Reverse Logistics Network Design for Infected Medical Waste Management in Epidemic Outbreaks under Uncertainty: A Case Study of COVID-19 in Pathum Thani, Thailand

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Received: January 24, 2022 / Revised: February 15, 2022 / Accepted: February 28, 2022

Abstract— **Disease outbreaks cause disruption in the economy and threaten human life. This study proposes a Fuzzy Multi-Objective Multi-Period Mixed-Integer Linear Programming (FMOMILP) model for effective IMW management in outbreaks under uncertain environments considering financial and risk aspects. The strategic decision is to determine optimal locations and suitable capacity levels of temporary facilities, including temporary storage centers and temporary treatment centers, as well as optimal transportation strategies. To solve the proposed FMOMILP model, an integrated interactive fuzzy approach is employed. First, an equivalent auxiliary crisp model is used to handle the uncertainties by the feasibility degree (α) concept. The problem is solved using Fuzzy Goal Programming (FGP). A case study of the COVID-19 outbreak in Pathum Thani province in Thailand was carried out to demonstrate the proposed model's performance. The proposed method yields solutions with varying feasibility degrees and allowed percentage deviations, providing alternatives for the decision-makers. The contribution of this study helps identify the optimal setting of temporary facilities in appropriate locations and seizes and improves the performance of IMW management subject to the uncertainty of data by trading off between conflicting objectives. A comparison of the results with (optimal solution) and without (actual solution) temporary facilities is also presented.**

Index Terms—**Epidemic Logistics, Fuzzy Goal Programming, Medical Wastes, Multi-Objective Fuzzy Programming, Operational Risks, Reverse Logistics**

I. Introduction

The amount of Infected Medical Waste (IMW) increases drastically as the number of infected people exponentially increases. This leads to one important challenge in outbreaks situation, which is effective reverse logistics to manage IMW. An effective reverse logistics plan of IMW is crucial in controlling the spreading of the disease since improper collection and treatment can hugely create risk for the medical staff, patients, and communities around hospitals and treatment centers.

Coronavirus disease (COVID-19) is the most recent pandemic transmitted by human-to-human caused by a newly discovered coronavirus. On 31st December 2019, the first case was reported in Wuhan, China, and later developed into a global crisis [1]. The situation in Thailand might not be as critical as in some other countries. However, a surge in the number of infected people generates an increasing amount of IMW, which should be treated properly in a timely manner to control the risk of spreading the disease. Since the number of IMW rapidly increases, as well as the existing treatment centers' capacity is not sufficient, the decision the establishment of temporary facilities is significant in designing effective reverse logistics of IMW.

Considering the actual outbreak situation, the availability and accuracy of collected information are always problems. These uncertainties cause ineffectiveness in designing each network since the problems are no longer purely deterministic. Thus, the inclusion of the uncertainty assumptions should be effectively applied when considering such problems where a great deal of unknown and uncertain parameters exists.

In this study, considering a real situation in a province in Thailand, Pathum Thani, a Fuzzy Multi-Objective Multi-Period Mixed-Integer Linear Programming (FMOMILP) model is developed for the reverse logistics network design of IMW management in outbreaks with the purpose of improving the decisions of establishing temporary facilities with optimal locations and sizes, and determining the transportation strategies under uncertain environment.

The remainder of this paper is arranged as follows. Section 2 presents a literature review on relevant topics. Section 3 contains the problem description and mathematical formulation. Section 4 proposes an integrated interactive fuzzy programming approach. Section 5 validates the proposed model and approach via a case study of COVID-19 in Pathum Thani province, Thailand. Section 6 discusses and analyses the results. Lastly, Section 7 concludes the study and states limitations and further research directions.

II. Literature Review

Our literature review would be focused on three related topics, i.e., (1) Risks in the supply chain, (2) Multi-objective fuzzy programming, and (3) Reverse logistics network model for IMW management.

A. Risks in Supply Chain

Risks in the supply chain are classified into 2 types: operational risks and disruptive risks [2]. Operational risks are concerned with risks from uncertain internal processes or external events, for example, demand uncertainties and cost uncertainties. Disruptive risks, on the other hand, are concerned with natural disasters, e.g., earthquakes, or man-made disasters. Epidemic outbreaks are one of the special cases of supply chain disruptive risk, which has dynamic nature over many regions, i.e., SARS, Ebola, and the latest one, which is COVID-19.

Risk is an abstract concept that is hard to evaluate accurately. Cheng and Yu [3] proposed a fuzzy comprehensive evaluation with the Delphi method to evaluate and assign weight to the risks in emergency logistics. Sherali et al. [4] developed a branch-and-bound framework to minimize weighted and mitigate risks arising from the post-disaster. Considering multi-objective problems, Nolz et al. [5] presented a post-disaster problem considering transportation risk and location risk as one of the objectives. Three approaches to measuring risks were analyzed and the unreachability approach turned out to be the most suitable one for this problem. Abkowitz and Cheng [6] proposed a methodology for estimating costs and risks in hazardous waste transportation optimization. Several causes of accidents and their consequences were used in evaluating the risk.

B. Multi-Objective Fuzzy Programming

In a real situation, data are not always known or accurately obtained since there might be all kinds of unpredictable impacts from both environmental uncertainty and system uncertainty. As the outbreak nature is dynamic and there are several unpredictable conditions, uncertainties arise in various parameters such as disease transmission rate and recovery rate. As a result, Linear Programming (LP) based on crisp values is no longer capable to solve such problems. So, the fuzzy theory has been introduced to deal with problems containing uncertainties.

In addition, real-world problems are quite complex and usually contain more than one objective. Conflicting among objectives is a common problem in many cases, so there is no ideal outcome, which can improve all objectives concurrently [7], [8]. To solve these conflictive multi-objective programming problems, several approaches have been proposed based on the flexibility and ability to play with the degree of satisfaction among objectives of fuzzy programming approaches. Fuzzy programming approaches can start from preliminary methods such as weighted max-min, weighted additive, and Zimmermann methods. However, the solutions generated by these methods might not be efficient or practical [9]. Thus, several methods have been developed to generate more effective results. Interactive Fuzzy Linear Programming (i-FLP) is one of the methods developed to consider efficiency and user dependency in generating satisfactory outcomes. The i-FLP has the advantage of assisting decision-makers in obtaining preferable solutions at various levels of feasibility. To make the method interactive, different approaches have been implemented such as Torabi and Hassini (TH) method, Selim and Ozkarahan (SO) method, and the Jimenez approach. Each method has its own advantages and disadvantages subject to its application in each situation.

Goal Programming (GP) is a part of linear programming that can solve multiple objectives. It was first introduced by Charnes et al. [10]. Charnes and Cooper [11] later provided a more precise definition. Because of its effectiveness, it has been widely used in a variety of research [12]. Traditional goal programming requires precise determination of aspiration levels and weights in order to minimize deviations. However, due to incomplete information and uncertain natures, it is difficult to determine these values precisely in practice. Therefore, Fuzzy Goal Programming (FGP) was developed to deal with fuzziness in the aspiration levels. Several FGP approaches were developed. For example, Narasimhan [13] developed an FGP approach considering both fuzziness in aspiration levels and weights. Later, Rubin and Narasimhan [14] proposed

a nested hierarchy approach to assign the priorities of each goal. Then, Arora and Gupta [15] developed a bilevel interactive FGP that incorporates the concept of tolerance.

C. Reverse Logistics Network Model for IMW Management

Recently, medical waste management during epidemic outbreaks has become more popular among researchers. This medical waste management is vital in designing effective waste management since it can help in controlling the spreading of diseases. The first known concept of Reverse Logistics (RL) was proposed by Stock [16] as the backward flow with the role of managing materials, recycling materials, and disposing of wastes. In another word, reverse logistics considers the flow starting from End-of-Use (EOU) products to the recovery of those products. Fleischmann et al. [17] analyzed the impact of the return flow and developed a Mixed-Integer Linear Programming (MILP) model, which was commonly used in further Closed-Loop Supply Chains (CLSC) problems.

