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Viable vaccine supply chain network design by considering risk and robustness

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Abstract

Background:

This research suggests a novel network design as a Viable Vaccine Supply Chain Network Design (VVSCND) by integrating sustainability, resiliency, and agility approach with risk and robustness. We propose a hybrid robust stochastic optimization by minimizing weighted expected and maximum cost function. We add sustainable, resiliency and agility requirements. These requirements include CO₂ emission, flexible capacity with reliable and redundancy facilities and responsive SCND.

Results:

We locate SCND components and assign flow in the healthcare industry. The results show that the cost function of VVSCND is almost 0.04% greater than VSCND without risk and worst case. If the conservative coefficient increases up to 50%, the cost function will change 0.04%, but the time solution changes slightly. By growing 10% for agility coefficient, the cost function changed 0.34%. In addition, growing the resiliency coefficient increases the cost function, too. When the scale of problems increases, the time solution and cost function increase.

Conclusions:

Finally, this research suggests sustainability, agility, and resiliency for VSCND by considering risk and robustness for the first time. These requirements include CO₂ emission, flexible capacity with reliable facilities and responsive SCND. As a result, we, as researchers and designers of SC, try to apply this type of VSCND to delivering vaccines on time because it causes to face pandemics

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and epidemics like COVID-19 as well as possible. It is possible to consider viability to increase cost, but we complied with sustainable, resiliency, and agility requirements. Effect of this form designing is a long time and decrease CO2 emissions, improve the level of responding to citizen and customers. Therefore, as a designer of VVSCND, we suggest to healthcare managers to use and apply comprehensive designing like VVSCND.

Keywords:

Vaccine; Supply chain network design; Viable; Risk; Robustness;

1. Introduction

The Vaccine Supply Chain (VSC) tends to move vaccines from manufacturing to the health center for vaccinating people against illnesses like COVID-19, SARS, etc. (Lim, Norman, & Rajgopal, 2022; Montoya-Torres, Muñoz-Villamizar, & Mejia-Argueta, 2021). This movement should do in minimum time until it stops infection between men (PG Petroianu et al., 2021). Therefore, we need to design a Viable VSC (VVSC) to deliver vaccines with agility, improve resiliency in SC network design (SCND) with sufficient sustainability (minimum pollution and CO₂ emission) that consider robustness and risks against demand fluctuation (Lotfi, Safavi, et al., 2021; Lotfi, Sheikhi, Amra, AliBakhshi, & Weber, 2021; Tseng, Ha, Lim, Wu, & Iranmanesh, 2020). The COVID-19 outbreak makes to pay attention to VVSC to increase the speed of delivering vaccines with minimum disruption and resiliency to prevent an epidemic. Furthermore, we need to distribute stability until breaking in distribution does not happen. We draw VVSCND that contain suppliers, manufacturers, warehouse, health center, and customers in Figure 1.

Figure 1. Vaccine Supply Chain Network Design (VSCND).

Every components of VSCND that is drawn in Figure 1 are possible to cope with disruption. As a result, the importance of this research is paying attention to resiliency and flexibility in facilities

of vaccine production and distribution process. We need to receive kind of vaccines on time. Therefore, SC's agility and responsivity are very important for this type of SCND with minimum emission and pollution.

Further, we define questions of this research as follow:

1. What are the effects of viability on location and flow in VSCND?
2. What are the effects of viability on cost and emission in VSCND?
3. What are the effects of paying attention to risk and robustness on cost and emission in VSCND?

This research tries to design VVSCND to improve the production, distribution, and logistics of vaccine delivery to customers as soon as possible. When viability considers in VSCND, all facilities are resilient against demand fluctuation, respond to all neediness of customers with agility to satisfy it, and keep sustainability by paying attention to environmental impact and energy consumption. Risk disruption and robustness of modeling and facility are methods to tackle resilience against uncertainty (Adobor, 2019; Jeihoonian, Kazemi Zanjani, & Gendreau, 2020). Therefore, all managers and researchers of healthcare need a novel VVSCND by considering risk and robustness in a hard situation like COVID-19.

Eventually, the contributions of this research and the main objectives are as follows:

- Viable VSCND,
- Integrating resiliency, sustainability, agility,
- Considering the risks in demand fluctuation,
- Robustification of the model and improving resiliency.

