
2. In the treatment centers, a percentage of the waste becomes recyclable and is sent to a recycling center, and the waste residue is also sent to a disposal facility.

Table 2 presents some examples of the different hazardous waste according to their classification, taking into account the research carried out in Yilmaz et al. [5]. For treatable waste, waste compatible with chemical treatment and waste compatible with incineration are separated.

Table 2: Hazardous waste classification and examples.

Recyclable waste	Treatable waste		Disposable waste
	Chemical treatment	Incineration	
Wood preservatives Oily wastes Waste solvents Contaminated containers and packaging Waste batteries Photographic chemicals	Oil/water, hydrocarbon/water emulsions Laboratory chemicals Sludges from treatment operations Tempering salts containing cyanide	Medical wastes Pharmaceuticals waste Halogenated organics PCB containing wastes Waste inks, varnishes Ion exchange residues	Explosive wastes Inorganic wastes that do not contain heavy metals Waste ash and cinder Waste soil and sand Spent catalysts

4.2 Challenges for future research

The literature review carried out and the description of the network structures implemented as multi-objective location and routing problems show how researchers have tried to simulate the true conditions required by the design of a hazardous waste management system. However, addressing these complex systems as mathematical models is a challenging task due to the computational effort required for their solution. Recent studies have not only formulated the traditional location and routing problem to develop hazardous waste management systems but have also incorporated other features such as:

- Modeling waste collection and transportation processes with multiple periods. The foregoing considers that the activities associated with waste management are carried out by periods (daily, weekly, monthly, etc. depending mainly on the needs of the generator and the type of waste).
- Stochastic programming for parameters such as the amount of waste generated at each node. The conditions of uncertainty bring the problem closer to real-life because the amount of waste that can be generated in each source is not known with certainty.

- Multi-objective optimization with objectives other than cost and risk. Most studies of hazardous waste management have been formulated to minimize the total costs and risks to the system. However, environmental or customer satisfaction objectives can also be considered.

According to this, the challenges for future research on this topic require the implementation of the network structures proposed in this study, however, the formulation of mathematical models should focus on applying existing characteristics and conditions in reality. The development of case studies with real applications is a line of research of great importance since most studies are based on models solved from generic data.

5 CONCLUSION

Rapid economic growth and urbanization have caused a waste generation to increase over the years. Within this waste, it is possible to find hazardous wastes, which have characteristics that represent a risk to people who are exposed to them and the environment. The absence of efficient practices for hazardous waste management adversely affects human health and the environment. Therefore, the design of a hazardous waste management system is a fundamental task to guarantee the correct handling of this waste from its collection to its final disposal. The modeling of these systems as multi-objective location and routing problems have been widely studied in the literature since they can solve the location and transport decisions that these systems must define, and in the same way, they allow optimization of objectives such as costs, risks, environmental effects, among others.

Considering that to formulate these models it is necessary to establish an efficient network structure involving all parts of the system, this paper discusses the different frameworks used over the years by researchers to design hazardous waste management systems. The main conclusion of the research is that to achieve an effective system, the following must be defined: the hazardous waste collection processes between the generation nodes; the location of three types of facilities: recycling centers, treatment centers with their type of technology, and disposal facilities and the transportation of waste residue between previously selected facilities. This document proposes a framework that serves as a point of departure for developing a hazardous waste management system, taking into account the characteristics and advances found in the literature so that it can be applied in future research on this topic.

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