The very first research of multi-objective reverse logistics associated with waste management was proposed by Shih and Lin [18] where the developed MILP and a dynamic programming model were employed to determine optimal routing and scheduling in managing IMW in Taiwan. Their models considered both ecological aspects and risks associated with transportation, which have been widely used in later research. Budak and Ustundag [19] proposed a MILP model to decide the suitable number of facilities and their locations for establishing an effective reverse logistics of wastes in Turkey. By considering an environmental impact, Alshraideh and Qdais [20] developed a stochastic model to optimize a capacitated vehicle routing schedule for of collection of medical wastes considering both transportation costs and the amount of gas emission. Mantzaras and Voudrias [21] proposed a nonlinear model to minimize the costs corresponding to the management of IMW in Greek. Temporary facilities are one important strategic decision in recent research. In addition, risks of disease spreading whether from hospitals or from transportation are considered a critical issue [22].

Regarding the uncertainty of the data arising from a limitation of data availability and imprecise in operations, much research has implemented fuzzy concepts to handle these uncertainties. For example, Negarandeh and Tajdin [23] developed a MOMILP model to manage wastes from hospitals considering profitability, environmental impact, social impact, and resilience of the network under uncertain environments. They implemented robust fuzzy programming to cope with uncertainty where LP-metric and goal programming were used to find efficient results from conflicting objectives.

A summary of the literature on the reverse logistics of IMW is presented in Table I. It is clearly seen that previous works are still limited. Therefore, the purpose of this study is to develop a fuzzy multi-objective multi-period mixed-integer linear programming model for designing an effective reverse logistics network for IMW in outbreaks. The proposed model's objectives are to minimize total costs, risks at hospitals, and risks from transportation and treatments. The strategic decisions involve the establishment of temporary facilities, the size of the temporary treatment center, and the flow of the IMW. An integrated interactive fuzzy approach is employed to handle uncertainties in the costs and capacity of the facilities. By doing so, the optimal solutions can be generated to create a preferable trade-off among conflicting objectives under different degrees of feasibility. This study can assist the decision-makers in making better strategic decisions in designing the reverse logistics network for IMW in outbreaks under uncertain environments. The main contributions of this paper can be summarized as follows:

- This study proposed a fuzzy multi-objective multi-period mixed-integer linear programming model for designing an effective reverse logistics network for IMW in outbreaks considering data uncertainty and conflicting objectives (both financial efficiency and risks in operations).
- To handle the uncertainty of the data and balance the trade-off between conflicting objectives, an integrated interactive fuzzy approach is applied. Jimenez's approach is applied to handle the uncertainty with the feasibility concept. The Fuzzy Goal Programming (FGP) method is then used to generate effective solutions that assist decision-makers in making effective strategic decisions.
- To the best of our knowledge, this study is the first of its kind to integrate the Jimenez approach; and the Fuzzy Goal Programming (FGP) method to solve the reverse logistics network of IMW in outbreaks under an uncertain environment.

TABLE I
SUMMARY OF RELATED RESEARCH

References	Model specification			Objectives			Problem formulation	Optimization
	Multi-objectives	Multi-periods	Data uncertainty	Financial aspect	Risk	Others		
Shih and Lin (2003)	x	x	-	x	x	-	DP, ILP	Multiple criteria optimization
Alshraideh and Qdais (2016)	x	x	-	x	-	x	MILP	Genetic algorithm
Budak and Ustundag (2017)	-	x	-	x	-	-	MILP	Solver software
Mantzara and Voudrias (2017)	-	x	-	x	-	-	MINLP	Solver software
Yu et al. (2020)	x	x	-	x	x	-	MOMILP	Interactive fuzzy approach
Kargar et al (2020)	x	-	-	x	x	x	MOMILP	Revised Multi-Choice Goal programming method
Negarandeh and Tajdin (2021)	x	-	x	x	-	x	RMOMILP	Chance Constraint Fuzzy Programming (CCFP) Improved Goal programming LP-metric
Zhao et al. (2021)	x	-	x	x	x	-	RMOMILP	Goal programming lexicographic weighted Tchebycheff AUGMECON
This study	x	x	x	x	x	-	FMOMILP	Integrated interactive fuzzy approach

Abbreviations: DP: Dynamic programming, ILP: Integer linear programming, MILP: Mixed-integer linear programming, MOMILP: Multi-objective mixed-integer linear programming, MINLP: Multi-objective stochastic mixed-integer nonlinear programming, RMOMILP: Robust multi-objective mixed-integer linear programming, FMOMILP: Fuzzy multi-objective mixed-integer linear programming.

III. Problem Description and Mathematical Model

A. Problem Description

In order to design an effective reverse logistics network of IMW in outbreak circumstances under uncertain environments, the principal challenge is to balance between financial efficiency and risks that arise from operations, which include the risk of disease spreading at the hospitals, storage centers, treatment centers, and along the transportation routes. Unlike any normal reverse logistics network design, the amount of IMW dramatically increases in a very short horizon due to the outbreak. To handle this situation, the framework of the proposed reverse logistics network design for IMW management in outbreak circumstances is presented in Fig. 1. The network consists of hospitals, existing treatment centers, and temporary facilities, including temporary storage centers and temporary treatment centers. Considering the rapid increase of IMW generated during outbreaks, temporary facilities help in providing adequate capacity for the treatment of the IMW. A FMOMILP model is presented to optimize the decisions of locations in establishing the temporary facilities, deciding the suitable size of temporary treatment centers, and determining the optimal flow of amount of IMW transferred among the facilities.

The problem assumptions are as follows:

• A set of capacity levels is provided to be chosen for each candidate location as temporary treatment centers. Each level is subject to a particular capacity limitation and incurs a particular installation cost.

• There is a lower limit on the utilization of facilities to be considered in each period.

• All uncertain parameters are assumed to have fuzziness under the triangular distribution.

• The total costs have a higher priority over the risk impact due to the preference of the decision-makers.

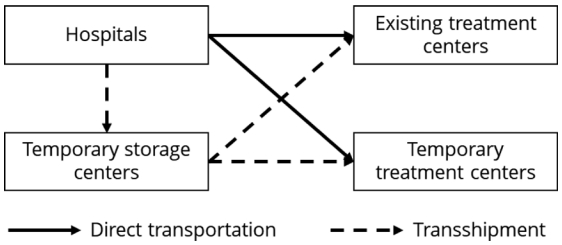

Fig. 1. The framework of the reverse logistics for IMW in outbreak circumstance.

B. Mathematical Model

1) Notations

The notations used in the mathematical model of the facility location problem are expressed as follows:

Please be noted, the symbol (~) represents the uncertain parameters in this model.