The paper is arranged as follows. In Section 2, we survey related work in the scope of VSCND. In Section 3, the mathematical VVSCND is stated. In Section 4, the research results, sensitivity analysis and discussion are explained. In Section 5, the managerial insights and practical implications is discussed. In Section 6, the conclusion is summarized.

2. Survey on related work

We survey related work based on the literature review on the scope of VSCND. We consider and classify related work in

Table 1. This table shows the kind, decisions, objectives, methodology, uncertainty, and case study of VSCND. Therefore, we explain recent work in the following.

2.1. Related work on VSCND

Nagurney (2010) redesigned a SCND that is applicable in VSCND. They tried to determine capacity, flows, manufacturing, storage and distribution. They minimized total costs. They applied variational inequalities to solve the model. Chen (2012) designed modeling for VSC in low and middle-income countries with considering the WHO-EPI. Their case study was in Niger. They maximized the number of fully immunized children. Decisions were inventory flow between locations. Hovav and Tsadikovich (2015) explained inventory management and distribution of influenza vaccines. They applied this model through a healthcare supply chain. They attained optimal flow in a network. Their decisions include flow, inventory, and assignment.

Sadjadi, Ziaei, and Pishvae (2019) surveyed a VSCND in Iran. They considered uncertainties in vital parameters. They used a Mixed-Integer Linear Programming (MILP) with Robust Optimization (RO) approach to cope with uncertainties. They modeled strategic and tactical policy together in their model. Georgiadis and Georgiadis (2021) suggested optimal planning for VSC. They contributed with a MILP to obtain optimal quantity inventory between hubs and centers. They minimized total costs that include inventory, storage and indirect costs. They used the decomposition method for large-scale problems based on a divide-and-conquer and an aggregation approach. Srivastava et al. (2021) suggested a cold chain network optimization in India. They proposed a model with the location-allocation problem for the assignment of demand. They embedded a Greedy Adding Algorithm-Based Optimization (GAABO).

Manupati et al. (2021) developed a dynamic MILP cold chain for distributing vaccines. They utilized a dynamic formulation by considering MILP for locating and allocating facilities for cold storage. They suggested a heuristic algorithm to solve the model. Rastegar, Tavana, Meraj, and Mina (2021) configured an inventory location to distribute vaccines in VSCND. They used their

model in developing countries during the COVID-19 pandemic. They applied their model in Iran. Sinha, Kumar, and Chandra (2021) contributed to the inventory as strategies for COVID-19 herd immunity. They applied this model in Indian VSC. Also, they used the required service level for delivering with minimum lead time. They identified scenario-based modeling to show disruption in their model. Lim et al. (2022) reconfigured a vaccine distribution networks. They located intermediate distribution centers and determined flow quantity. They utilized a hybrid heuristic–MIP method for large scale.

2.2. Related work on Resilience and Sustainable VSCND (RSVSCND)

Zhang and Jiang (2014) surveyed a bi-objective MILP model for Emergency Medical Service Network Design (EMND). They applied this model for demand assignment with a robust counterpart approach. They compared the certainty model with the robust counterpart problem and found its better performance. de Carvalho, Ribeiro, and Barbosa-Povoa (2019) proposed a sustainable VSC for designing and planning vaccines. They developed a Multi-Objective MILP model for creating a sustainable VSC. They maximized net present value (NPV) social impacts and minimized environmental impacts. Sazvar, Tafakkori, Oladzad, and Nayeri (2021) developed a sustainable-resilient VSCND (SRVSCND) under uncertainty. They utilized a capacity planning approach. Their case study was influenza VSCND in Iran. They used a robust fuzzy optimization approach (RFO) to tackle with uncertainties and solved the multi-objective model by applying goal programming.

2.3. Related work on Closed-loop VSCND (VCLSCND)

Alizadeh, Makui, and Paydar (2020) considered a closed-loop SCND for consumer medical considering biological risk. They maximized the profit and minimized biological risks by reducing the distance and travel time between locations. They utilized De Novo Programming (DNP) for solving this problem. Another work of Alizadeh, Paydar, Hosseini, and Makui (2021) proposed influenza VSCND during the COVID-19. They considered dynamic demand in their model. Their model includes three objective functions: cost, demand allocation, and lost customer demand. Their case study was in Mazandaran province, Iran. They found that by increasing the capacity of facility, satisfy demand improved.

Table 1. Survey of related work.

