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Reverse Logistics Network Design for Plastic Waste Management in Jakarta: Robust Optimization Method

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Abstract. Indonesia experiences a consistent annual escalation in plastic production, primarily attributed to the high demands from numerous industries. As a result of this escalated production rate, more significant quantities of plastic waste continue to be produced each year. In this regard, it is essential to comprehend that uncontrolled plastic waste generates harmful substances for humans and the environment. A reverse logistics network was introduced and developed to decrease the damaging effects of this waste on the environment. The Indonesian plastic waste reverse logistics system encountered some uncertainties due to limited data availability, showing significant fluctuations. To address these uncertainties, this study proposed a robust optimization model for the management of plastic waste within the reverse logistics system in Jakarta. The results showed that the model could accurately identify optimal facility locations and determine the exact quantity to transport between facilities while considering social, economic, and environmental factors. The results also showed that the proposed model minimized cost by 332 million USD, reduced gas emissions to 626 million m^3 (ca. 1.2 billion $kgCO_2$), and maximized labor by 611 thousand people.

Keywords: Network design; Plastic waste management; Reverse Logistics; Robust optimization

1. Introduction

The increasing rate of plastic material production has corresponded to a significant rise in generated plastic waste. This increase can be attributed to population growth and economic expansion (Liang *et al.*, 2021). Furthermore, during the COVID-19 pandemic, the demand for plastic materials such as masks, healthcare products, and package wraps was exacerbated (Khoo *et al.*, 2021). This led to a significant rise in the production of plastic-related products, which also proportionally resulted in the availability of an increased volume of plastic waste. Global plastic waste generation has exceeded 1.6 million tonnes daily (Benson, Bassey and Palanisami, 2021).

In 2010, Indonesia produced 3.2 million tons of plastic waste to the global volume, significantly polluting the ocean (Gabriel and Aninditya, 2017). Prior studies have also established that approximately 9% of plastic waste goes into recycling, 12% undergoes burning, and 79% is discarded in landfills (Khoo *et al.*, 2021).

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Uncontrolled plastic waste, particularly in the ocean, can cause environmental and human health issues, as it leads to an increased generation of pollutants that affect both humans and marine organisms (Aviso *et al.,* 2023; Kamaruddin *et al.,* 2022; Khoo *et al.,* 2021) . To address these adverse effects, a reverse logistics strategy was introduced. This strategy comprises planning, execution, and management of waste processes aimed at extracting residual values from end-of-life products (Valenzuela *et al.,* 2021; Stallkamp *et al.,* 2022). This is particularly advantageous as it reduces energy and raw material demands while mitigating the adverse effects of plastic waste (Kilic, Cebeci and Ayhan, 2015). According to a prior examination, reverse logistics network design simply refers to a strategic or long-term process of determining waste management facilities' quantity, location, and allocation (Valenzuela *et al.,* 2021). The network aims to reduce overall expenditures while considering additional considerations, such as environmental and social aspects (Govindan, Paam and Abtahi, 2016).

The absence of comprehensive and accurate data on reverse logistics requires the consideration of uncertain variables or parameters when making decisions regarding the networks (Rahimi and Ghezavati, 2018). To address these uncertainties, it was recommended that the reverse logistics network incorporate a robust design (Pishvaee, Rabbani and Torabi, 2011). Uncertainty conditions have prevailed in different regions, particularly in Jakarta, a city generating approximately eight thousand tons of plastic waste daily (Kristanto, Jansen and Koven, 2020). Following this, the Ministry of Environment and Forestry in Indonesia has stated that the availability and accuracy of data for plastic waste in Jakarta are currently sporadic and vary (Ministry of Environment and Forestry, 2020).

Previous studies on reverse logistics network design have utilized mathematical models for multi-product design primarily. These studies were observed to utilize specific parameters and single objective functions (Sadrnia, Langarudi, and Sani, 2020; Paydar and Olfati, 2018; Kilic, Cebeci, and Ayhan, 2015). Therefore, this study aims to develop a reverse logistics network design model for plastic waste management in Jakarta using a robust optimization method. The model has several objectives, including minimizing costs, reducing carbon emissions, and creating employment opportunities while optimizing the network. It is essential to acknowledge that this study expands a previous work comprising a mixed-integer programming model for designing a reverse logistics network dedicated to plastic waste management in urban settings (Nurkamila and Ardi, 2022). Our current study utilizes a robust optimization approach, and its results could serve as the foundation to provide essential insights to aid the government in decision-making.

