

# Viable Medical Waste Chain Network Design by Considering Risk and Robustness

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## Research Article

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# Viable medical waste chain network design by considering risk and robustness

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## Abstract

Medical Waste Management (MWM) is an important and necessary problem in the COVID-19 situation for treatment staff. When the number of infectious patients grows up and amount of MWMs increases day by day. We present Medical Waste Chain Network Design (MWCND) that contains Health Center (HC), Waste Segregation (WS), Waste Purchase Contractor (WPC) and landfill. We propose to locate WS to decrease waste and recover them and send them to the WPC. Recovering medical waste like metal and plastic can help the environment and return to the production cycle. Therefore, we proposed a novel Viable MWCND by a novel two-stage robust stochastic programming that considers resiliency (flexibility and network complexity) and sustainable (energy and environment) requirements. Therefore, we try to consider risks by Conditional Value at Risk (CVaR) and improve robustness and agility to demand fluctuation and network. We utilize and solve it by GAMS CPLEX solver. The results show that by increasing the conservative coefficient, the confidence level of CVaR and waste recovery coefficient increases cost function and population risk. Moreover, increasing demand and scale of the problem make to increase the cost function.

**Keywords:** Viable; Medical waste; Network design; Resiliency; Sustainable; Robust optimization.

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31 **1. Introduction**

32 Medical Waste Management (MWM) is a critical problem in the COVID-19 situation. In the  
33 COVID-19 condition, amount of infectious patients grow up and amount of MWMs increase. As  
34 a result, we must pay more attention to MWMs and improve waste disposal. Many workers that  
35 do waste disposal, this subject threatens them very much. MWMs include infectious waste,  
36 hazardous waste, radioactive waste and general waste (municipal solid waste). The WHO classifies  
37 medical waste into sharps, infectious, pathological, radioactive, pharmaceuticals, other (including  
38 toilet waste produced at hospitals). About 85% of MWMs are general waste and 15% of MWMs  
39 are infectious waste, hazardous waste, radioactive waste (Tsai, 2021). Therefore, the importance  
40 of MWMs, make many researchers contribute this subject and present mathematical approach and  
41 decision support system. Some researchers consider a location-routing problem for medical waste  
42 management (Suksee & Sindhuchao, 2021; Tirkolaei, Abbasian, & Weber, 2021). Others  
43 investigate reverse logistics by the mathematical model (Sepúlveda, Banguera, Fuentes, Carrasco,  
44 & Vargas, 2017; Suksee & Sindhuchao, 2021). Also, some scientists analysis of MWM systems  
45 by multi-criteria-decision approach (Aung, Luan, & Xu, 2019; Narayananamoorthy et al., 2020). The  
46 objective of these tools is to improve waste management performance and decrease risks for  
47 workers that we can see in Figure 1.



**Figure 1.** MWM in the COVID-19 situation.

48 One of the new discussions in the present age is the viability of network design in post-pandemic  
49 adaptation. The viability of networks that are proposed by Ivanov and Dolgui (2020) is integrated  
50 agility, resilience and sustainability in the network. Therefore, it is needed to suggest a systematic  
51 and mathematical model for setting up Viable Medical Waste Chain Network Design  
52 (VMWCND). Because improving the performance of waste management is urban need and make  
53 to prevent COVID-19 outbreak. Eventually, we should design a new mathematical model to  
54 consider agility, resilience, sustainability, risks and robustness to cope with environmental  
55 requirements and disruption.

56 Eventually, the innovation of this research and the main objective is as follows:

- 57 • First time designing viable medical waste chain network design (VMWCND),  
58 • Considering robustness and risk in VMWCND.

59 The paper is organized as follows. In Section 2, we survey on related work in scope of MWCND.  
60 In Section 3, the VMWCND and risk-average VMWCND is stated. In Section 4, the results of  
61 research and sensitivity analysis are presented. In Section 5, the managerial insights and practical  
62 implications is discussed. In Section 6, the conclusion is summarized.

## 63 **2. Survey on recent MWCND**

64 The amount of waste has increased because of the COVID-19 situation. Therefore, researchers  
65 research to manage, improve and decrease losses from medical centers. We survey on the recent  
66 investigation on MWCND is as follows.

67 Mantzaras and Voudrias (2017) considered an optimization model for medical waste in Greece.  
68 They tried to minimize total cost include location and transfer between location. The Genetic  
69 Algorithm (GA) is applied to solve the model. Budak and Ustundag (2017) designed a reverse  
70 logistic for multiperiod, multitype waste products. The model's objective was to minimize total  
71 cost and the model's decision included location, flow, inventory. The case was in Turkey. They  
72 found that by increasing waste amounts, the numbers of facilities and strategies are changed.  
73 Wang, Huang, and He (2019) designed a two-stage reverse logistics network for urban healthcare  
74 waste with multi-objective and multi-period. In stage one, they predicted the amount of medical  
75 waste, and in the second stage, they minimized total cost and environmental impact.

76 Kargar, Paydar, and Safaei (2020) presented a reverse supply chain for medical waste. They used  
77 mix-integer programming (MIP) to model problem. The objectives included total costs, technology  
78 selection and the total medical waste stored that are minimized. A robust possibilistic  
79 programming (RPP) approach are applied to cope with uncertainty. A Fuzzy Goal Programming  
80 (FGP) method is embedded to solve the objectives. The real case study is investigated in Babol,  
81 Iran. Other works of Kargar, Pourmehdi, and Paydar (2020) studied a reverse logistics network  
82 design for MWM in the COVID-19 situation. They minimized the total costs, transportation and  
83 treatment MW risks, and maximized the amount of uncollected waste. They employed the Revised  
84 Multi-Choice Goal Programming (RMGP) method. Homayouni and Pishvaee (2020) surveyed  
85 hazardous hospital waste collection and disposal network design problem with a bi-objective  
86 robust optimization (RO) model. The objectives include total costs, the total operational and  
87 transportation risk. An augmented  $\epsilon$ -constraint (AUGEPS) method is embedded to solve the  
88 problem. The real case study is investigated in Tehran, Iran.

89 Yu, Sun, Solvang, and Zhao (2020) considered a reverse logistics network design for MWM in  
90 epidemic outbreaks in Wuhan (China). The objectives included risk at health centers, risk related  
91 to the transportation of medical waste and total cost. They solved the model by Fuzzy  
92 Programming (FP) approach for multi-objective. They determine temporary transit centers and  
93 temporary treatment centers in their model. In addition, Yu, Sun, Solvang, Laporte, and Lee (2020)  
94 studied a stochastic network design problem for hazardous WM. They minimized cost and  
95 transportation cost of hazardous waste and the population exposure risk. They applied stochastic  
96 programming with Sample average approximation (SAA) for scenario reduction. They solved the  
97 model by Goal Programming (GP). Z Saeidi-Mobarakeh, R Tavakkoli-Moghaddam, M  
98 Navabakhsh, and H Amoozad-Khalili (2020) presented bi-level programming (BP) for a hazardous  
99 WM problem. They used an enviornmental approach for upper-level and routing and cost for lower-  
100 level. They solve Mix-Integer Non-Linear Programming (MINLP) by GA.