• Indexes

h Hospitals as well as other sources of medical waste

t Candidate locations for temporary storage centers

e Existing treatment centers

d Candidate locations for temporary treatment centers

p Periods

n Capacity levels

• Parameters

$PbAh_h$ Risk probability at hospital h

$PbAt_t$ Risk probability at temporary storage center t

$PbAe_e$ Risk probability at existing treatment center e

$PbAd_d$ Risk probability at temporary treatment center d

$PbTht_{ht}$ Probability of transportation risk between hospital h and temporary storage center t

$PbTte_{te}$ Probability of transportation risk between temporary storage center t and existing treatment center e

$PbTtd_{td}$ Probability of transportation risk between temporary storage center t and temporary treatment center d

$PbThe_{he}$ Probability of transportation risk between hospital h and existing treatment center e

$PbThd_{hd}$ Probability of transportation risk between hospital h and temporary treatment center d

$Npat^p{}_h$ Number of patients in hospital h in period p

$Popt_t$ Population exposure at temporary storage center t

$Pope_e$ Population exposure at existing treatment center e

$Popd_d$ Population exposure at temporary treatment center d

$PopTht_{ht}$ Population exposure from transportation between hospital h and temporary storage center t

$PopTte_{te}$ Population exposure from transportation between temporary storage center t and existing treatment center e

$PopTtd_{td}$ Population exposure from transportation between temporary storage center t and existing treatment center d

$PopThe_{he}$ Population exposure from transportation between hospital h and existing treatment center e

$PopThd_{hd}$ Population exposure from transportation between hospital h and existing treatment center d

RI Infection rate of the disease

$\widetilde{Gw_h^p}$ Quantity of IMW generated at hospital h in period p

$Caph_h$ Maximum capacity of IMW collection room in hospital h

$\widetilde{Capt_t}$ Capacity of temporary storage center t

$\widetilde{Cape_e}$ Capacity of existing treatment center e

$\widetilde{Capd_{dn}}$ Capacity of temporary treatment center d with capacity level n

LBe_e Minimum quantity requirement of operating an existing treatment center e

LBd_d Minimum quantity requirement of operating a temporary treatment center d

$\widetilde{inst_t}$ Cost of installing temporary storage center t

$\widetilde{insd_{dn}}$ Cost of installing temporary treatment center d with capacity level n

$\widetilde{pct_t}$ Cost of processing one unit of IMW at temporary storage center t

$\widetilde{pce_e}$ Cost of processing one unit of IMW at existing treatment center e

$\widetilde{pcd_d}$ Cost of processing one unit of IMW at temporary treatment center d

$\widetilde{tcht_{ht}}$ Cost of transporting one unit of IMW between hospital h and temporary treatment center t

$\widetilde{tcte_{te}}$ Cost of transporting one unit of IMW between temporary storage t and existing treatment center e

$\widetilde{tctd_{td}}$ Cost of transporting one unit of IMW between temporary storage t and temporary treatment center d

$\widetilde{tche_{he}}$ Cost of transporting one unit of IMW between hospital h and existing treatment center e

$\widetilde{tchd_{hd}}$ Cost of transporting one unit of IMW between hospital h and temporary treatment center d

• Decision Variables

Yt_t 1 if a temporary storage center is established at location t; 0 otherwise

Yd_{dn} 1 if a temporary treatment center with capacity level n is established at location d; 0 otherwise

$OTpe_e^p$ 1 if an existing treatment center e is operated in period p; 0 otherwise

$OTpd_d^p$ 1 if a temporary treatment center d is operated in period p; 0 otherwise

UQ_h^p Quantity of uncollected IMW at hospital h in period p

Qt_t^p Quantity of IMW stored at temporary storage center t in period p

Qe_e^p Quantity of IMW treated at existing treatment cnter e in period p

Qd_d^p Quantity of IMW treated at temporary treatment center d in period p

$QTht_{ht}^p$ Quantity of IMW transported from hospital h to temporary storage center t in period p

$QTte_{te}^p$ Quantity of IMW transported from temporary storage center t to existing treatment center e in period p

$QTtd_{td}^p$ Quantity of IMW transported from temporary storage center t to temporary treatment center d in period p

$QThe_{he}^p$ Quantity of IMW transported from hospital h to existing treatment center e in period p

$QThd_{hd}^p$ Quantity of IMW transported from hospital h to temporary treatment center d in period p

2) Mathematical Model

A mathematical model of a reverse logistic network of IMW in outbreak circumstance is formulated as follows:

• Objective functions

The mathematical model aims to balance the trade-off between financial performance and the risks from operations in drastic increases of IMW in outbreak circumstances.

$$Min\ z_1 = \sum_{t=1}^{T} Yt_t\, \widetilde{inst}_t + \sum_{d=1}^{D} Yd_{dn}\, \widetilde{insd}_{dn} + \sum_{t=1}^{T}\sum_{p=1}^{P} \widetilde{pct}_t Qt_t^p + \sum_{e=1}^{E}\sum_{p=1}^{P} \widetilde{pce}_e Qe_e^p + \sum_{d=1}^{D}\sum_{p=1}^{P} \widetilde{pcd}_d Qd_d^p + \sum_{h=1}^{H}\sum_{t=1}^{T}\sum_{p=1}^{P} \widetilde{tcht}_{ht}\, QTht_{ht}^p + \sum_{t=1}^{T}\sum_{e=1}^{E}\sum_{p=1}^{P} \widetilde{tcte}_{te}\, QTte_{te}^p + \sum_{t=1}^{T}\sum_{d=1}^{D}\sum_{p=1}^{P} \widetilde{tctd}_{td}\, QTtd_{td}^p + \sum_{h=1}^{H}\sum_{e=1}^{E}\sum_{p=1}^{P} \widetilde{tche}_{he}\, QThe_{he}^p + \sum_{h=1}^{H}\sum_{d=1}^{D}\sum_{p=1}^{P} \widetilde{tchd}_{hd}\, QThd_{hd}^p \quad (1)$$

The first objective function as presented in Equation (1) represents the total costs of the reverse logistics network of IMW. The first and the second terms are installation costs of temporary facilities. The third is the processing cost at the temporary storage center. The fourth and the fifth terms are treatment costs. The other terms are transportation costs in the network.

The risks from operations are measured by a risk estimation model proposed by Nema and Gupta [24] where it concerns the probability of occurrence and the consequence of the risk.

$$Risk = Probability \times Consequence \quad (2)$$

Two objective functions including risk at hospials and risk from transportation and treatment are formulated as shown in Equation (2). The risks are unitless, with the higher the risks, the greater the possibility of disease spreading.

$$Min\ z_2 = \sum_{p=1}^{P}\sum_{h=1}^{H} PbAh_h\, UQ_h^p\, Npat_h^p\, RI \quad (3)$$

The second objective function as presented in Equation (3) represents the risk at the hospitals where a great amount of IMW is generated in a very short horizon. According to Yu et al. [25], the probability of accidental risk at the hospitals is estimated by experts. The consequence of accidental risk at the hospital ($PbAh_h$) is corresponding to the uncontrolled amount of IMW (UQ_h^p) the number of patients at the hospital ($Npat_h^p$), and the spreading rate of the disease (RI). This objective aims to minimize the quantity of uncollected IMW at the hospital to reduce the risk of disease spreading to medical staff, patients, and the community around the hospital.

$$Min\ z_3 = \sum_{h=1}^{H}\sum_{t=1}^{T}\sum_{p=1}^{P} PbTht_{ht}\, QTht_{ht}^p PopTht_{ht} + \sum_{t=1}^{T}\sum_{e=1}^{E}\sum_{p=1}^{P} PbTte_{te}\, QTte_{te}^p PopTte_{te} + \sum_{t=1}^{T}\sum_{d=1}^{D}\sum_{p=1}^{P} PbTtd_{td}\, QTtd_{td}^p PopTtd_{td} + \sum_{h=1}^{H}\sum_{e=1}^{E}\sum_{p=1}^{P} PbThe_{he}\, QThe_{he}^p PopThe_{he} + \sum_{h=1}^{H}\sum_{d=1}^{D}\sum_{p=1}^{P} PbThd_{hd}\, QThd_{hd}^p PopThd_{hd} + \sum_{t=1}^{T}\sum_{p=1}^{P} PbAt_t\, Qt_t^p Popt_t + \sum_{e=1}^{E}\sum_{p=1}^{P} PbAe_e\, Qe_e^p Pope_e + \sum_{d=1}^{D}\sum_{p=1}^{P} PbAd_d\, Qd_d^p Popd_d \quad (4)$$

The third objective function as presented in Equation (4) represents the risk associated with transportation and treatment of IMW The transportation risks are calculated by the probability of accidents along the route and the consequence of accidents along the route. According to Yu et al. [25], the probability of accidents along the route is corresponding to the probability of accidents ($PopT$) and the amount of IMW transported (QT). For processing risk at the storage center and treatment risk, the consequences are corresponding to the amount of IMW at the facilities (Q), and population exposure (Pop).