2. Literature Review

2.1. Plastic Waste Management in Indonesia

Plastic waste management refers to the systematic handling, collection, disposal, recycling, and overall regulation of plastic materials to minimize environmental impact, promote sustainability, and mitigate the adverse effects of plastic pollution. This definition aligns with what was posited in the Government Regulation of Indonesia Number 81 of 2012 on the Management of Household and Household-like Wastes. Here, it was established that the handling of all waste, including plastic, comprises a series of processes, namely sorting, collection, transportation, processing, and ultimate waste disposal. Accordingly, these processes were executed at designated facilities such as temporary dumping places (TPS), final landfills (TPA), Waste Banks, Hoarders, and Recyclers.

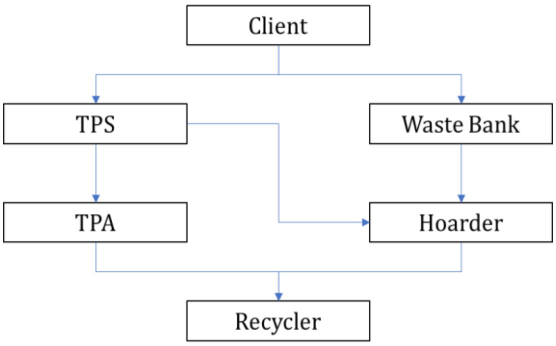

Figure 1 Reverse logistics network of plastic waste management in Indonesia

Initiating the reverse logistics network for plastic waste in Indonesia comprised the transfer of plastic waste to designated facilities, including Waste Banks or temporary dumping places, informally known as "TPS" in Indonesia. This process extends from the point of origin to the recycling phase at the Recycler. Figure 1 shows a schematic representation of the reverse logistics network for plastic waste in Indonesia (Ministry of Environment and Forestry, 2020).

2.2. Reverse Logistics Network Design of Plastic Waste

The importance of the circular economy and sustainability underscore the significance of reverse logistics for plastic waste (Valenzuela *et al.*, 2021). A reverse logistics network design comprises strategic decisions concerning waste management facilities, allocation, and product movement, including opening or closing facilities.

Many previous works developed plastic waste reverse logistics analysis using mathematical models, particularly emphasizing the use of mixed-integer linear programming (Demirel, Demirel and Gökçen, 2016). Accordingly, some studies have utilized robust optimization models (Xu *et al.*, 2021). Some of the objective functions of these models have considered the environmental (Bing *et al.*, 2015; Trochu, Chaabane and Ouhimmou, 2020), economic (Galvez *et al.*, 2015), and social (Pedram *et al.*, 2017) impact. In this regard, the objective function, incorporating environmental considerations, was oriented towards minimizing emissions and mitigating production processes that harm the environment within the logistics network (Safdar *et al.*, 2020). A specific environmental consideration in a previous study was the reduction of the costs of carbon dioxide emission associated with the processing and transportation of plastic waste products within the networks (Bing, Bloemhof-Ruwaard, and van der Vorst, 2014).

Moreover, the objective function, incorporating economic considerations, is concerned with assessing the impact of various cost components on the profitability or lack thereof of the network (Safdar *et al.*, 2020). An economic consideration aimed to minimize the fixed costs associated with facility construction, processing costs at hoarder centers and all reprocessing facilities, manufacturing and material costs, shortage costs, and transportation costs. The study aimed to decrease the entire cost of a closed-loop supply chain (Pourjavad and Mayorga, 2018). Finally, the objective function incorporating social aspects focused on how to enhance social responsibility (Pedram *et al.*, 2017).

It is essential to acknowledge that only a few studies have considered the collective impact of the triple bottom line, namely economic, environmental, and social (Safdar *et al.*, 2020). Most studies considered either only the economic aspect (Roudbari, Ghomi, and Sajadieh, 2021; Xu *et al.*, 2017; Kilic, Cebeci, and Ayhan, 2015) or economic and environmental aspects (Xiao *et al.*, 2019; Yu and Solvang, 2016). In addition, several models have also considered uncertainty (Roudbari, Ghomi, and Sajadieh, 2021; Sadrnia, Langarudi and Sani, 2020; Xu *et al.*, 2017).