101 In addition, Zahra Saeidi-Mobarakeh, Reza Tavakkoli-Moghaddam, Mehrzad Navabakhsh, and  
102 Hossein Amoozad-Khalili (2020) developed a robust bi-level optimization model to model  
103 hazardous WCND. They suggested a robust optimization approach to cope with the uncertainty.  
104 Also, the decisions of the model include location, determining capacity and routing. Eventually, a  
105 commercial solver is utilized to solve the model. Tirkolaee et al. (2021) surveyed a sustainable

106 fuzzy multi-trip location-routing problem for MWM during the covid-19 outbreak. They  
 107 embedded Fuzzy Chance-Constrained Programming (FCCP) technique to tackle the uncertainty.  
 108 Therefore, they implemented Weighted GP (WGP) method to analyze and solve the problem. A  
 109 case study is determined in Sari, Iran to show the performance of the proposed model. Tirkolaee  
 110 and Aydin (2021) suggested a sustainable MWM for collection and transportation for pandemics.  
 111 They minimized total cost and the total risk exposure imposed by the collection. Eventually, a  
 112 commercial solver is utilized to solve the model with Meta-Goal Programming (MGP) for multi-  
 113 objective. Shadkam (2021) designed a reverse logistics network for COVID-19 and vaccine waste  
 114 management. They utilized Cuckoo Optimization Algorithm (COA). They tried to minimize total  
 115 cost. Nikzamir, Baradaran, and Panahi (2021) suggested a location routing network design for  
 116 MWM that tried to minimize the total cost and risks of population contact with infectious waste.  
 117 They offered a Mix-Integer Linear Programming (MILP) and solved it by a hybrid meta-heuristic  
 118 algorithm based on Imperialist Competitive Algorithm (ICA) and GA. Li et al. (2021) surveyed a  
 119 Vehicle Routing Problem (VRP) for MWM by considering transportation risk. They suggested MILP for  
 120 time window VRP and developed a Particle Swarm Optimisation (PSO) algorithm to solve large-scale  
 121 problems.

**Table 1.** Survey of MWCND.

Reference	Kind	Decision	Objectives				Methodology	Uncertainty	Case study	
			Economic	Environmental	Energy	Social				
(Mantzaras & Voudrias, 2017)	-	Location, capacity	✓	-	-	-	MILP+ GA	-	Greece	
(Budak & Ustundag, 2017)	-	Location, flow, inventory	✓	-	-	-	MILP	-	Turkey	
(Wang et al., 2019)	Green	Location, flow, inventory	✓	✓	-	-	MILP	-	Shanghai, China	
(Kargar, Paydar, et al., 2020)	-	Location, flow, inventory	✓	-	-	-	MILP+ FGP	RPP	Babol, Iran	
(Kargar, Pourmehdi, et al., 2020)	-	Location, flow	✓	-	-	-	✓	MILP+RMGP	-	Iran
(Homayouni & Pishvaei, 2020)	-	Location, flow	✓	-	-	-	✓	MILP+ AUGEPS	RO	Tehran, Iran

(Yu, Sun, Solvang, & Zhao, 2020)	-	Location, flow	✓	-	-	-	✓	MILP+FP	-	Wuhan, China
(Yu, Sun, Solvang, Laporte, et al., 2020)	-	Location, flow	✓	-	-	-	✓	MILP+GP	Stochastic	Numerical example (NE)
(Z Saeidi-Mobarakeh et al., 2020)	-	Routing, environmental	✓	✓	-	-	-	MINLP (BP)+GA	-	Isfahan, Iran
(Zahra Saeidi-Mobarakeh et al., 2020)	-	Location, capacity, routing	✓	-	-	-	✓	MILP (BP)	RO	Isfahan, Iran
(Tirkolaee et al., 2021)	Sustainable	Location, routing	✓	-	-	-	-	MILP+WGP	FCCP	Sari, Iran
(Tirkolaee & Aydin, 2021)	Sustainable	Location, routing	✓	-	-	-	✓	MILP+ MGP	-	NE
(Shadkam, 2021)	-	Location, flow	✓	-	-	-	-	MILP + COA	-	NE
(Nikzamir et al., 2021)	Green	Location, routing	✓	-	-	-	✓	MILP+ICA, GA	-	NE
(Li et al., 2021)	-	Routing	✓	-	-	-	-	MILP + PSO	-	NE
This research	Viable (Resilience +sustainable +agile)	Location, flow	✓	-	-	-	-	MILP	RO Stochastic	Tehran

122 The classification of the literature is addressed in Table 1. It can be seen; researchers do not survey  
 123 the VMWCND problem. This study investigates the VMWCND problem and used mathematical  
 124 problems to locate the best place for MWCND.

125 The main innovation of this research is as follows:

- 126 • First time designing VMWCND,  
 127 • Considering agility, resilience, sustainability, robustness and risk-averse.