• Constraints

$$UQ_h^p = \widetilde{Gw_h^p} + UQ_h^{p-1} - \sum_{t=1}^{T} QTht_{ht}^p - \sum_{e=1}^{E} QThe_{he}^p - \sum_{d=1}^{D} QThd_{hd}^p,\ \forall h, p \quad (5)$$

$$Qt_t^p = Qt_t^p + \sum_{h=1}^{H} QTht_{ht}^p - \sum_{e=1}^{E} QTte_{te}^p - \sum_{d=1}^{D} QTtd_{td}^p,\ \forall t, p \quad (6)$$

$$Qe_e^p = \sum_{t=1}^{T} QTte_{te}^p + \sum_{h=1}^{H} QThe_{he}^p, \forall e, p \quad (7)$$

$$Qd_d^p = \sum_{t=1}^{T} QTtd_{td}^P + \sum_{h=1}^{H} QThd_{hd}^p, \forall d\ , p \quad (8)$$

Equations (5) and (6) balance the flow among facilities in the network. Equations (7) and (8) calculate amount of IMW received at existing treatment centers and temporary treatment centers, respectively.

$$UQ_h^p \le Caph_h, \forall h\ , p \quad (9)$$

$$Qt_t^p \le Yt_t \widetilde{Capt}_t, \forall t, p \quad (10)$$

$$Qe_e^p \le OTpe_e^p \widetilde{Cape}_e, \forall e, p \quad (11)$$

$$Qe_e^p \ge LBe_e OTpe_e^p \widetilde{Cape}_e, \forall e, p \quad (12)$$

$$Qd_d^p \le OTpd_d^p \widetilde{Capd}_d, \forall d, p \quad (13)$$

$$Qd_d^p \ge LBd_d\ OTpd_d^p\ \widetilde{Capd}_d, \forall d, p \quad (14)$$

Equation (9) ensures that the quantity of uncollected IMW does not exceed the capacity of the hospitals. Equations (10), (11), and (13) ensure the amount of IMW does not exceed the capacity of the facilities. Equations (12) and (14) represent a lower limit of IMW receiving at each facility.

$$OTpd_d^p \le \sum_{n=1}^{N} Yd_{dn}, \forall d, p \quad (15)$$

$$\sum_{n=1}^{N} Yd_{dn} \le 1, \forall d \quad (16)$$

Equations (15) ensures that a temporary facility cannot operate if it is not established. Equation (16) imposes that only one capacity level is chosen for a temporary treatment center. Equations (17) - (21) are non-negativity and binary constraints.

$$Yt_t, Yd_{dn}, \in \{0,1\}, \ \forall t, d, n \quad (17)$$

$$OTpe_e^p, OTpd_d^p \in \{0,1\}, \forall e, d, p \quad (18)$$

$$UQ_h^p, Qt_t^p \ge 0, \forall h, t, p \quad (19)$$

$$Qe_e^p, Qd_d^p \ge 0, \forall e, d, p \quad (20)$$

$$QTht_{ht}^p, QTte_{te}^p, QTtd_{td}^p, QTtd_{td}^p, QThd_{hd}^p \ge 0, \forall h, t, e, d, p, n \quad (21)$$

IV. Proposed Solution Approach

According to the uncertain environment of a reverse logistics network of IMW in outbreak circumstance, some uncertain parameters (i.e., IMW generated, costs and facilities' capacity) are described by triangular fuzzy numbers. In order to deal with such uncertainties, an integrated interactive fuzzy approach is applied. In the first phase, an equivalent auxiliary crisp model of Jimenez et al. [26] is used to turn a fuzzy number into a crisp number. In the second phase, FGP method is applied to generate the best solution based on the priority of the objectives. The flow chart of the proposed approach is presented in Fig. 2.

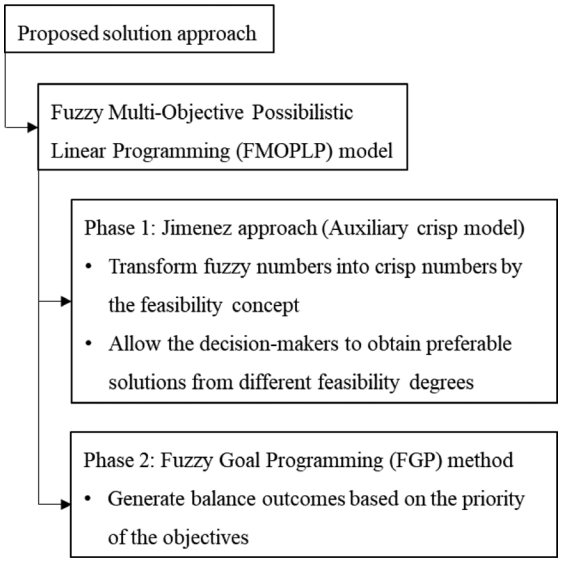

Fig. 2. Flow chart of the proposed solution approach.

A. Solving Fuzzy Multi-Objective Possibilistic Linear Programming (FMOPLP) Model

The Possibilistic Linear Programming (PLP) approach is used to handle the uncertainty and ill-known parameters. The imprecise parameters in our study include the amount of IMW generated, all related costs, and the facilities' capacity in which they are depicted by triangular fuzzy numbers. Each number is composed of three prominent data points which are the optimistic value point (a^o), the most likely value point (a^m), and the pessimistic value point (a^p) as shown in Fig. 3.

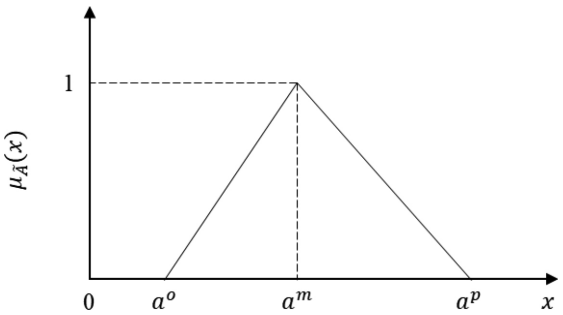

Fig. 3. Triangular distribution of ã

1) Phase 1: Auxiliary Crisp Model

The proposed reverse logistics network of IMW in the outbreak circumstance model contains fuzzy parameters that mimic the uncertainty of the practical environment in such a situation. By applying Jimenez et al. [26] approach, an interactive approach, the fuzzy possibilistic linear programming model is transformed into an auxiliary crisp model with several feasibility degrees (α levels) based on the preference of the decision-makers. Moreover, this method provides computational efficiency since it maintains the models' linearity without increasing the number of objective functions.