3. Methodology

This study is an extension of an initial work (Nurkamila and Ardi, 2022) where the objective was only to minimize cost. The current study introduces three objective functions: minimizing costs, reducing gas emissions, and maximizing job creation. Under this, the study commenced with data collection through a literature review on reverse logistics network design and reverse logistics network applied for managing plastic waste in Jakarta. The methodology is shown in Figure 2.

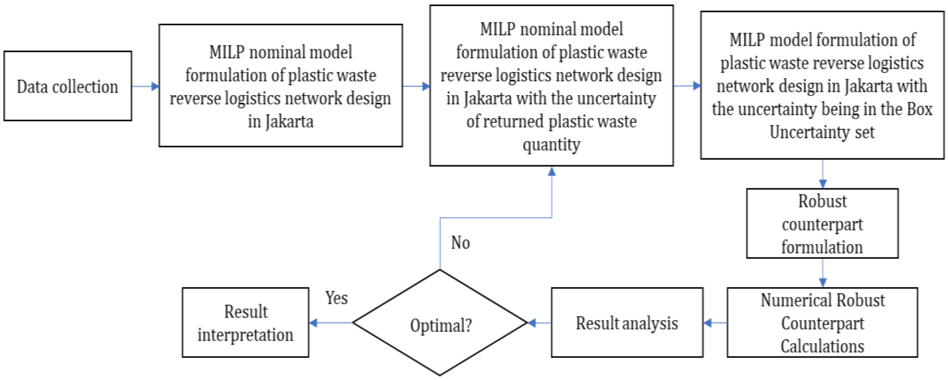

Figure 2 Methodology

3.1. Mixed Integer Linear Programming

Linear programming is an optimization method that addresses problems with objective functions, constraints, and decision variables in linear functions (Safdar *et al.*, 2020). It is the most widely used method for improving supply chain management in the context of the agri-food supply chain (Deepradit, Ongkunaruk and Pisuchpen, 2020). Furthermore, it could solve routing and planning ocean transportation (Soegiharto *et al.*, 2022). Previous works have adopted linear programming to optimize the plastic waste management network with specific consideration of costs (Castro-Amoedo *et al.*, 2021).

3.2. Robust Optimization

Robust Optimization is a method for handling data uncertainty, which is presumed to be encapsulated within a designated uncertainty set (Gorissen, Yanikoglu and den Hertog, 2015). This method could function reliably even under unfavorable circumstances, offering the best alternative in the worst-case situation (Ben-Tal, Ghaoui, and Nemirovski, 2009). The general linear programming model is shown by equation (1) as follows:

$$\min_{x}\{c^T x : Ax \geq b\} \quad (1)$$

where $c \in \mathbb{R}^n, x \in \mathbb{R}^n, A \in \mathbb{R}^{m\times n}, b \in \mathbb{R}^m$. By assuming that all the parameters (c, A, b) are uncertain and the parameters are in a primitive uncertainty set $\mathcal{U}$, the general form of linear programming with uncertainty becomes defined (Gorissen, Yanikoglu and den Hertog, 2015). The general uncertain linear programming then resembles as equation (2):

$$\min_{x}\{c^T x : Ax \geq b | (c, A, b) \in \mathcal{U}\} \quad (2)$$

Assume that the box uncertainty set $\mathcal{U}_{box} = \{\zeta : ||\zeta||\infty \leq \mu | \mu > 0\}$ where $\zeta \in \mathbb{R}^L$ contains each uncertain parameter. By removing the uncertainty from problems, robust optimization creates a single deterministic problem known as a robust counterpart. As a result, the following definition, as shown in equation (3) applies to a robust counterpart for an uncertain linear programming problem:

$$\min_{x}\{c^T x : a_i^T x + \mu\|P^T x\|_1 \geq b_i, \forall i = 1,2,3, \dots, m\} \quad (3)$$

3.3. Nominal Model for Jakarta Plastic Waste Management Reverse Logistics Network

The design of the plastic waste reverse logistics network in Jakarta was prototyped using a mathematical model. Before creating the mathematical model, this study proposed a conceptual model that could represent real systems. Following this, the conceptual model for reverse logistics network design for managing plastic waste in Jakarta is shown in Figure 3. This model consists of several assumptions including *c* Clients, *w* Waste Banks, *s* TPSs, *h* Hoarders, *r* Recyclers, and *a* TPAs.