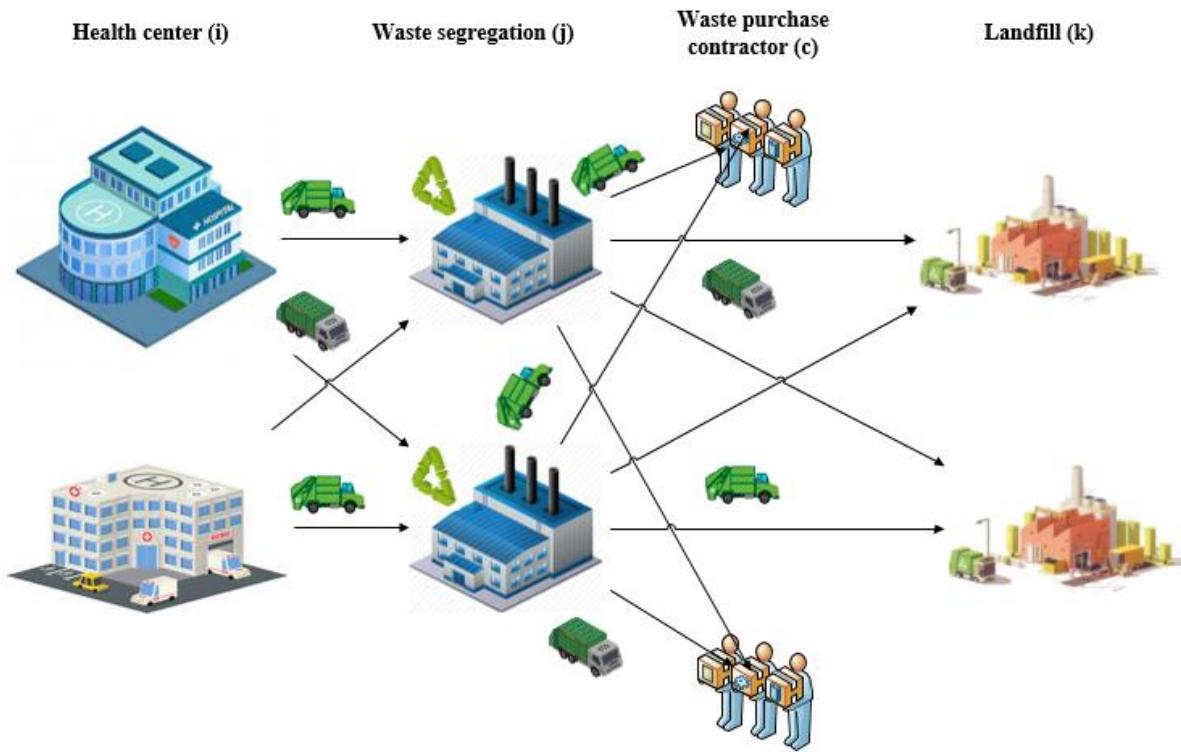
### 128 **3. Problem description**

129 In this research, we try to design VMWCND. The previous section shows a lack of research in  
 130 resilience, sustainability and agility MWCND. In the present study, we have Health Center (HC),  
 131 Waste Segregation (WS), Waste Purchase Contractor (WPC), landfill that waste move through  
 132 this network. Eventually, we present VMWCND through resilience strategy (flexible and scenario-  
 133 based capacity and node complexity), sustainability constraints (energy and environmental

134 pollution), and agility (balance flow and demand satisfaction). We need to locate WS to improve  
135 and recover waste and consider sustainability and environmental requirements in this situation.

136 Assumptions:

- 137 • All wastes should be transferred to HC (agility),  
138 • All forward MWCND constraints include flow and capacity constraint is active,  
139 • Sustainability constraints include allowed emission and energy consumption are added  
140 (sustainability),  
141 • Flexible capacity for facilities and node complexity in WS is considered as a resilience  
142 strategy (resiliency),  
143 • Using scenario-based robust optimization against risks (robustness, risk, resiliency)  
144 (Ivanov, 2020; Lotfi, Mehrjerdi, Pishvae, Sadeghieh, & Weber, 2021).



**Figure 2.** Viable medical waste chain network design (VMWCND).

145 Notations:

146 Indices:

- $i$  Index of Health Center (HC)  $i$ ,
- $j$  Index of Waste Segregation (WS)  $j$ ,
- $c$  Index of Waste Purchase Contractor (WPC)  $c$ ,
- $k$  Index of landfill  $k$ ,
- $t$  Index of time period,
- $s$  Index of scenario;

147 *Parameters:*

- $ww_{its}$  Waste generated in HC  $i$  for time period  $t$  under scenario  $s$ ,
- $vij_{ijts}$  Variable cost from HC  $i$  to WS  $j$  for time period  $t$  under scenario  $s$ ,
- $vjc_{jcts}$  Variable cost from WS  $j$  to WPC  $c$  for time period  $t$  under scenario  $s$ ,
- $vjk_{jkts}$  Variable cost from WS  $j$  to the landfill  $k$  for time period  $t$  under scenario  $s$ ,
- $fj_j$  Cost of activation WS  $j$ ,
- $Emij_{ijts}$  Emission CO<sub>2</sub> for transferring from HC  $i$  to WS  $j$  for time period  $t$  under scenario  $s$ ,
- $Emjc_{jcts}$  Emission CO<sub>2</sub> for transferring from WS  $j$  to WPC  $c$  for time period  $t$  under scenario  $s$ ,
- $Emjk_{jkts}$  Emission CO<sub>2</sub> for transferring from WS  $j$  to landfill  $k$  for time period  $t$  under scenario  $s$ ,
- $Enij_{ijts}$  Energy consumption for transferring from HC  $i$  to WS  $j$  for time period  $t$  under scenario  $s$ ,

- $Enjc_{jcts}$  Energy consumption for transferring from WS  $j$  to WPC  $c$  for time period  $t$  under scenario  $s$ ,
- $Enjk_{jcts}$  Energy consumption for transferring from WS  $j$  to landfill  $k$  for time period  $t$  under scenario  $s$ ,
- $Capj_{jts}$  Capacity WS  $j$  for time period  $t$  under scenario  $s$ ,
- $p_s$  Probably of scenario  $s$ ,
- $\lambda$  Coefficient of conservative,
- $EMSC_{ts}$  Maximum allowed emission for time period  $t$  under scenario  $s$ ,
- $ENSC_{ts}$  Maximum allowed energy consumption for time period  $t$  under scenario  $s$ ,
- $\rho_j$  Coefficient of availability of WS  $j$ ,
- $Mbig$  Big positive number,
- $eps$  Very little positive number,
- $\alpha$  The confidence level for conditional value at risk,
- $\pi$  Waste recovery coefficient,
- $TT$  Threshold of node complexity for resiliency,
- $\varphi$  The ratio of HC to WS.
- $popij_{ijts}$  Population risk contact from HC  $i$  to WS  $j$  for time period  $t$  under scenario  $s$ ,
- $popjc_{jcts}$  Population risk contact from WS  $j$  to WPC  $c$  for time period  $t$  under scenario  $s$ ,
- $popjk_{jcts}$  Population risk contact from WS  $j$  to landfill  $k$  for time period  $t$  under scenario  $s$ ;

148 *Decision variables:*

149 *Binary variables:*

$x_j$  If WS  $j$  is established, equal 1; otherwise 0;

150 *Continues Variables:*

$wij_{ijts}$  Waste transshipment from HC  $i$  to WS  $j$  for time period  $t$  under scenario  $s$ ,

$wjk_{jkt}$  Waste transshipment from WS  $j$  to landfill  $k$  for time period  $t$  under scenario  $s$ ,

$wjc_{jcts}$  Waste transshipment from WS  $j$  to WPC  $c$  for time period  $t$  under scenario  $s$ ;

151 *Auxiliary Variables:*

$FC$  Fix cost of establishing WS

$VC_s$  Variable cost for scenario  $s$ ,

$\Gamma_s$  Fix cost and variable cost for scenario  $s$ .