To convert PLP model into an auxiliary crisp model, firstly, the membership function $\mu_{\tilde{a}}(x)$ of is defined as follows:

$$\mu_{\tilde{a}}(x) = \begin{cases} f_a(x) = \frac{x - a^o}{a^m - a^o}, \ if \ a^o \le x \le a^m \\ 1 \ \ if \ x = a^m \\ g_a(x) = \frac{a^p - x}{a^p - a^m}, \ if \ a^m \le x \le a^p \\ 0 \ otherwise \end{cases} \quad (22)$$

According to Heilpern [27], the expected interval of a triangular fuzzy number $\tilde{a}$, denoted EI($\tilde{a}$), and the expected value of a triangular fuzzy number $\tilde{a}$, denoted EV($\tilde{a}$), are calculated as follows:

$$EI(\tilde{a}) = [E_1^a, E_2^a] = \left[\int_0^1 f_a^{-1}(x)dx, \int_0^1 g_a^{-1}(x)dx\right] = \left[\left(\frac{a^o + a^m}{2}\right), \left(\frac{a^m + a^p}{2}\right)\right] \quad (23)$$

$$EV(\tilde{a}) = \frac{E_1^a + E_2^a}{2} = \frac{a^o + 2a^m + a^p}{4} \quad (24)$$

As determined by Jimenez [28], for any two fuzzy numbers $\tilde{a}$ and $\tilde{b}$, the degree in which $\tilde{a}$ is larger than $\tilde{b}$ is as follows:

$$\mu_M(\tilde{a},\tilde{b})=\begin{cases} 0 & if\ E_2^a - E_1^b < 0 \\ \frac{E_2^a - E_1^b}{E_2^a - E_1^b - (E_1^a - E_2^b)} & if\ 0 \in [E_1^a - E_2^b, E_2^a - E_1^b] \\ 1 & if\ E_1^a - E_2^b > 0 \end{cases} \quad (25)$$

If $\mu_M(\tilde{a},\tilde{b}) \geq \alpha$, it indicates that $\tilde{a}$ is greater than or equal to $\tilde{b}$ in a degree of α and it is represented by $\tilde{a} \geq_\alpha \tilde{b}$. From Equation (25), this is equivalent to:

$$\frac{E_2^a - E_1^b}{E_2^a - E_1^b + E_2^b - E_1^a} \geq \alpha \quad (26)$$

According to Arenas et al. [29], for any two fuzzy numbers $\tilde{a}$ and $\tilde{b}$, we say that $\tilde{a}$ is indifferent to $\tilde{b}$ in a degree of α, denoted $\frac{\alpha}{2} \leq \mu_M(\tilde{a},\tilde{b}) \leq 1 - \frac{\alpha}{2}$. This is equivalent to:

$$\frac{\alpha}{2} \leq \frac{E_2^a - E_1^b}{E_2^a - E_1^b + E_2^b - E_1^a} \leq 1 - \frac{\alpha}{2} \quad (27)$$

Fuzzy multi-objective linear programming can then be solved by the following formulations:

$$Min\ \tilde{z} = (\tilde{z}_1, \tilde{z}_2, \dots, \tilde{z}_k) = (\tilde{c}_1 x, \tilde{c}_2 x, \dots, \tilde{c}_k x) \quad (28)$$

s.t. $\tilde{a}_i x \geq \tilde{b}_i, i = 1, \dots, l$

$\tilde{a}_i x = \tilde{b}_i, i = l+1, \dots, m$

$x \geq 0$

Considering Equations (26) and (27), they are equivalent to:

$$Min\ \tilde{z} = (\tilde{z}_1, \tilde{z}_2, \dots, \tilde{z}_k) = (\tilde{c}_1 x, \tilde{c}_2 x, \dots, \tilde{c}_k x) \quad (29)$$

s.t. $[(1-a)E_2^{a_i} - aE_1^{a_i}]x \geq aE_2^{b_i} + (1-a)E_1^{b_i}$, $i = 1, \dots, l$

$[(1-\frac{\alpha}{2})E_2^{a_i} - \frac{\alpha}{2}E_1^{a_i}]x \geq \frac{\alpha}{2}E_2^{b_i} + \left(1-\frac{\alpha}{2}\right)E_1^{b_i}$, $i = l+1, \dots, m$

$[\frac{\alpha}{2}E_2^{a_i} - (1-\frac{\alpha}{2})E_1^{a_i}]x \geq (1-\frac{\alpha}{2})E_2^{b_i} + \frac{\alpha}{2}E_1^{b_i}$, $i = l+1, \dots, m$

This approach enables the decision-makers to plan in an interactive manner with varying degrees of α. It provides information for the decision-makers to determine the level of feasibility that they are willing to accept.

2) Phase 2: Applying Fuzzy Goal Programming (FGP) Method

The Fuzzy Goal Programming (FGP) method is one of the most widely used methods to solve multi-objective problems due to its ability to deal with uncertainty in the data and aspiration level of objectives. The FGP method is used in this study to solve a fuzzy multi-objective problem by minimizing the deviations of the objectives with a priority among the objectives. The more important objective is regarded as having a higher priority and should be satisfied first. Each objective is assigned a priority level *k*, with the highest priority being satisfied first.

A multi-objective problem with *j* objective minimization functions can be formulated as:

$$Min\ [z_1, z_2, \dots, z_j] \quad (30)$$

s.t. Problem constraints

To illustrate the FGP method, considering a problem with three minimization objectives, where the first objective (z_1) has priority level 1, the second objective (z_2) has priority level 2, and the third objective (z_3) has priority level 3. The following is the steps in solving the FGP method:

Step 1: Solve the objective with priority level 1 (the most important objective).

$$Min\ z_1 \quad (31)$$

s.t. Problem constraints

Suppose the solution yield a minimum objective function value of $z_1 = z_1^*$.

Step 2: Solve the priority level 2's objective function subject to a deviation constraint of the priority level 1's objective function.

$$Min\ z_2 \quad (32)$$

s.t. Problem constraints

$z_1 \leq z_1^* \times (1 + d_1)$

where d_j is the percentage allowance of deviation of the objective function *j*. Suppose the solution yield a minimum objective function value of $z_2 = z_2^*$.

Step 3: Solve the priority level 3's objective function subject to a deviation constraint of the priority level 1's objective function and the priority level 2's objective function.

$$Min\ z_2 \quad (33)$$

s.t. Problem constraints

$z_1 \leq z_1^* \times (1 + d_1)$

$z_2 \leq z_2^* \times (1 + d_2)$

V. Case Study

A. Case Description

To highlight the application of the proposed method, a case study of coronavirus disease (COVID-19) outbreak in Pathum Thani, Thailand is presented. The scope of the reverse logistics problem for medical waste management is composed of IMW generation sources (hospitals), storage centers, and treatment centers. Pathum Thani province, a part of the metropolitan region of Thailand, had a rapid increase in the number of COVID-19 patients during July and August which is presented in Fig. 4.

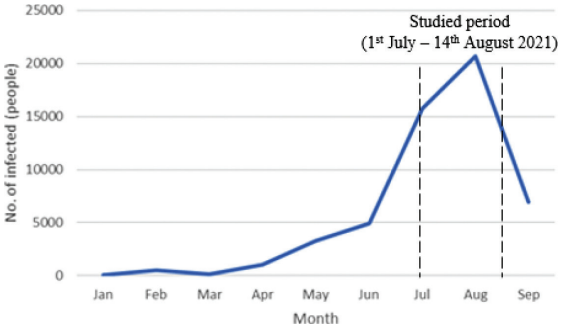

Fig. 4. No. of COVID-19 cases of Pathum Thani province from January - September 2021.

In this study, three districts of Pathum Thani province, including Muang district, Sam Khok district, and Lat Lum Kaeo district, are carried out as the case study. The planning horizon of the proposed model during the peak period of the outbreak, which is from 1st July-14th August 2021, which consists of 15 periods with 3 days each since IMW is normally picked up every 3 days.