Reference	Kind	Decisions	Objectives					Methodology	Uncertainty	Case study
			Economic	Environmental	Energy	Social	others			
(Nagurney, 2010)	VSCND	Capacity, flows, manufacturing, storage and distribution	✓	-	-	-	-	MILP+ variational inequalities	-	Numerical example (NE)
(Chen, 2012)	VSCND	Flow, inventory	-	-	-	-	✓	MILP	-	Nigeria
(Zhang & Jiang, 2014)	EMND	Assignment	✓	-	-	-	-	MILP	RO	NE
(Hovav & Tsadikovich, 2015)	VSCND	Flow, inventory, assignment	✓	-	-	-	-	MILP	-	Israel
(Sadjadi et al., 2019)	VSCND	Location and flow	✓	-	-	-	-	MILP	RO	Iran
(de Carvalho et al., 2019)	SVSCND	Location, flow, inventory and capacity	✓	✓	-	✓	-	MOMILP	-	European
(Alizadeh et al., 2020)	VCLSCND	Location and flow	✓	-	-	-	✓	MOMILP+ DNP	-	Iran
(Lim et al., 2022)	VSCND	Location and flow	✓	-	-	-	-	MILP+Heuristic	-	NE
(Alizadeh et al., 2021)	VCLSCND	Flow	✓	-	-	-	✓	MILP	-	Iran
(Sazvar et al., 2021)	RSVSCND	Location, flow and capacity	✓	✓	-	✓	✓	MOMILP+Goal programming	RFO	Iran
(Georgiadis & Georgiadis, 2021)	VSCND	Flow, assignment and inventory	✓	-	-	-	-	MILP+ Decomposition	-	Greek
(Srivastava et al., 2021)	VSCND	Location allocation	-	-	-	-	✓	MILP+ GAABO	-	India
(Manupati et al., 2021)	VSCND	Location, inventory	✓	-	-	-	-	Dynamic MILP+ heuristic	-	India

Reference	Kind	Decisions	Objectives					Methodology	Uncertainty	Case study
			Economic	Environmental	Energy	Social	others			
Rastegar et al. (2021)	VSCND	Flow, inventory, location	-	-	-	-	✓	MILP	-	Iran
(Sinha et al., 2021)	VSCND	Inventory	✓	-	-	-	-	MILP	S	Indian Japan
(Lim et al., 2022)	VSCND	Location and flow	✓	-	-	-	-	MILP	-	Sub-Saharan Africa.
This research	VVSCND	Location and flow	✓	**	-	-	-	MILP	ROS	Iran
** As constraint										

2.4. Research gap

As shown in

Table 1, we classify the related work on VSCND based on kind decisions, objectives, methodology, uncertainty, and case study. We can see that researchers do not review and contribute to the VVSCND problem. This study tries to show the VVSCND problem and apply a novel mathematical model based on viability for VSCND. Therefore, we need a VVSCND to cope with uncertainty and robustness in a complex situation like COVID-19.

Based on gap research in

Table 1, The contribution of this research is determined as follows:

- Considering viability (resiliency, sustainability, agility) in VSCND,

- Considering sustainability as a constraint of CO₂ emission,
- Considering agility as a constraint of satisfaction demand,
- Considering resiliency as constraints of flexible policy for capacity and redundancy of network,
- Robustification of the model by using hybrid robust stochastic optimization by minimizing weighted expected and maximum cost function.

3. Problem description

The problem of this research is considering viability in VSCND. We try to design a network that all facilities are resilient against demand fluctuation, respond to the neediness of customers with agility to satisfy it and keep sustainability by paying attention to environmental impact and energy consumption. Therefore, we survey VVSCND in this model, including resiliency, sustainability, and agility policy in vaccine distribution. We have suppliers, Vaccine Manufacturer (VM), warehouse, Province Warehouse (PW), District Warehouse (DW), and Health Center (HC) (see Figure 2).

1. Resilience strategy: we present resilience strategy through flexible capacity, availability coefficient, and level of reliable facility activation (Lotfi, Safavi, et al., 2021).
2. Sustainable strategy: we present emission constraints,
3. Agile approach: we add satisfaction demand as an agile strategy,
4. Risks: by considering stochastic optimization,
5. Robustness: by applying hybrid weighted expected and maximin cost function.

Assumptions:

- a) Flow, balance, capacity constraints between facilities are established (Lotfi, Zare Mehrjerdi, Pishvae, & Sadeghieh, 2019),
- b) The capacity is dependent on the scenario, and the probability of availability is considered for reliability and resiliency. Redundancy facilities are defined (Lotfi et al., 2019),
- c) Vaccines are moved between network components (Pishvae & Torabi, 2010),
- d) A pull mechanism is activated for moving vaccines in the forward loop of the network (Pishvae & Torabi, 2010).