$VaR$  Value at Risk

$\Delta$  Auxiliary variable for linearization max function,

$yij_{ijts}$  Auxiliary and binary variable for linearization sign function for  $wij_{ijts}$ ,

$yjk_{jkt}$  Auxiliary and binary variable for linearization sign function for  $wjk_{jkt}$ ,

$yjc_{jcts}$  Auxiliary and binary variable for linearization sign function for  $wjc_{jcts}$ .

152 **3.1. VMWCND mathematical model**

$$\text{minimize } Z = (1-\lambda) \sum_s p_s \Gamma_s + \lambda \left( \frac{\max(\Gamma_s) + CVaR_{(1-\alpha)}(\Gamma_s)}{2} \right) \quad (1)$$

subject to:

$$\Gamma_s = FC + VC_s, \quad (2)$$

$$FC = \sum_j f_j x_j, \quad (3)$$

$$VC_s = \sum_t (\sum_i \sum_j wij_{ijts} wijk_{jcts} + \sum_j \sum_k wjk_{jcts} wjk_{jcts} + \sum_j \sum_c wjc_{jcts} wjc_{jcts}), \quad \forall s \quad (4)$$

Agility constraints (flow constraints):

$$\sum_j wij_{ijts} = ww_{its}, \quad \forall i, t, s \quad (5)$$

$$\sum_j wij_{ijts} \leq \sum_j wjk_{jcts} + \sum_j wjc_{jcts}, \quad \forall i, k, c, t, s \quad (6)$$

$$\sum_i wij_{ijts} = \sum_k wjk_{jcts} + \sum_c wjc_{jcts}, \quad \forall j, t, s \quad (7)$$

$$\sum_k wjk_{jcts} \geq (1 - \pi) \sum_i wij_{ijts}, \quad \forall j, t, s \quad (8)$$

Resiliency constraints (flexible and scenario-based capacity and node complexity)

$$\sum_k wjk_{jcts} + \sum_c wjc_{jcts} \leq \rho_j Capj_{jts} x_j, \quad \forall j, t, s \quad (9)$$

$$\frac{\sum_j x_j}{|i|} \geq \varphi, \quad (10)$$

$$\sum_i wij_{ijts} + \sum_k wjk_{jcts} + \sum_c wjc_{jcts} \leq TT, \quad \forall j, t, s \quad (11)$$

Sustainability constraints (allowed emission and energy consumption):

$$\begin{aligned} & \sum_i \sum_j Emij_{ijts} wij_{ijts} + \sum_j \sum_k Emjk_{jcts} wjk_{jcts} \\ & + \sum_j \sum_c Emjc_{jcts} wjc_{jcts} \leq EMSC_{ts}, \end{aligned} \quad \forall t, s \quad (12)$$

$$\begin{aligned} & \sum_i \sum_j Enij_{ijts} wij_{ijts} + \sum_j \sum_k Enjk_{jcts} wjk_{jcts} \\ & + \sum_j \sum_c Enjc_{jcts} wjc_{jcts} \leq ENSC_{ts}, \end{aligned} \quad \forall t, s \quad (13)$$

$$Pop_s = \sum_t (\sum_i \sum_j popij_{ijts} [wij_{ijts}] + \sum_j \sum_k popjk_{jkts} [wjk_{jkts}] \\ + \sum_j \sum_c popjc_{jcts} [wjc_{jcts}]), \quad \forall s \quad (14)$$

$$\sum_s p_s Pop_s \leq \theta, \quad (15)$$

Decision variables:

$$x_j \in \{0,1\}, \quad \forall j \quad (16)$$

$$wij_{ijts}, wjk_{jkts}, wjc_{jcts} \geq 0, \quad \forall i, j, c, k, t, s \quad (17)$$

153 The objective (1) considered minimizing the weighted expected value, minimax and conditional  
 154 value at risk of the cost function and for all scenarios. This form of the cost function is proposed  
 155 for robustness and risk-averse against disruption with worst condition. Constraints (2) include fix  
 156 and variable costs. Constraints (3) show fix-costs that include fix-cost activating WS for all  
 157 periods. Constraints (4) indicate the variable costs of HC, WS, WPC and landfill. Constraints (5)  
 158 show waste transshipment from HC to WS. Constraints (6) to (7) are flow constraints in forwarding  
 159 VMWCND. Constraints (8) determine the ratio of waste that goes to the landfill. Constraints (9)  
 160 are flexible capacity constraints for WS that less than the capacity of WS system. Constraints (10)  
 161 are resilience constraints and the number of WS is greater than the coefficient of HC. Constraints  
 162 (11) are resilience constraints and show node complexity in WS that summation of input and output  
 163 of every WS is less than the threshold. Constraints (12) guarantee the network's total environmental  
 164 emissions are less than allowed emission. Constraints (13) guarantee that the network's total energy  
 165 consumption is less than the allowed energy consumption. Constraints (14) risks related to the  
 166 transportation of medical waste. Constraints (15) show summation risks related to medical waste  
 167 transport that contact with population is less than threshold. Constraints (16) to (17) are decision  
 168 variables, and constraints (16) are facilities location for WC and binary variables and constraints  
 169 (17) are flow variables that are positive between facilities.

170 **3.2. Linearization of VMWCND**

171 The objective function (1) is nonlinear and makes the model mixed-integer nonlinear programming  
 172 (MINLP). We transform them to mixed-integer programming (MIP) by mathematical method to  
 173 improve time solution and solve smoothly (Gondal & Sahir, 2013; Sherali & Adams, 2013).

174 Linearizing max and sign function:

175 Suppose: If  $\beta = \max(\Omega_s)$ , then we can change  $\beta \geq \Omega_s, \forall s$ .

176 Suppose: If  $\beta_s = \text{sign}(\Omega_s)$ , then we can change  $\beta_s \leq 1 + \frac{\Omega_s}{Mbig} - \text{eps}$ ,  $\beta_s \geq \frac{\Omega_s}{Mbig}, \forall s$ .

177 We used Conditional Value at Risk (CVaR), which is a coherent risk measure. Uryasev and Rockfeller  
 178 designed the CVaR criterion applied to a novel embed risk measure (Soleimani & Govindan, 2014). CVaR  
 179 (also known as the expected shortfall) is considered as a measure for assessing the risk. CVaR is embedded  
 180 in portfolio optimization to better risk management (Goli, Zare, Tavakkoli-Moghaddam, & Sadeghieh,  
 181 Kara, Özmen, & Weber, 2019). This measure is the average of losses are beyond the VaR point in  
 182 confidence level. CVaR has a higher consistency, coherence, and conservation than other risk-related  
 183 criteria.