The proposed model is composed of three echelons as presented in Fig. 4. The first echelon is comprised of ten IMW generation sources. To design an effective reverse logistics of IMW in this area, storage centers (the second echelon) are an alternative option to be used to store and aggregate the IMW that are overflown from the hospitals. Then, the IMW are delivered to be treated at treatment centers (the third echelon). Currently, there is no storage center and treatment center for IMW in Pathum Thani province. The IMW of Pathum Thani province are normally treated by two existing treatment centers, one in Nonthaburi province and another in Ayutthaya province. However, these two incinerators have to be responsible for IMW from many nearby provinces and the incinerators will not be able to handle these wastes very soon since the number of patients keeps rising during this crisis. By concerning this problem, six potential locations for temporary storage centers and five potential locations for temporary treatment centers are studied to alleviate the facing problem by locating them in suitable areas. A digital map of the three districts of Pathum Thani province containing spatial data is analyzed using Quantum Geographic Information System (QGIS) 3.16.6 with criteria specified by the Pollution Control Department [30]. For example, a treatment center must be at least one kilometer away from residential areas and archaeological heritage sites. The locations of all facilities in the proposed reverse logistics network for IMW management can be presented in Fig. 5.

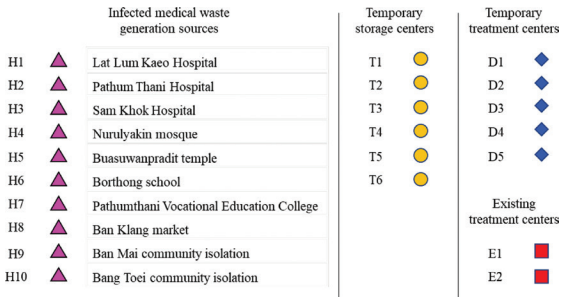

Fig. 5. Facilities in the network

B. Input Parameters

Generally, the daily generation of IMW in Thailand is 0.54 kg/bed/day [31]. However, in the COVID-19 outbreak, there is an increase in generation of IMW due to a requirement in additional medical equipment, e.g., medical masks and personal protective equipment. According to evaluations from professionals, the daily IMW generation in most likely case is 2.85 kg/bed/day at hospitals and 1.82 kg/bed/day at field hospitals [32]. The amount of IMW generated at each hospital in each period is proportional to the number of patients and the daily IMW generation. The number of patients in hospitals (H1, H2, and H3) is estimated based on the number of new cases reported by the Pathum Thani province public health office and the assumption that the length of hospital stay for COVID-19 is 14 days. During this crisis, the field hospitals and community isolations (H4-H10) were full as soon as they opened. The estimated number of patients at each IMW generation sources in each period is presented in Table II.

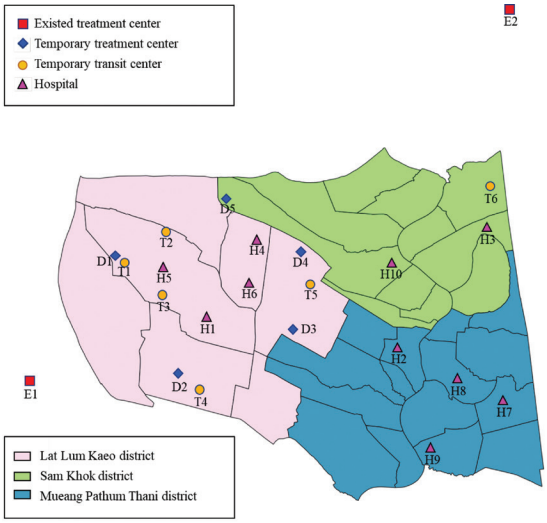

Fig. 6. The location of facilities of the reverse logistics for IMW management in Pathum Thani province

Considering facilities in the network, the lists of IMW generation sources and existing treatment centers are shown in Table III and IV, respectively. The capacities of the existing treatment centers in this case study are assumed to be a portion of their full capacities since these two treatment centers must service the IMW from other provinces as well. Six candidate locations for temporary storage centers and five candidate locations for temporary treatment centers are selected based on the criteria specified by [30]. The candidate locations for those temporary facilities and their population densities are shown in Table V and VI.

TABLE II
ESTIMATED NUMBER OF PATIENTS AT EACH IMW GENERATION SOURCES IN EACH PERIOD

Period	Number of patients at each IMW generation sources (people)									
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
1	464	186	39							
2	565	190	173							
3	577	145	208							
4	700	105	258				450			
5	758	89	281				1,350			
6	815	452	223				1,350			
7	922	683	352	90		90	1,350	300		300
8	1,070	825	616	90		90	1,350	450	300	900
9	1,232	1,101	1,037	90	160	90	1,350	450	300	900
10	1,291	1,348	1,241	90	240	90	1,350	450	300	900
11	1,309	988	1,715	90	240	90	1,350	450	300	900
12	1,390	725	1,511	90	240	90	1,350	450	300	900
13	1,241	654	2,036	90	240	90	1,350	450	300	900
14	1,052	446	1,924	90	240	90	1,350	450	300	900
15	915	210	1,938	90	240	90	1,350	450	300	900

TABLE III
NAMES OF IMW GENERATION SOURCES

No.	IMW generation source	Maximum capacity of IMW collection room (kg/period)
1	Lat Lum Kaeo Hospital	8,160
2	Pathum Thani Hospital	4,650
3	Sam Khok Hospital	7,710
4	Nurulyakin mosque	480
5	Buasuwanpradit temple	1,320
6	Borthong school	480
7	Pathumthani Vocational Education College	7,380
8	Ban Klang market	2,460
9	Ban Mai community isolation	1,650
10	Bang Toei community isolation	4,920

TABLE IV
NAMES OF EXISTING TREATMENT CENTERS

No.	Existing treatment center	Population density (people/km^2)
1	Nonthaburi Provincial Administrative Organization's (PAO) waste processing facility	380.64
2	Bangpain Land company limited	4,650

TABLE V
CANDIDATE LOCATION FOR TEMPORARY TREATMENT CENTERS

No.	Location (Latitude, Longitude)	Sub-district	Population density (people/km^2)
1	14.066303, 100.362195	Rahaeng	403.71
2	14.012116, 100.399202	Lat Lum Kaeo	183.68
3	14.032922, 100.469977	Khu Bang Luang	347.36
4	14.074859, 100.468714	Khu Bang Luang	347.36
5	14.105289, 100.423597	Bang Toei	516.05

The traveling distances between two nodes in Pathum Thani province are obtained by using the fastest route in QGIS 3.16.6 and Google Map. For the transportation cost, it is proportional to the distance travelled and the weight of the IMW, which is estimated to be 0.185 baht/kg/km [25].

TABLE VI
CANDIDATE LOCATION FOR TEMPORARY STORAGE CENTERS

No.	Location (Latitude, Longitude)	Sub-district	Population density (people/km^2)
1	14.068801, 100.374156	Rahaeng	403.71
2	14.088797, 100.395403	Rahaeng	403.71
3	14.047686, 100.393543	Rahaeng	403.71
4	13.997883, 100.413293	Lat Lum Kaeo	183.68
5	14.055485, 100.475268	Khu Bang Luang	347.36
6	14.110869, 100.573855	Chiang Rak Noi	274.74

Considering the probability of accidental risk at the IMW generation sources ($PbAh_h$), the risk is 0.003 for hospitals and 0.007 for temporary hospitals [25]. The accidental risk of the storage center ($PbAt_t$) and treatment center ($PbAe_e$ and $PbAd_d$) are 0.0001 and 0.0006, respectively. According to Yu et al. [25] and Zhao et al. [33], the probability of risk along the route is calculated by Equation (34). The population exposure is calculated by Equation (35), where the affected radius is set to be 2.5 kilometers for treatment centers and 1 kilometer for storage centers. The population exposure along the route between facilities is calculated by Equation (36).

$$PbTht_{ht}, PbTte_{te}, PbTtd_{td}, PbThe_{he}, PbThd_{hd} = \frac{0.4*10^{-6}*0.9}{(km)} \times travel\ distance\ (km) \quad (34)$$

$$Popt_t, Pope_e, Popd_d = \pi r^2(km^2) \times population\ density\ (people/km^2) \quad (35)$$

$$PopTht_{ht}, PopTte_{te}, PopTtd_{td}, PopThe_{he}, PopThd_{hd} = 2(km^2) \times population\ density\ (people/km^2) \times travel\ distance\ (km) \quad (36)$$

The relevant costs and capacities of existing treatment centers, temporary treatment centers, and temporary storage centers are presented in Table VI, respectively. The installation cost of a temporary storage center is composed of costs of the land, its construction, and equipment. For temporary treatment centers, three capacity levels (S, M, and L) are provided as an alternative (decision variable), which incur different installation costs and are subject to different capacity limitations. The processing cost of temporary storage centers and temporary treatment centers in most likely cases is set to 0.9 Baht/kg and 3.23 Baht/kg, respectively. The size and cost parameter of temporary facilities are calculated based on [25], [34], [35]. The optimistic value and pessimistic value of the cost parameters and the amount of IMW generated are subject to 0.8 and 1.2 times of the most likely case, respectively.