Viable vaccine supply chain network design

Figure 2. VVSCND.

Notations:

Indices:

s' Index of supplier $s' \in S' = \{1, 2, \dots, S'\}$,

m Index of Vaccine Manufacturer (VM) $m \in M = \{1, 2, \dots, M\}$,

w Index of warehouse $w \in W = \{1, 2, \dots, W\}$,

p Index of Province Warehouse (PW) $p \in P = \{1, 2, \dots, P\}$,

d Index of District Warehouse (DW) $d \in D = \{1, 2, \dots, D\}$,

h Index of Health Center (HC) $h \in H = \{1, 2, \dots, H\}$,

v Index of vaccine $v \in V = \{1, 2, \dots, V\}$,

t Index of time period $t \in T = \{1, 2, \dots, T\}$,

s Index of scenario $s \in S = \{1, 2, \dots, S\}$,

Parameters:

dd_{vts} Demand for the vaccine v for time period t under scenario s ,

fm_m Cost of activation VM m ,

fw_w	Cost of activation warehouse w ,
fp_p	Cost of activation PW p ,
fd_d	Cost of activation DW d ,
fh_h	Cost of activation HC h ,
$vsm_{s'mvts}$	Variable cost from supplier s' to VM m for vaccine v for time period t under scenario s ,
vmw_{mwvts}	Variable cost from VM m to warehouse w for vaccine v for time period t under scenario s ,
vwp_{wpvts}	Variable cost from warehouse w to PW p for vaccine v for time period t under scenario s ,
vpd_{pdvts}	Variable cost from PW p to DW d for vaccine v for time period t under scenario s ,
vdh_{dhvts}	Variable cost from DW d to HC h for vaccine v for time period t under scenario s ,
em_m	Emission of activation VM m ,
ew_w	Emission of activation warehouse w ,
ep_p	Emission of activation PW p ,
ed_d	Emission of activation DW d ,
eh_h	Emission of activation HC h ,
$esm_{s'mvts}$	Variable emission from supplier s' to VM m for vaccine v for time period t under scenario s ,
emw_{mwvts}	Variable emission from VM m to warehouse w for vaccine v for time period t under scenario s ,
ewp_{wpvts}	Variable emission from warehouse w to PW p for vaccine v for time period t under scenario s ,
epd_{pdvts}	Variable emission from PW p to DW d for vaccine v for time period t under scenario s ,

edh_{dhvts}	Variable emission from DW d to HC h for vaccine v for time period t under scenario s ,
$EmMax_t$	Maximum CO ₂ emission for time period t ,
pm_m	Availability coefficient of VM m ,
pw_w	Availability coefficient of warehouse w ,
pp_p	Availability coefficient of PW p ,
pd_d	Availability coefficient of DW d ,
ph_h	Availability coefficient of HC h ,
cm_{mvtst}	Capacity of VM m for vaccine v for time period t under scenario s ,
cw_{wvtst}	Capacity of warehouse w for vaccine v for time period t under scenario s ,
cp_{pvtst}	Capacity of PW p for vaccine v for time period t under scenario s ,
cd_{dvtst}	Capacity of DW d for vaccine v for time period t under scenario s ,
ch_{hvtst}	Capacity of HC h for vaccine v for time period t under scenario s ,
p_s	Probably of scenario s ,
β	Conservative importance,
γ	Coefficient of agility and response to the customer,
δ	Coefficient of resiliency of facilities,

Decision variables:

Binary variables:

xm_m	If VM m is activated, equal 1; otherwise 0;
xw_w	If warehouse w is activated, equal 1; otherwise 0;
xp_p	If PW p is activated, equal 1; otherwise 0;
xd_d	If DW d is activated, equal 1; otherwise 0;

xh_h If HC h is activated, equal 1; otherwise 0;

Continues Variables:

$qvsm_{s'mvts}$ Quantity from supplier s' to VM m for vaccine v for time period t under scenario s ,

$qvmw_{mwvts}$ Quantity from VM m to warehouse w for vaccine v for time period t under scenario s ,

$qvwp_{wpvts}$ Quantity from warehouse w to PW p for vaccine v for time period t under scenario s ,

$qvpd_{pdvts}$ Quantity from PW p to DW d for vaccine v for time period t under scenario s ,

$qvdh_{dhvts}$ Quantity from DW d to HC h for vaccine v for time period t under scenario s ,

Auxiliary Variables:

FC Fix cost of establishing facility,

VC_s Variable cost for scenario s ,

Γ_s Fix cost and variable cost for scenario s .

