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Presenting a Multi-Objective Model for the Allocation and Capacity Building of Industrial Wastewater Recycling Centers with the Aim of Minimizing Transportation Costs and Maximizing Recycled Water Production

* Mustafa Mahmoodabadi ** Sadegh Abedi
*** Masoumeh Danesh Shakib

* Ph.D. Student in Industrial Management, Department of Industrial Management, Qazvin branch Islamic Azad university,Qazvin, Iran. mostafa.mahmoodabadi936@gmail.com

** Assistant Professor, Faculty of Management, Department of Industrial Management, Qazvin branch Islamic Azad university,Qazvin, Iran. abedi.sadegh@gmail.com

*** Assistant Professor, Faculty of Management, Department of Industrial Management, Qazvin branch Islamic Azad university,Qazvin, Iran. ms.danesh.shakib@gmail.com

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Abstract

Wastewater, especially industrial wastewater, serves as a reservoir for pathogenic microorganisms capable of causing contamination and infection. If wastewater disposal management is not conducted with proper health and hygiene considerations, these microorganisms can spread through air, water, or via carriers to others. High competition among manufacturing industries, coupled with environmental pressures and internal requirements to reduce costs and delivery times, improve quality, and enhance suppliers' ability to produce diverse and new products in shorter timeframes, as well as the potential entry of foreign competitors into the industry, alongside environmental and health issues, necessitate better performance compared to other competitors in this industry, which provides a suitable context for this research. In this research, an intelligent model for planning and investing in urban surface wastewater collection infrastructure and its impact on pollutant dispersion was developed. After collecting data and modeling, and considering the problem's assumptions, it can determine the reduction of surface wastewater collection costs and the reduction of pollutant emissions to the environment based on the optimal routing of wastewater collection vehicles. Moreover, due to the NP-Hard nature of the problem, the multi-objective grey wolf optimization algorithm was used to minimize both objective functions under different scenarios and conditions. The results showed that the proposed model is capable of determining the problem in various dimensions from the perspective of increasing the number of wastewater collection vehicles, the number of candidate wastewater collection locations, the increase in wastewater accumulation at locations, the increase in the number of vehicles in the network, and the increase in the distance of candidate wastewater locations in a desirable manner to ensure that all accumulated wastewater at the candidate locations is collected by the network vehicles.

Keywords: Industrial Wastewater Recycling, Capacity Building, Recycled Water Production, Multi-Objective Model, Grey Wolf Algorithm.

Corresponding Author: Sadegh Abedi- Abedi.sadegh@gmail.com

Introduction

The supply chain is a system composed of facilities and activities aimed at procuring, producing, and distributing goods to customers. Supply chain management integrates suppliers, manufacturers, warehouses, and retailers to deliver the right goods, at the right place and time, with minimal cost (Khosravi et al., 2022). Due to increasing competition and reliance on information technology, supply chain management has gained attention in recent decades (Goudarziyan & Hosseini Nesab, 2021). Generally, there are two types of supply chains: forward and reverse. The forward supply chain (FSC) involves activities from raw material to product conversion (Abarzadeh et al., 2018). Reverse supply chain (RSC) involves collecting and recovering returned products, forming the closed-loop supply chain (CLSC) (Devika et al., 2014). Reverse logistics involves planning, execution, and control of the flow and storage of secondary goods for proper disposal and value improvement. It includes customers, collection centers, recycling, and disposal of used products. Proper wastewater management remains critical for human health and economic development globally. Although industrialized nations have reached near-standard levels of water and wastewater control, severe issues persist in low and middle-income countries, with 2 billion people lacking wastewater treatment systems (Awad et al., 2019). This research aims to evaluate industrial wastewater treatment through a multi-objective mathematical model within a reverse supply chain. The goals include reducing industrial wastewater transport, increasing recycled water production, and converting pollutants into useful materials using the multi-objective grey wolf optimization approach (MOGWO).

Research methodology

Mathematical Modeling

In this study, we present an intelligent model for a closed-loop supply chain for collecting and recycling industrial wastewater, based on Kabir et al. (2021). Their approach involves a Mixed Integer Linear Programming (MILP) model that maximizes profit while efficiently utilizing reverse logistics. Two models are introduced: the first minimizes distance and transportation costs, while the second maximizes profit by considering urban water overflow.

Assumptions

The assumptions include vehicles with limited and uniform capacity, defined capacities for industrial wastewater locations, vehicles starting and ending at the depot, and distance calculations based on positions. Movement costs per unit distance include fuel and maintenance, and revenue is generated from treated wastewater. Each vehicle makes only one trip per day, and data from fill sensors is sent to the center at the start of the day. Vehicle speed and driver skill are constant, and emissions depend on load and road slope.

Mathematical Model

The mathematical model defines the problem with potential industrial wastewater locations, homogeneous vehicles, and a depot. Each location has a maximum capacity, with vehicle movement costs and revenue for collected wastewater. Fill sensors at each location send data, which is converted to weight, to the center.

Objective functions and constraints

Objective functions and constraints include maximizing profit by subtracting transportation costs from revenue and minimizing emissions based on road slope, vehicle load, and emission rate. Constraints ensure service levels allowing overflow, mandatory collection for over-threshold locations, single entry/exit for collection locations, total vehicle load within capacity, and binary/natural number constraints for decision variables.