TABLE VII
COST PARAMETERS AND CAPACITY OF EXISTING TREATMENT CENTERS

No.	Processing cost (Baht)	Capacity (kg/period)
1	(10.4,13.00,15.6)	(453.6,567.0,680.4)
2	(3.60,4.50,5.40)	(2416.8,3021,3625.2)

TABLE VIII
INSTALLATION COST AND CAPACITY OF TEMPORARY TREATMENT CENTERS

No.	Capacity level	Installation cost (Baht)	Capacity (kg/period)
1	S	(7477240,9346550,11215860)	(1920,2400,2400)
	M	(9995920,12494900,14993880)	(5760,7200,7200)
	L	(15932200,19915250,23898300)	(11520,14400,14400)
2	S	(8277240,10346550,12415860)	(1920,2400,2400)
	M	(11195920,13994900,16793880)	(5760,7200,7200)
	L	(17532200,21915250,26298300)	(11520,14400,14400)
3	S	(8437240,10546550,12655860)	(1920,2400,2400)
	M	(11435920,14294900,17153880)	(5760,7200,7200)
	L	(17852200,22315250,26778300)	(11520,14400,14400)
4	S	(8437240,10546550,12655860)	(1920,2400,2400)
	M	(11435920,14294900,17153880)	(5760,7200,7200)
	L	(17852200,22315250,26778300)	(11520,14400,14400)
5	S	(7157240,8946550,10735860)	(1920,2400,2400)
	M	(9515920,11894900,14273880)	(5760,7200,7200)
	L	(15292200,19115250,22938300)	(11520,14400,14400)

TABLE IX
INSTALLATION COST AND CAPACITY OF TEMPORARY STORAGE CENTERS

No.	Installation cost (Baht)	Capacity (kg/period)
1	(5189000,6486250,7783500)	(25200,31500,31500)
2	(5189000,6486250,7783500)	(25200,31500,31500)
3	(5189000,6486250,7783500)	(25200,31500,31500)
4	(6789000,8486250,10183500)	(25200,31500,31500)
5	(8069000,10086250,12103500)	(25200,31500,31500)
6	(3909000,4886250,5863500)	(25200,31500,31500)

VI. RESULT AND DISCUSSION

A. Results

The feasibility degrees (α) is subjective to the preferences and experiences of the decision-makers. The α level indicates the level of feasibility that the decision-makers are willing to accept. In this case study, the α level was fixed at 0.7 with 25% allowed percentage deviation for an illustrative purpose. Full details of the sensitivity analysis on different levels of the allowed percentage deviation are not included in this paper due to a suitable paper length. Fig. 6 presents the sensitivity analysis of the feasibility degree (α) with 25% allowed percentage deviation. It was found that as the α increases, the total costs (z_1) and the risk associated with transportation and treatment (z_3) tend to become worse. The reason is that as the decision-makers have the desire to encounter the uncertainty with a higher confidence level in satisfying the constraints, the constraints become more restricted and fewer solution sets are feasible. However, this is not the case for risk at hospitals (z_2) because a variety of factors contribute to the fluctuation of this objective function.

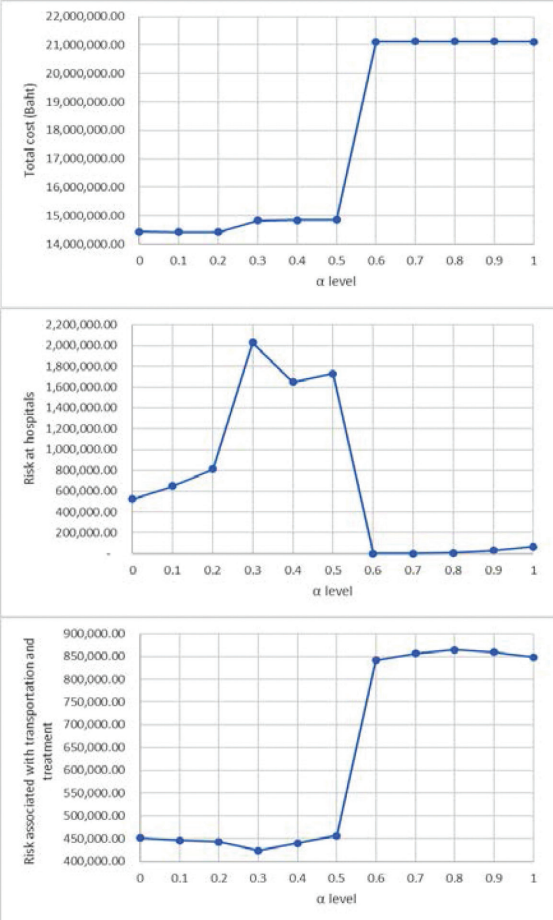

Fig. 7. The sensitivity analysis of the feasibility degree (α) with 25% allowed percentage deviation.

To clarify this issue, the risk at hospitals is directly correlated to the number of the uncollected wastes at the hospitals. One of the factors that leads to the fluctuation is the conflict between objectives. To reduce the risk at hospitals, a greater number of the IMW must be delivered out of the hospitals to be treated. This leads to an increase in transportations among facilities, treatments of the wastes, and establishment of more temporary facilities. It also lead to an increase in the total costs and the risk associated with transportation and treatment. For $\alpha \geq 0.6$, the solutions suggest establishing one temporary treatment center with capacity size L, resulting in a very low risk at hospital (z_2) since most of the IMW can be treated.

To handle the FMOMILP model for the reverse logistics network design of IMW in outbreaks problem, the Fuzzy Goal Programming (FGP) method is applied to obtain an effective solution based on the priority of the objective functions. The priority of the objective functions in this case study are as follows:

- Priority level 1 – Minimize total costs (z_1)
- Priority level 2 – Minimize risk at hospitals (z_2)
- Priority level 3 – Minimize risk associated with transportation and treatments (z_3)

Table X shows the objective function values and the establishment of the temporary storage centers and temporary treatment centers from varying the allowed percentage deviations from 10% to 30%.