184 We used linearization for model (1) by operational research method. Solving the model by MIP is  
 185 more straightforward than MINLP in the solver in equations (18) to (30), and this methods decrease  
 186 time solution and the complexity of the model.

187 Linearization of VMWCND

$$\text{minimize } Z = (1-\lambda) \sum_s p_s \Gamma_s + 0.5(\lambda \Delta + CVaR_{(1-\alpha)}(\Gamma_s)), \quad (18)$$

subject to:

$$\Delta \geq \Gamma_s \quad \forall s \quad (19)$$

$$CVaR_{(1-\alpha)}(\Gamma_s) = VaR + \frac{1}{1-\alpha} \sum_s p_s v_s, \quad \forall s \quad (20)$$

$$v_s \geq \Gamma_s - VaR, \quad \forall s \quad (21)$$

$$v_s \geq 0, \quad \forall s \quad (22)$$

$$Pop_s = \sum_t (\sum_i \sum_j popij_{ijts} yij_{ijts} + \sum_j \sum_k popjk_{jkts} yjk_{jkts} \\ + \sum_j \sum_c popjc_{jcts} yjc_{jcts}), \quad \forall s \quad (23)$$

$$yij_{ijts} \leq 1 + \frac{wij_{ijts}}{Mbig} - eps, \quad \forall i, j, t, s \quad (24)$$

$$yij_{ijts} \geq \frac{wij_{ijts}}{Mbig}, \quad \forall i, j, t, s \quad (25)$$

$$yjk_{jkts} \leq 1 + \frac{wjk_{jkts}}{Mbig} - eps, \quad \forall j, k, t, s \quad (26)$$

$$yjk_{jkts} \geq \frac{wjk_{jkts}}{Mbig}, \quad \forall j, k, t, s \quad (27)$$

$$yjc_{jcts} \leq 1 + \frac{wjc_{jcts}}{Mbig} - eps, \quad \forall j, c, t, s \quad (28)$$

$$yjc_{jcts} \geq \frac{wjc_{jcts}}{Mbig}, \quad \forall j, c, t, s \quad (29)$$

$$yij_{ijts}, yjk_{jkts}, yjc_{jcts} \in \{0, 1\}, \quad \forall i, j, c, k, t, s \quad (30)$$

Constraints (2)-(13), (15)-(17).

188 The complexity of linearization of VMWCND includes numbers of binary, positive, free variables  
 189 and constraints is indicated in equations (31) to (34). As can be seen, one of the essential factors  
 190 for constraints, positive and free variables, is scenario sets. Relation between scenario and  
 191 constraints, positive and free variables is completely linear.

$$\text{Binary variables} = |j| + |t|.|s|(|i|.|j| + |j|.|c| + |j|.|k|), \quad (31)$$

$$\text{Positive variables} = |t|.|s|(|i|.|j| + |j|.|c| + |j|.|k|) + 1, \quad (32)$$

$$\text{Free variables} = 6 + 2|s|, \quad (33)$$

$$\text{Constraints} = 6 + 4|s| + |t|.|s|(|i| + |i|.|k|.|c| + 4|j| + 2 + |i|.|j| + |j|.|c| + |j|.|k|). \quad (34)$$

192 We suggested scenario reduction and new algorithms to remove constraints and binary variables.  
 193 This subject can help solve minimum time.

194 **4. Results and discussion**

195 We surveyed hospitals in Tehran, Iran, and estimated parameters from data of MWCND by  
 196 managers of health centers. The performance of the mathematical model is presented. The number  
 197 of indices are defined in Table 2 and the values of the parameters are determined in Table 3. The  
 198 probability of occurrence is the same and optimistic, pessimistic and possible scenarios has  
 199 happened.

200 **Table 2.** Number of indices, constraints, and variables for case study.

Problem	$ i  \cdot  j  \cdot  c  \cdot  k  \cdot  t  \cdot  s $	Binary variable	Positive variable	Free variable	Constraint	Cost function	Time solution	Population risk
P1-main	118.4.3.1.3.3	4396	4393	12	8818	1520407	9.422	54026.33

201 **Table 3.** Parameters of case study.

Parameters	Value	Unit	Parameters	Value	Unit
$ww_{its}$	$U(1000,1100)(0.8 + 0.4(s - 1)/( s  - 1))$	Ton	$\lambda$	50	%
$vij_{ijts}$	$U(0.5,1)$	\$/Ton	$EMSC_{ts}$	$U(20000,40000) ( i  +  j   c  +  j   k );$	Ton
$vjc_{jcts}$	$U(0.5,1)$	\$/Ton	$ENSC_{ts}$	$U(40000,50000) ( i  +  j   c  +  j   k );$	MJ
$vjk_{jkts}$	$U(0.5,1)$	\$/Ton	$\rho_j$	90	%
$fj_j$	$U(500000,600000)$	\$	$\alpha$	5	%
$Emij_{ijts}$	$U(2,4)/1000$	Ton	$\pi$	90	%
$Emjc_{jcts}$	$U(2,4)/1000$	Ton	$TT$	$3000( i   j  +  j   c  +  j   k )$	Ton
$Emjk_{jkts}$	$U(2,4)/1000$	Ton	$\varphi$	1	%
$Enij_{ijts}$	$U(4,5)/1000;$	MJ	$\theta$	$200( i   j  +  j   c  +  j   k )/ s $	Person
$Enjc_{jcts}$	$U(4,5)/1000;$	MJ	$popij_{ijts}$	$[U(100,200)]$	Person
$Enjk_{jkts}$	$U(4,5)/1000;$	MJ	$popjc_{jcts}$	$[U(150,200)]$	Person

$Cap_{jts}$	$U(222222,233333)$ $\cdot(0.8+0.4(s-1)/( s -1))$	Ton	$popjk_{jts}$	[U(100,200)]	Person
$p_s$	$100/ s $	%		[:] Sign function	

202 We applied a computer with this configuration: CPU 3.2 GHz, Processor Core i3-3210, 6.00 GB  
 203 RAM, 64-bit operating system. Finally, we solve the mathematical models by GAMS-CPLEX  
 204 solver.

205 **Table 4.** Assigning location for the VMWCND facility.

Problem: P1	Binary variable	Place			
		Robat karim	Shurabad	Parand	Nasim shahr
WPC	$xj_j$	1	0	1	0

206 We show the potential location for assigning HC, WS, WPC, landfill in Tehran, Iran (cf. Figure  
 207 3). After solving the model, it suggests that we activate WS and determine the location and the  
 208 flow of VMWCND components. The objective function is 1520407 in Table 2 and the final  
 209 location-allocation is drawn in Figure 4. Finally, we calculate population risk (left-hand side of  
 210 Constraint (15)) that are 54026.33 persons. Eventually, we compare VMWCND with risk and  
 211 worst case and without risk and worst case in Table 5. We can see that by embedding risk and  
 212 worst case, the cost function is almost 1.65% greater than without risk and worst case.