Proposed Method

The proposed mathematical model uses the Multi-Objective Grey Wolf Optimizer (MOGWO) algorithm, starting with a randomly generated initial population P. The population is evaluated based on minimization and maximization objectives. After sorting using non-dominated sorting, the wolves' positions are calculated to determine the prey's location, enhancing population diversity. Some answers from each wolf population P_E are randomly selected using vector $\vec{c}$ and compared, with the better one chosen. Selection criteria prioritize the wolves' distances from each other and the prey. The closer the wolves are to each other and the prey, the more desirable the solution. No Pareto front solutions have precedence, and any can be optimal depending on the conditions. The overall approach of this algorithm is illustrated in Figure 1 below.

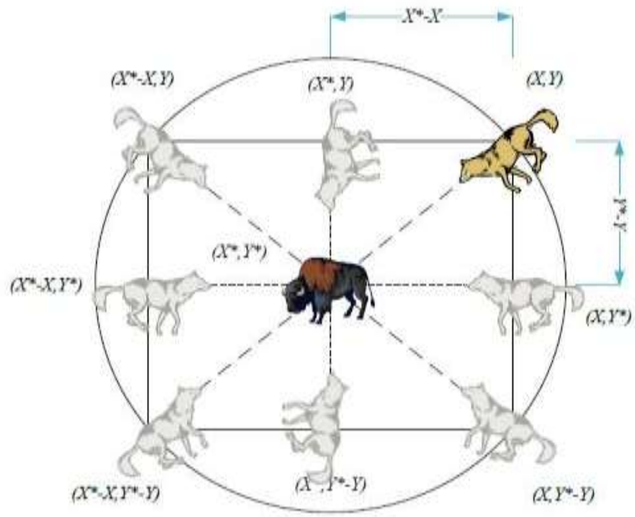

Figure 1. Mechanism of MOGWO Algorithm.

Findings

The problem model is a multi-objective, single-period, multi-product green closed-loop supply chain model. Table 1 presents the initial values of some of the main parameters.

Table 1. Initial Parameter Values.

Parameter	Symbol	Value
Vehicle movement cost per unit distance (USD)	C	15000
Revenue per kg of collected treated wastewater (USD)	R	60000
Penalty for using vehicles (USD)	Ω	25000
Capacity of wastewater collection vehicles (kg)	Q	5000
Wastewater density (kg/m^3)	B	190
Distance between nodes i and j (km)	dij	4

Wastewater amount at location i (kg)	Si	3.5
Predicted daily accumulation rate at industrial wastewater location i	ai	7

On the other hand, since the proposed model has several levels based on 10 candidate wastewater locations and 5 vehicles, the flow of wastewater collection is determined by the number of disposal and collection locations. Therefore, Table 2 presents the capacity of each of the 10 wastewater collection vehicles.

Table 2. Wastewater Accumulation in Collection Vehicles.

Density of Collected Wastewater	Wastewater Collection Vehicle
176	١
329	٢
427	٣
729	٤
102	٥
356	٦
449	٧
224	٨
234	٩
332	١٠

Based on the above table, it is clear that the first collection vehicle has wastewater with a density of 176 kg/m³, the second has a density of 329 kg/m³, and so on. It should be noted that the maximum time required to check each collection vehicle's bin is 8 hours. Another point to consider is that since the initial values in the model are determined randomly by the Grey Wolf algorithm, the solutions may sometimes be infeasible. In such cases, the algorithm immediately acts to overcome this and reach a feasible solution. This process is repeated 300 times for the algorithm. Accordingly, Table 3 presents the results of the model execution with the Multi-Objective Grey Wolf Optimizer for both objective functions.

Table 3: Results from Solving the Problem with the Grey Wolf Algorithm (MOGWO).

Objective Function	Cost Objective (USD)	Pollutant Emission Objective (PPM)
Value	10,981,185	11,744

As shown in Table 3, the proposed model with the given numerical example provides desirable results. Table 4 presents the amounts of wastewater collected and transported by the designated vehicles. Based on this table, it can be determined that not all vehicles need to visit every candidate wastewater location. Instead, each vehicle only needs to follow the designated route to the nearest specified wastewater collection location and collect the wastewater. This approach will reduce costs and pollutant emissions.

Table 4. Wastewater Transfer (kg/m³) from Candidate Locations by Vehicles.

	W	Second Vehicle	Third Vehicle	Fourth Vehicle	Fifth Vehicle
Candidate Wastewater Locations	0	0	0	176	0
	0	0	2	0	327
	427	0	0	0	0
	691	0	0	0	38
	0	0	0	96	6
	277	0	0	0	79
	449	0	0	0	0
	0	0	0	0	227
	9	0	0	0	225
	0	٠	0	0	332

Conclusion

Wastewater, particularly industrial wastewater, harbors pathogenic microorganisms that can cause contamination and infection. Improper disposal management can spread these microorganisms through air, water, or carriers, leading to significant health and environmental risks. Effective wastewater management is crucial, especially in rural areas with limited mechanization resources. Comprehensive water and wastewater management remains critical globally. Despite near-standard control in industrial nations, severe issues persist in low and middle-income countries, with 2 billion people lacking wastewater treatment systems. These countries often prioritize water supply over sanitation. This research developed an intelligent model for urban surface wastewater collection and its impact on pollutant dispersion. After a literature review, a two-objective model addressing investment costs and pollutant dispersion was proposed. The study collected data and modeled assumptions to determine reduced wastewater collection costs and pollutant emissions through optimal vehicle routing. The multi-objective grey wolf optimization algorithm was used to minimize both objectives under various scenarios. Results demonstrated the model's effectiveness in managing multiple dimensions, including increasing the number of collection vehicles, candidate locations, wastewater accumulation, network vehicles, and the distance between candidate locations, ensuring efficient collection.

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