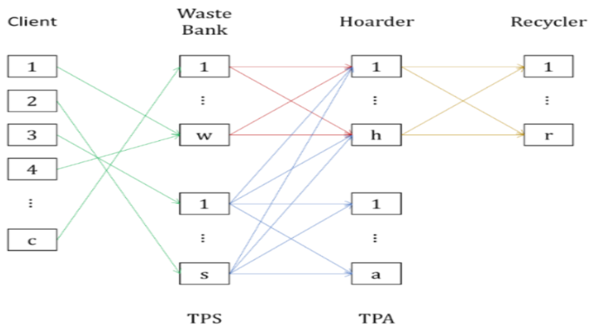

Figure 3 The conceptual model of Jakarta plastic waste management reverse logistics

The model of the reverse logistics network introduced in previous studies (Roudbari, Ghomi, and Sajadieh, 2021; Safdar *et al.*, 2020; Xu *et al.*, 2017) served as the basis for the nominal model proposed in this study. Sets, parameters, and decision variables are shown from Table 1 to Table 3.

Table 1 Definition of the model sets

Set	Definition	Index	Unit	Set	Definition	Index	Unit
P	Plastic	p	kg	H	Hoarder	h	unit
C	Client	c	unit	R	Recycler	r	unit
W	Waste Bank	w	unit	A	TPA	a	unit
S	TPS	s	unit				

Table 2 Definition of the model parameters

Parameter	Definition	Unit
Q_{pc}	Amount of plastic p returned by a Client c	kg
FP_{pw}	The expense of processing plastic p in Waste Bank w	rupiah/kg
FP_{ps}	The expense of processing plastic p in TPS s	rupiah/kg
FP_{ph}	The expense of processing plastic p in Hoarder h	rupiah/kg
FP_{pr}	The expense of processing plastic p in Recycler r	rupiah/kg
FP_{pa}	The expense of processing plastic p in TPA a	rupiah/kg
KK	Vehicle's capacity	kg
D_{cw}	The range among Client c and Waste Bank$w$	km
D_{cs}	The range among Client c and TPS s	km
D_{wh}	The range among Waste Bank w and Hoarder h	km
D_{sh}	The range among TPS s and Hoarder h	km
D_{sa}	The range among TPS s and TPA a	km
D_{hr}	The range among Hoarder h and Recycler r	km
FT	Transportation Cost	rupiah/kg
FL_w	Cost of choosing Waste Bank w	rupiah
FL_s	Cost of choosing the TPS s	rupiah
FL_h	Cost of choosing the Hoarder h	rupiah
FL_r	Cost of choosing the Recycler r	rupiah
FL_a	Cost of choosing the TPA a	rupiah
ET	Carbon emissions from transportation	m^3/km
KO_{pw}	Quantity of plastic p processed by one worker at Waste Bank w	kg/person

Parameter	Definition	Unit
KO_{ps}	Quantity of plastic p processed by one worker at TPS s	kg/person
KO_{pa}	Quantity of plastic p processed by one worker at TPA a	kg/person
KO_{ph}	Quantity of plastic p processed by one worker at Hoarder h	kg/person
KO_{pr}	Quantity of plastic p processed by one worker at Recycler r	kg/person
OK_{cw}	Number of personnel required to transport the trucks between Client c to Waste Bank w	person/vehicle
OK_{cs}	Number of personnel required to transport the trucks between Client c to TPS s	person/vehicle
OK_{wh}	Number of personnel required to transport the trucks between Waste Bank w to Hoarder h	person/vehicle
OK_{sh}	Number of personnel required to transport the trucks between TPS s to Hoarder h	person/vehicle
OK_{sa}	Number of personnel required to transport the trucks between TPS s to TPA a	person/vehicle
OK_{hr}	Number of personnel required to transport the trucks between Hoarder h to Recycler r	person/vehicle
KL_w	Waste Bank w capacity	kg
KL_s	TPS s capacity	kg
KL_h	Hoarder h capacity	kg
KL_r	Recycler r capacity	kg
KL_a	TPA a capacity	kg
S	Permitted fraction of plastic to be carried from TPS s to TPA a	-