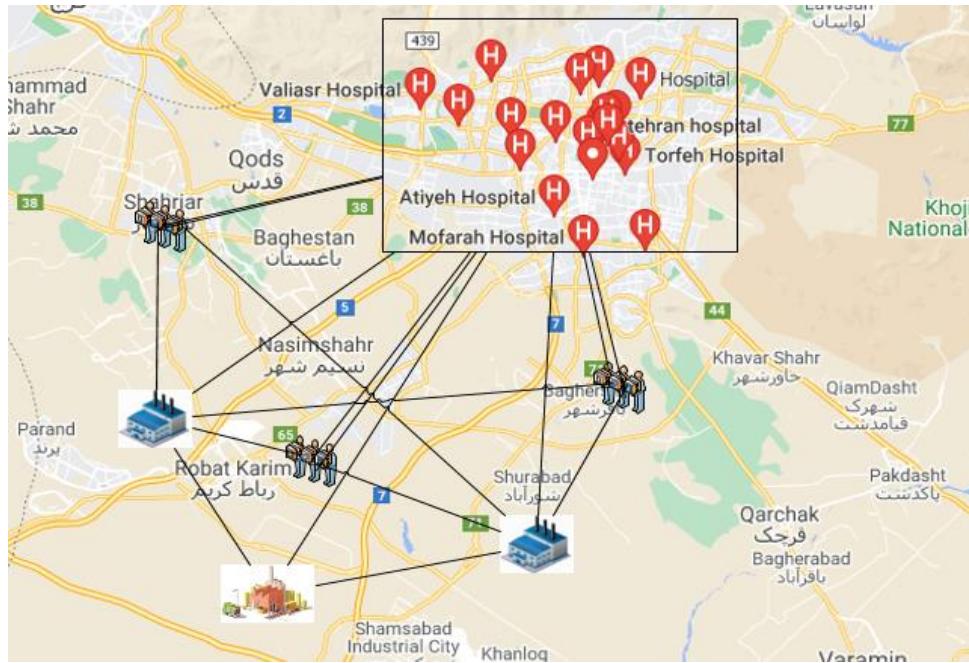
213 **Figure 3.** Potential location for the facilities.

214

**Table 5.** Comparing P1- VMWCND with risk and worst case and without risk and worst case.

Model	P1- VMWCND	P1- VMWCND without risk and worst case	Gap
P1-main	1520407	1495346.97	1.65%

215

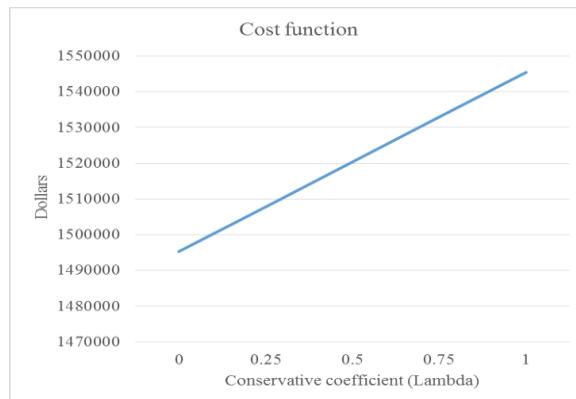
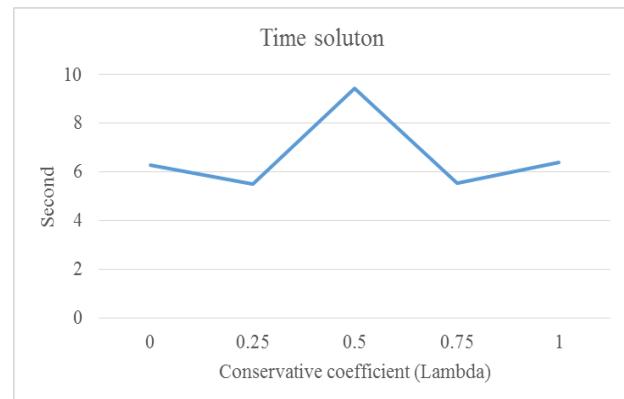
**Figure 4.** Final location for VMWCND facility.

216

#### 4.1. Variation on the conservative coefficient

217

The conservative coefficient ( $\lambda$ ) is the amount of conservative decision-makers. We change it by varying between 0-1 that the conservation of decision-maker has been changed.

**Figure 5.** Cost function for different Lambda.**Figure 6.** Time solution for different Lambda.

219 If the conservative coefficient increases to 1, the cost function grows in Table 6, Figure 5 and Figure 6. If  
 220 the conservative coefficient increases 50%, the cost function will increase by 1.65%, but time solution and  
 221 population risk do not change significantly.

222 **Table 6.** Effects of variation of conservative coefficient.

<b>Problem</b>	<b>Conservative coefficient (<math>\lambda</math>)</b>	<b>Cost function</b>	<b>Time solution</b>	<b>Cost variation</b>	<b>Population risk</b>
P1	0.00	1495346.97	6.289	-1.65%	54026.33
P1	0.25	1507877.11	5.52	-0.82%	54026.33
<b>P1-main model</b>	<b>0.5</b>	<b>1520407.25</b>	<b>9.422</b>	<b>0.00%</b>	<b>54026.33</b>
P1	0.75	1532937.39	5.526	0.82%	54026.33
P1	1.00	1545467.53	6.4	1.65%	54026.33

223 **4.2. Variation on confidence level of CVaR**

224 The confidence level of CVaR ( $\alpha$ ) is the amount of risk-averse decision-makers. If the confidence  
 225 level grows up, we can see, the cost function will increase (cf. Table 7 and Figure 7). By increasing  
 226 2% for confidence level, the cost function increase 0.03%.

227 **Table 7.** Effects of the confidence level of CVaR.