FE Fix emission of establishing facility,

VE_{ts} Variable emission for time period t under scenario s ,

$\Gamma\Gamma_{ts}$ Fix cost and variable emission for time period t under scenario s ,

ww_{vts} Auxiliary variable for agility and response to customer,

Δ Auxiliary variable for linearization max function,

Δ'_i Auxiliary variable for linearization max function for constraints.

3.1. VVSCND mathematical model

$$\text{minimize } Z = (1 - \beta) \sum_s p_s \Gamma_s + \beta (\max_s (\Gamma_s)), \quad (1)$$

subject to:

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

$$FC = \sum_m fm_m xm_m + \sum_w fw_w xw_w + \sum_p fp_p xp_p + \sum_d fd_d xd_d + \sum_h fh_h xh_h, \quad (3)$$

$$VC_s = \sum_t \sum_v (\sum_{s'} \sum_m vsm_{s'mvts} qvsm_{s'mvts} + \sum_m \sum_w vmw_{mwvts} qvmw_{mwvts} + \sum_w \sum_p vwp_{wpvts} qvwp_{wpvts} + \sum_p \sum_d vpd_{pdvts} qvpd_{pdvts} + \sum_d \sum_h vdh_{dhvts} qvdh_{dhvts}), \quad \forall s \quad (4)$$

Balance constraints (flow constraints):

$$\sum_d \sum_h qvdh_{dhvts} + ww_{vts} = dd_{vts}, \quad \forall v, t, s \quad (5)$$

$$\sum_d qvdh_{dhvts} \leq \sum_d qvpd_{pdvts}, \quad \forall h, p, v, t, s \quad (6)$$

$$\sum_p qvpd_{pdvts} \leq \sum_p qvwp_{wpvts}, \quad \forall d, w, v, t, s \quad (7)$$

$$\sum_w qvwp_{wpvts} \leq \sum_w qvmw_{mwvts}, \quad \forall p, m, v, t, s \quad (8)$$

$$\sum_m qvmw_{mwvts} \leq \sum_m qvs'm_{s'mvts}, \quad \forall w, s', v, t, s \quad (9)$$

Agility constraints (satisfaction demand):

$$\frac{\sum_d \sum_h \sum_v \sum_t \sum_s qvdh_{dhvts}}{\sum_v \sum_t \sum_s dd_{vts}} \geq \gamma, \quad (10)$$

Resiliency constraints (flexible policy for capacity and redundancy of network)

$$\sum_d qvdh_{dhvts} \leq ph_h Ch_{hvts} xh_h, \quad \forall h, v, t, s \quad (11)$$

$$\sum_p qvpd_{pdvts} \leq pd_d Cd_{dvts} xd_d, \quad \forall d, v, t, s \quad (12)$$

$$\sum_w qvwp_{wpvts} \leq pp_p Cp_{pvts} xp_p, \quad \forall p, v, t, s \quad (13)$$

$$\sum_m qvmw_{mwvts} \leq pw_w Cw_{wvts} xw_w, \quad \forall w, v, t, s \quad (14)$$

$$\sum_{s'} qvs'm_{s'mvts} \leq pm_m Cm_{mvts} xm_m, \quad \forall m, v, t, s \quad (15)$$

$$\frac{\sum_h ph_h xh_h + \sum_d pd_d xd_d + \sum_p pp_p xp_p + \sum_w pw_w xw_w + \sum_m pm_m xm_m}{|H| + |D| + |P| + |W| + |M|} \geq \delta, \quad (16)$$

Sustainability constraints (maximum allowed emission):

$$\Gamma_{ts} = FE + VE_{ts}, \quad \forall t, s \quad (17)$$

$$FE = \sum_m em_m xm_m + \sum_w ew_w xw_w + \sum_p ep_p xp_p + \sum_d ed_d xd_d + \sum_h eh_h xh_h, \quad (18)$$

$$VE_{ts} = \sum_v \left(\sum_{s'} \sum_m esm_{s'mvts} qvsm_{s'mvts} + \sum_m \sum_w emw_{mwvts} qvmw_{mwvts} + \right. \\ \left. \sum_w \sum_p ewp_{wpvts} qvwp_{wpvts} + \sum_p \sum_d epd_{pdvts} qvpd_{pdvts} + \right. \\ \left. \sum_d \sum_h edh_{dhvts} qvdh_{dhvts} \right), \quad \forall t, s \quad (19)$$

$$(1 - \beta) \sum_s p_s \Gamma_{ts} + \beta (\max_s (\Gamma_{ts})) \leq EmMax_t, \quad \forall t \quad (20)$$