Table 3 Decision variables of the model

Decision Variable	Definition	Unit
x_w	$x_w = \begin{cases} 1, \text{ if Waste Bank } w \text{ is selected} \\ 0, \text{ otherwise.} \end{cases}$	-
x_s	$x_s = \begin{cases} 1, \text{ if TPS } s \text{ is selected} \\ 0, \text{ otherwise.} \end{cases}$	-
x_h	$x_h = \begin{cases} 1, \text{ if Hoarder } h \text{ is selected} \\ 0, \text{ otherwise.} \end{cases}$	-
x_r	$x_r = \begin{cases} 1, \text{ if Recycler } r \text{ is selected} \\ 0, \text{ otherwise.} \end{cases}$	-
x_a	$x_a = \begin{cases} 1, \text{ if TPA } a \text{ is selected} \\ 0, \text{ otherwise.} \end{cases}$	-
q_{pcw}	Amount of transported plastic p from Client c to Waste Bank w	kg
q_{pcs}	Amount of transported plastic p from Client c to TPS s	kg
q_{pwr}	Amount of transported plastic p from Waste Bank w to Recycler r	kg
q_{psh}	Amount of transported plastic p from TPS s to Hoarder h	kg
q_{psa}	Amount of transported plastic p from TTPS s to TPA a	kg
q_{phr}	Amount of transported plastic p from Hoarder h to Recycler r	kg

The nominal model aims to minimize facility costs, reduce carbon emissions from transportation, and maximize job creation. Its economic, environmental, and social objectives are to reduce costs (equation 4), minimize emissions (equation 5), and maximize work generation (equation 6) respectively.

$$\min \{\sum_w FL_w x_w + \sum_s FL_s x_s + \sum_h FL_h x_h + \sum_r FL_r x_r + \sum_a FL_a x_a + \sum_p \sum_c \sum_w FP_{pw} q_{pcw} + \sum_p \sum_c \sum_s FP_{ps} q_{pcs} + \sum_p \sum_w \sum_s \sum_h FP_{ph} (q_{pwh} + q_{psh}) + \sum_p \sum_s \sum_a FP_{pa} q_{psa} + \sum_p \sum_h \sum_r FP_{pr} q_{phr} + \sum_p \sum_c \sum_w \frac{q_{pcw}}{KK} J_{cw} FT + \sum_p \sum_c \sum_s \frac{q_{pcs}}{KK} J_{cs} FT + \sum_p \sum_w \sum_h \frac{q_{pwh}}{KK} J_{wh} FT + \sum_p \sum_s \sum_h \frac{q_{psh}}{KK} J_{sh} FT + \sum_p \sum_s \sum_a \frac{q_{psa}}{KK} J_{sa} FT + \sum_p \sum_h \sum_r \frac{q_{phr}}{KK} J_{hr} FT\} \quad (4)$$

$$\min\left\{\sum_p\sum_c\sum_w \frac{q_{pcw}}{KK}J_{cw}ET + \sum_p\sum_c\sum_s \frac{q_{pcs}}{KK}J_{cs}ET + \sum_p\sum_w\sum_h \frac{q_{pwh}}{KK}J_{wh}ET + \sum_p\sum_s\sum_h \frac{q_{psh}}{KK}J_{sh}ET + \sum_p\sum_s\sum_a \frac{q_{psa}}{KK}J_{sa}ET + \sum_p\sum_h\sum_r \frac{q_{phr}}{KK}J_{hr}ET\right\} \quad (5)$$

$$\max\left\{\sum_p\sum_c\sum_w \frac{q_{pkb}}{KO_{pb}} + \sum_p\sum_c\sum_s \frac{q_{pcs}}{KO_{ps}} + \sum_p\sum_w\sum_s\sum_h \frac{(q_{pwh}+q_{psh})}{KO_{ph}} + \sum_p\sum_s\sum_a \frac{q_{psa}}{KO_{pa}} + \sum_p\sum_h\sum_r \frac{q_{phr}}{KO_{pr}} + \sum_p\sum_c\sum_w \frac{q_{pcw}}{KK}OK_{cw} + \sum_p\sum_c\sum_s \frac{q_{pcs}}{KK}OK_{cs} + \sum_p\sum_w\sum_h \frac{q_{pwh}}{KK}OK_{wh} + \sum_p\sum_s\sum_h \frac{q_{psh}}{KK}OK_{sh} + \sum_p\sum_s\sum_a \frac{q_{psa}}{KK}OK_{sa} + \sum_p\sum_h\sum_r \frac{q_{phr}}{KK}OK_{hr}\right\} \quad (6)$$

Transshipment constraints are formulated in equations (7) through (12), while the constraints in (equation 13) through (19) comprised limitations on capacity. Finally, the constraints in equation (18) and equation (19) are for defining the decision variables as binary & continuous.