TABLE X
RESULTS FROM VARIOUS ALLOWED PERCENTAGE DEVIATION

Objectives	PIS[1]	NIS[2]	Allowance percentage deviation				
			10%	15%	20%	25%	30%
Z_1 (Baht)	17,493,541.08	43,664,290.85	18,475,527.75 (+57.69%[3])	19,945,979.89 (+54.32%[3])	20,263,851.15 (+53.59%[3])	21,123,563.91 (+51.62%[3])	21,123,456.58 (+51.62%[3])
Z_2	-	3,967,593.15	135,019.88 (+96.60%[3])	135,007.57 (+96.60%[3])	619.18 (+99.98%[3])	644.97 (+99.98%[3])	670.77 (+99.98%[3])
Z_3	56,294.72	1,263,055.67	678,840.37 (+46.25%[3])	460,085.94 (+63.57%[3])	1,028,494.52 (+18.57%[3])	856,024.77 (+32.23%[3])	855,873.74 (+32.24%[3])
Installed D			D1(size M)	D2(size M)	D5(size L)	D1(size L)	D1(size L)
Installed T			T6	T6	-	-	-

[1] Positive Ideal Solution (PIS) is the best value obtaining from the payoff table.
[2] Negative Ideal Solution (NIS) is the worst value obtaining from the payoff table.
[3] Percentage improved as compared to the NIS,

The optimal solutions in two cases of 10% to 15% allowed percentage deviation (little increase from the case of minimum total cost) select to establish a temporary storage center T6 at Chiang Rak Noi sub-district and a temporary treatment center with capacity size M at Rahaeng sub-district. However, in the cases of 20% to 30% allowed percentage deviation, where the total costs are allowed to moderately increase up to 30% from the case of minimum total costs, a temporary treatment center with capacity size L at Bang Toei sub-district for the case of 20% allowed percentage deviation and at Rahaeng sub-district for the cases of 25% and 30% allowed percentage deviation is selected. For these cases of moderate increase in the total costs, IMW is suggested to be delivered directly to the treatment centers without any storage. Since capacity size L is selected, the total costs and the risk associated with transportation and treatments increases, but the risk at hospitals is extremely low due to high IMW treatment capability of the facilities.

For an illustration of the result obtained from the IMW reverse logistics network design, the optimal solutions of 25% and 30% allowed percentage deviation cases are selected since their total costs and the risk associated with transportation and treatments increase in acceptable levels while their total costs slightly increase but the risk at hospitals improved dramatically up to 99.98% as compared to the NIS. Based on Table 10 with the case of 25% allowed percentage deviation, the total costs is 21,123,563.91 Baht, the risk at hospitals is 644.97, and the risk associated with transportation and treatments is 856,024.77 in which one temporary treatment center, D1(size L) at Rahaeng sub-district, is selected to be established. The risk associated with transportation and treatments is significantly higher than the risk at hospitals because it has the lowest priority level and optimizes last.

The allocation of IMW is presented in Table XI and the utilization of each facility is presented in Table XII. From Table XI and Table XII, the temporary

treatment center D1 serves as the primary treatment center and the two existing treatment centers are used as supplement when the capacity of the temporary treatment center D5 is reached. In the first 8 periods, none of the IMW are sent to the existing treatment centers because the temporary treatment center D1 is still capable of treating all IMW. However, as the amount of IMW increases, the IMW is overflown to the two existing treatment centers. For example, in period 9, the IMW from most hospitals are treated at the temporary treatment center D1. Once the capacity of the temporary treatment center D1 is full, the IMW is overflown to the existing treatment centers E1 and E2, where the IMW from H1 and H3 are treated at E1, and the IMW from H9 is treated at E2.

TABLE XII
ALLOCATION OF IMW IN EACH PERIOD

Allocation of IMW from hospitals to existing treatment centers															
Existing treatment centers	**Period**														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
E1									H1 H9	H1 H9	H1 H9	H1 H9	H1 H9	H1 H9	H1 H9
E2									H3	H3	H3	H3	H3	H3	H3
Allocation of IMW from hospitals to temporary treatment centers															
TEMPORARY TREATMENT CENTERS	**Period**														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
D1	H1 H2 H3	H1 H2 H3	H1 H2 H3	H1 H2 H3 H7	H1 H2 H3 H7	H1 H2 H3 H7	H1 H2 H3 H4 H6 H7 H8 H10	H1 H2 H3 H4 H6 H7 H8 H9 H10	H1 H2 H3 H4 H5 H6 H7 H8 H10	H1 H2 H3 H4 H5 H6 H7 H8 H10	H1 H2 H3 H5 H6 H7 H8 H10	H1 H2 H3 H4 H5 H6 H7 H8 H10	H1 H2 H3 H4 H5 H6 H7 H8 H10	H1 H2 H3 H4 H5 H6 H7 H8 H10	H1 H2 H3 H4 H5 H6 H7 H8 H10

A comparison with the actual situation where there is no temporary facilities is also carried out as shown in Table XIII to show the huge damage from the excess amount of uncollected or untreated IMW from the actual situation. Because of an increase in IMW during the COVID-19 outbreak, the existing treatment centers were unable to treat all delivered amount of IMW, and the remaining amount IMW eventually started to pile up. In the actual case, without these temporary facilities, the total costs is surely lower than the proposed situation but the IMW would be severely accumulated at the hospitals or at the existing treatment centers causing the risks to increase tremendously beyond the acceptable level.

TABLE XIII
RESULTS COMPARISON WITH 25% ALLOWANCE PERCENTAGE DEVIATION

Actual situation			
Objective	**Accumulate at hospitals**	**Accumulate at existing treatment centers**	**Proposed situation (Establish D1 (size L))**
(Baht)	499,257.14	2,419,904.02	21,123,563.91
	5,346,463.77	1,826,198.57	644.97
	415,175.32	2,983,867.64	856,024.77
Excess amount of IMW remaining (kg)	258,453.27	302,113.82	None

The improper accumulation of IMW definitely caused concerns about the disease spreading to communities during that time [36]. Our proposed temporary facilities can lead to far better effective management of the IMW, lowering the risk of disease spreading. However, once the outbreak is over, the amount of IMW would return to a normal level. This temporary treatment center will still be useful because it can be used to treat the IMW and other wastes from Pathum Thani, where the IMW generation is expected to be 4,712 kg/day this year without the outbreak [37]. In addition, these facilities help Pathum Thani province to be ready or prepared for future outbreaks, which are likely to occur again soon. This will also reduce the processing cost of waste treatment as well as the transportation risk from using the existing treatment centers in nearby provinces. Most importantly, it certainly helps to avoid the risk of disease spreading from the huge excess amount of IMW (Table XIII) as reported in the past.

VII. Conclusions

To handle the rapid increase of IMW due to outbreaks, an effective IMW reverse logistics network design using a fuzzy multi-objective multi-period mixed-integer linear programming model under an uncertain environment was proposed in this study. The model aimed to simultaneously minimize the total costs, the risk at hospitals, and the risk associated with transportation and treatments, by determining the optimal locations and size of temporary facilities and the flow of IMW among facilities. To deal with the uncertainty and the conflict among objectives, an integrated interactive fuzzy approach, which is an integration of an auxiliary model of Jimenez approach and the Fuzzy Goal Programming (FGP) method, was proposed. The auxiliary model was used to cope with uncertain parameters with feasibility concept, and the FGP method was applied to generate effective solutions based on the priority of the objective functions and the allowed percentage deviation determined by the decision-makers.

The effectiveness and applicability of the proposed methodology were demonstrated with an actual study of the COVID-19 outbreak in Pathum Thani province. The cases of 25% and 30% allowed percentage deviation with an establishment of one temporary treatment center, D1(size L) at Rahaeng sub-district were chosen because the total costs and the risk associated with transportation and treatments are in acceptable levels, whereas the risk at hospitals is very low. However, it would depend on the decision-makers to decide the best solution in their particular situations.

The primary limitation of this study is belonging to the data estimation. Since the COVID-19 outbreak is a new pandemic, and there has been an incomplete in the collected data and subjective knowledge of the experts is still required in generating the appropriate data. As a result, further possible studies can be recommended as follows:

- More advanced methods in estimating the amount of IMW generated and the risk parameters could make the result more practical.
- An outbreak is an incident that incurs a high level of uncertainty. More advanced methods in handling the risks, e.g., robust programming, could be applied for better outcomes.
- For the network design, more facilities (e.g., different IMW sources and disposal centers) could be added. As the problems get bigger and more complex, metaheuristic algorithms could be considered.

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