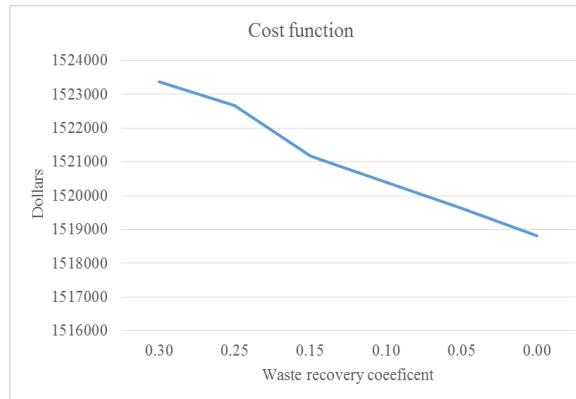
<b>Problem</b>	<b>Confidence level</b>	<b>Cost function</b>	<b>Time solution</b>	<b>Cost variation</b>
P1	1%	1519419.405	5.92	-0.06%
P1	2%	1519658.805	5.666	-0.05%
P1	3%	1519903.141	5.751	-0.03%
<b>P1-main model</b>	<b>5%</b>	<b>1520407.25</b>	<b>5.45</b>	<b>0.00%</b>
P1	6%	1520667.342	5.544	0.02%
P1	7%	1520933.032	5.728	0.03%



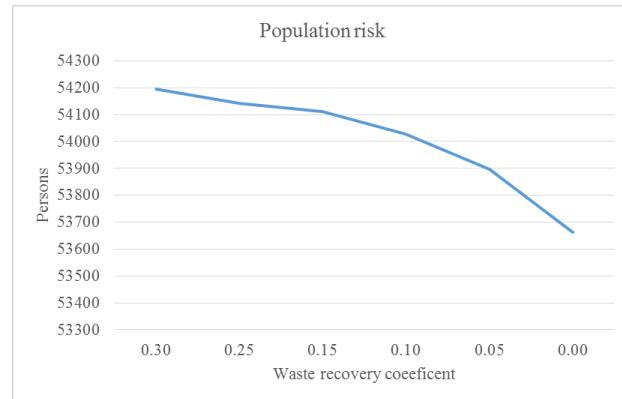
**Figure 7.** Effects of the confidence level of CVaR.

228 **4.3. Variation on waste recovery coefficient**

229 The waste recovery coefficient ( $\pi$ ) is the ratio of waste that goes to landfills. If the waste recovery  
 230 coefficient grows, we can see that the cost function and population risk will decrease (cf. Figure  
 231 8, Figure 9 and Table 8). Increasing waste recovery coefficient, transportation to WPC increases  
 232 and then the cost function increase. But this issue helps systems to use and recover waste.



**Figure 8.** Effects of variation waste recovery coefficient on the cost function.



**Figure 9.** Effects of variation waste recovery coefficient on population risk.

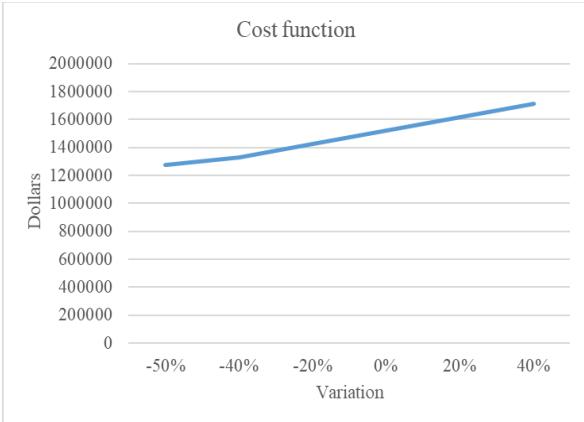
233

**Table 8.** Effects of changing waste recovery coefficient.

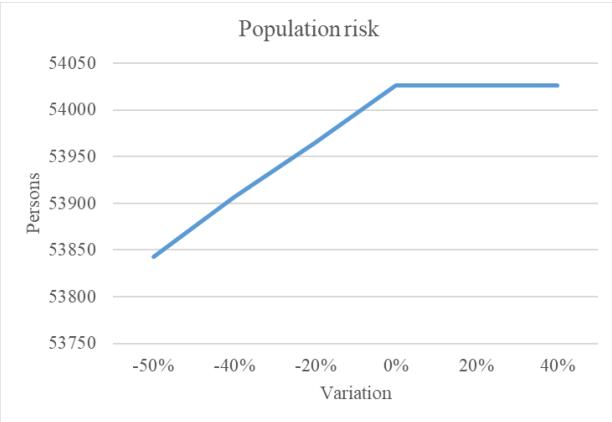
Problem	Waste recovery coefficient	Cost function	Time solution	Cost variation	Population risk
P1	30%	1523371	6.004	0.19%	54196
P1	25%	1522667	5.436	0.15%	54142.3
P1	15%	1521177	5.676	0.05%	54112.7
<b>P1-main model</b>	<b>10%</b>	<b>1520407</b>	<b>5.45</b>	<b>0.00%</b>	<b>54026.3</b>
P1	5%	1519622	5.967	-0.05%	53897.7
P1	0%	1518823	6.07	-0.10%	53662.3

234 **4.4. Variation on demand**

235 We test the effects of changing demand. By increasing demand, the cost function increase, too  
 236 (cf. Table 9). As can be seen, When the demand increases 40%, the cost function grows 12% and  
 237 when demand decreases 50%, it grows down 16% (cf. Figure 10 and Figure 11).



**Figure 10.** Effects of variation demand on cost function.



**Figure 11.** Effects of variation demand on population risk.

238

**Table 9.** Effects of changing demand.

Problem	Changing demand	Cost function	Time solution	Cost variation	Population risk
P1	-50%	1277474.078	5.941	-15.98%	53843.001
P1	-40%	1326060.712	5.888	-12.78%	53906.334
P1	-20%	1423233.979	6.528	-6.39%	53965.334
P1-main model	0%	1520407	5.45	0.00%	54026.334
P1	+20%	1617580.513	6.295	6.39%	54026.334
P1	+40%	1714753.780	5.963	12.78%	54026.334

239

#### 240 4.5. Variation on scale of the main model

241 The several large-scale problems is defined in Table 10. When the scale of problems is increased,  
242 the time solution and cost function increase in Figure 12 and Figure 13. As can be seen, the  
243 proposed model show NP-hard and the behavior of this model is exponential for large scale.  
244 Therefore, we need to solve the model by heuristic, metaheuristic and new exact solution in  
245 minimum time on large scale.

246 **Table 10.** Cost and time solution for several problems.