$$Q_{pc} = \sum_w q_{pcw} + \sum_s q_{pcs}\ , \forall p \in P, c \in C \quad (7)$$

$$\sum_c Q_{pc} = \sum_s\sum_a q_{psa} + \sum_h\sum_r q_{hr}\ , \forall p \in P \quad (8)$$

$$\sum_h q_{pwh} = \sum_c q_{pcw}\ , \forall p \in P, w \in W \quad (9)$$

$$\sum_a q_{psa} \leq S \sum_c q_{pcs}\ , \forall p \in P, s \in S \quad (10)$$

$$\sum_h q_{psh} = \sum_c q_{pcs} - \sum_a q_{psa}\ , \forall p \in P, s \in S \quad (11)$$

$$\sum_r q_{phr} = \left(\sum_w q_{pwh} + \sum_s q_{psh}\right), \forall p \in P, h \in H \quad (12)$$

$$\sum_p\sum_c q_{pcw} \leq KL_w x_w\ , \forall\ w \in W \quad (13)$$

$$\sum_p\sum_c q_{pcs} \leq KL_s x_s\ , \forall\ s \in S \quad (14)$$

$$\sum_p\sum_w q_{pwh} + \sum_p\sum_s q_{psh} \leq KL_h x_h\ , \forall\ h \in H \quad (15)$$

$$\sum_p\sum_s q_{psa} \leq KL_a x_a\ , \forall\ a \in A \quad (16)$$

$$\sum_p\sum_h q_{phr} \leq KL_r x_r\ , \forall\ r \in R \quad (17)$$

$$x_w, x_s, x_h, x_r, x_a \in \{0, 1\} \quad (18)$$

$$q_{pcw}, q_{pcs}, q_{pwh}, q_{psh}, q_{psa}, q_{phr} \geq 0 \quad (19)$$

4. Results

4.1. Application of the Model

This study adopted a robust optimization model in a case study on plastic waste management in Jakarta, Indonesia, focusing on a specific set of plastic waste. The Jakarta reverse logistics network for plastic waste management comprises 260 Clients, 1262 Waste Banks, 1262 TPS, one TPA, 784 Hoarders, and 19 Recyclers.

The results identified the location and allocation of plastic waste from each facility by optimizing the first and second objective functions while simultaneously maximizing the third. Accordingly, approximately 40% of plastic waste was transferred from Clients to Waste Banks, with the remaining directed to TPS due to lower processing costs. In this context, TPS is generally favored over Waste Banks due to its more economical processing costs, attributed to the absence of sorting activities. As stated in the Regional Regulation of a Regency in Indonesia, the disposal costs of TPS were approximately 0.0032 USD/kg, while Waste Bank's was 0.0036 USD/kg. It is also important to establish that approximately 70% of plastic waste sent to TPS is directed to Hoarders, while the remaining 30% is routed to

TPA. On the other hand, all plastic waste entering the Waste Bank is forwarded to Hoarders, and subsequently, waste from Hoarders is channeled to Recyclers for reuse as new material.

The strategic decision to optimize plastic waste management is to open new facilities. This expansion includes the establishment of 125 Waste Banks, 154 TPS, 275 Hoarders, and 2 Recyclers, with the primary aim of enhancing the recycling capacity for plastic waste. The decision-making process was grounded in a worst-case scenario, considering uncertainties in the return of plastic waste from clients. Factors such as minimum facility costs, processing costs, transportation costs, carbon emissions, and the maximum number of workers generated at each facility were also considered. The results show that the minimum cost and emission gas are 332 million USD and 626 million m^3 (ca. 1.2 billion $kgCO_2$), respectively. Meanwhile, the maximum number of workers obtained is 611 thousand people.

5. Conclusions

This study proposed a robust optimization model designed specifically for Jakarta's reverse logistics network, addressing the effective management of plastic waste. The model incorporated the process of clients transferring waste to Waste Banks and TPS, which subsequently experienced recycling at Hoarder or disposal at TPA. Regarding tackling data uncertainty, the model considers economic, environmental, and social aspects. It also aided the determination of optimal locations and transportation routes for plastic waste in Jakarta. This study showed that the availability of several new facilities, including 125 Waste Banks, 154 TPS, and 275 Hoarders, along with two Recyclers, was essential to optimize plastic waste management. Following this, the considered uncertainty in this model was confined to the parameter of the quantity of returned plastic from consumers, which was assumed to reside within a box of uncertainties. Hence, future studies might explore additional uncertainty issues, such as facility capacity and plastic waste quality.

Acknowledgments

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