Problem	$ i  \cdot  j  \cdot  c  \cdot  k  \cdot  t  \cdot  s $	Binary var.	Positive var.	Free var.	Constraint	Cost function	Time solution	Population risk
P1	118.4.3.1.3.3	4396	4393	12	8818	1520407	9.422	54026.33
P2	10.8.4.2.7.7	6280	6273	20	12380	609257	6.796	9201.68

P3	118.4.3.1.3.5	7324	7321	16	14694	1591272	13.49	54408.4
P4	120.5.4.1.5.3	9380	9376	12	18721	1906117	21.548	91725.33
P5	120.5.4.2.7.3	13235	13231	12	36388	2160152	72.426	128016.7
P6	120.8.4.2.7.3	21176	21169	12	44578	2152882	249.904	127924

247

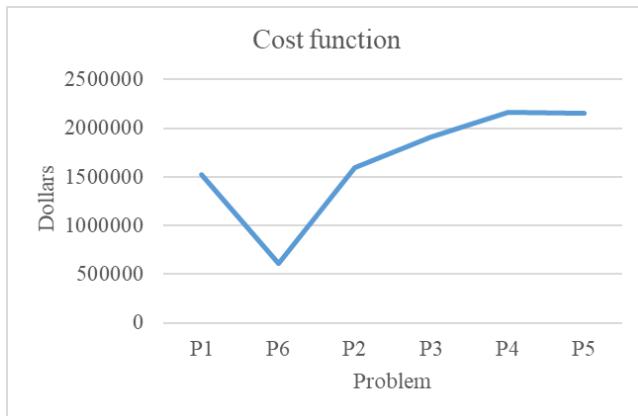


Figure 12. Cost function for several problems.

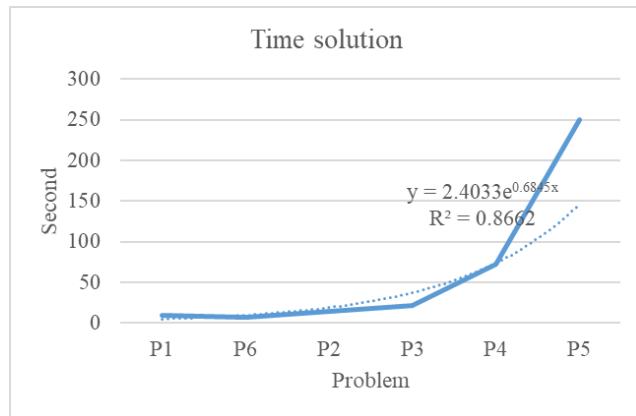


Figure 13. Time solution for several problems.

## 248 5. Managerial insights and practical implications

249 We surveyed viable waste medical chain network design (VWMCND). We try to pay more  
 250 attention to five concepts in medical waste network design. We design VWMCND that considers  
 251 agility, resilience, sustainability, risks and robustness to cope with disruption and requirements of  
 252 government. As managers of the VWMCND, we should move forward to applying the novel  
 253 concept in MCND to decrease cost and population risk, increase the resiliency of facility,  
 254 robustness, risk-averse and agility of network. In this research, we have Health Center (HC), Waste  
 255 Segregation (WS), Waste Purchase Contractor (WPC) and landfill. We propose to locate WS to  
 256 decrease waste and recover them and send to the WPC. Recovering medical waste like metal and  
 257 plastic can help the environment and return to production cycle. In this situation of COVID-19 and  
 258 because of economic problem, we should use all power to utilize waste and move to circular  
 259 economy and sustainable development. This issue is compatible Sustainable Development Goal  
 260 (SDG12-Ensure sustainable consumption and production patterns) and the circular economy  
 261 pillars.

## 262 6. Conclusions and Outlook

263 Medical Waste Management (MWM) is an important and necessary problem in the COVID-19  
 264 situation for treatment staff. The number of infectious patients grows up and amount of MWMs

265 increases day by day. We should think about this issue and find a solution for this issue. We suggest  
266 to recovery MWM by waste segregation. Therefore, we proposed a novel Viable Medical Waste  
267 Chain Network Design (VMWCND) that consider resiliency (flexibility and network complexity)  
268 and sustainable (energy and environment) requirement. Finally, we try to tackle decrease risks and  
269 increase robustness and agility to demand fluctuation and network. We utilize a novel two-stage  
270 robust stochastic programming and solve with a GAMS CPLEX solver.

271 Therefore, the results are as follows:

- 272 1. If the conservative coefficient increases up to 1, the cost function grows up in If the  
273 conservative coefficient increases to 1, the cost function grows in Table 6, Figure 5 and  
274 Figure 6. If the conservative coefficient increases 50%, the cost function will increase by  
275 1.65%, but time solution and population risk do not change significantly.
- 276 2. If the conservative coefficient increases up to 50%, the cost function will increase 1.65%,  
277 but time solution and population risk do not change significantly.
- 278 3. If the confidence level of CVaR grows up, we can see, the cost function will increase (cf.  
279 Figure 7 and Table 7). Increasing for confidence level by 2%, the cost function increase  
280 0.03%.
- 281 4. If the waste recovery coefficient grows, we can see that the cost function and population  
282 risk will decrease (cf. Figure 8, Figure 9 and Table 8). By increasing the waste recovery  
283 coefficient, transportation to WPC increases and then the cost function increase. But it  
284 helps systems to use waste and recover them.
- 285 5. When demand increases 40%, the cost function grows 12% and when demand decreases  
286 50%, it grows down 16% (cf. Figure 10 and Figure 11).
- 287 6. When the scale of problems is increased, the cost function and time solution grow up in  
288 Figure 12 and Figure 13. As can be seen, the behavior of the proposed model is NP-hard  
289 and exponential on large scale. Therefore, we need to solve the model by heuristic,  
290 metaheuristic and new exact solution in minimum time on large scale.

291 Finally, solving the main model on a large scale is the research constraint. We propose to apply  
292 exact algorithms like benders decomposition, branch and price, branch and cut, column generation,  
293 heuristic and meta-heuristic algorithms to solve models in minimum time (Fakhrzad & Lotfi, 2018;

294 Lotfi, Mehrjerdi, & Mardani, 2017). We can add other resilience and sustainable tools to the model  
295 until increasing the resiliency and sustainability of the model like backup facility and redundancy.

296 Further, we suggest adding coherent risk criteria like Entropic Value at Risk (EVaR) (Ahmadi-  
297 Javid, 2012) for considering risks. Researchers intend to investigate method uncertainty like robust  
298 convex (Lotfi, Mardani, & Weber, 2021). Using new and novel uncertainty methods like data-  
299 driven robust optimization is advantageous for a conservative decision-maker in the recent decade.  
300 Eventually, we suggest equipping VMWCND with novel technology like blockchain for the  
301 viability of MWCND.

302 **7. Ethical Approval**

303 Not applicable

304 **8. Consent to Participate**

305 Not applicable

306 **9. Consent to Publish**

307 Not applicable

308 **10. Authors Contributions**

309 Reza Lotfi: conceptualization, supervision, software, methodology; software; formal analysis;  
310 data curation; writing original draft; visualization;

311 Bahareh Kargar: methodology; software; formal analysis; data curation; writing original draft;  
312 writing review and edit; visualization;

313 Alireza Gharehbaghi: methodology, validation;

314 Gerhard-Wilhelm Weber: validation, writing review and edit;

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317 **12. Competing Interests**

318 The authors declare no competing interests.

319 **13. Availability of data and materials**

320 Not applicable

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