Decision variables:

$$xm_m, xw_w, xp_p, xd_d, xh_h \in \{0, 1\}, \quad \forall m, w, p, d, h \quad (21)$$

$$qvsm_{s'mvts}, qvmw_{mwvts}, qvwp_{wpvts}, qvpd_{pdvts}, qvdh_{dhvts} \geq 0. \quad \forall s', m, w, p, d, h, v, t, s \quad (22)$$

The objective function (1) tries to minimize the weighted expected and minimax of the cost function. We proposed this cost function model for robustness and risk-averse against demand disruption. Constraints (2) contain fixed and variable costs. Constraints (3) show the fixed cost

that includes activating facilities in VSCND for all periods. Constraints (4) indicate the variable costs of VM, warehouse, PW, DW, and HC. Constraints (5) to (9) are flow constraints in forwarding VVSCND. Constraints (10) show the agile approach and ratio of total transshipment from DWs to the citizen for all demand in retailer is greater than the threshold. Constraints (11) to (15) show capacity constraint by including the flexible facility capacity dependent on the scenario as a resiliency strategy. Constraints (16) consider the ratio of resiliency in available facilities to all facilities is greater than the threshold. Constraints (17) include fixed and variable emissions. Constraints (18) to (19) show fixed and variable emissions by activating and variable emissions for every period, scenarios of VSCND components. Constraints (20) guarantee that the network's total environmental emissions are less than the maximum allowed. Constraints (21) are binary variables and facilities' locations for VVSCND. Constraints (22) are positive and flow quantities between facilities.

3.2. Linearization of max (Preliminary)

As can be seen, the max function makes the model to Nonlinear MILP (MINLP) in the objective function (1). We should change to MIP to decrease the time of solving smoothly (Gondal & Sahir, 2013; Sherali & Adams, 2013). Linearizing max function in objective function and constraint:

Suppose: If there is $\beta = \max(\Omega_s)$, then we can add these forms of constraint to the model:

$$\beta \geq \Omega_s, \forall s.$$

3.3. Linearization of VVSCND

We utilized operational research methods to linearize the main model (1). Solving the model by a commercial MIP solver is more comfortable than MINLP and does not stick to the local optimum. This method decreases the time solution and the complexity of the model. We linearized objective (1) and constraint (20) for max. As a result, we change equations (23) to (26):

Linearization of VVSCND

$$\text{minimize } Z = (1 - \beta) \sum_s p_s \Gamma_s + \beta(\Delta), \quad (23)$$

subject to:

$$\Delta \geq \Gamma_s \quad \forall s \quad (24)$$

$$\Delta'_t \geq \Gamma_{ts} \quad \forall t, s \quad (25)$$

$$(1 - \beta) \sum_s p_s \Gamma_{ts} + \beta(\Delta'_t) \leq EmMax_t, \quad \forall t \quad (26)$$

Constraints (2)-(19), (21)-(22).

3.3. Complexity of VVSCND

We define the complexity of VVSCND that determine in equations (27) to (30). We can see that constraints, positive and free variables depending on the scenario, are linear approximately. We propose scenario reduction algorithms to decrease scenario, constraints, and binary variables. This subject can help solution time.

$$\text{Binary variables} = |M| + |W| + |P| + |D| + |H|, \quad (27)$$

$$\text{Positive variables} = (|S'| + |M| + |W| + |P| + |D| + |H| + 1) |V| |T| |S|, \quad (28)$$

$$\text{Free variables} = 5 + 2|S| + 3|T| + 2|S| |T|, \quad (29)$$

$$\begin{aligned} \text{Constraints} = & 5 + 3|S| (1 + |T|) + 3|T| + \\ & (1 + |H| + |P| (|H| + 1 + |M|) + |D| + |W| (|D| + 1 + |S'|) + |M|) |V| |T| |S|. \end{aligned} \quad (30)$$

4. Results and discussion

We survey and estimate parameters by managers of health centers for VSCND in Iran. We show the performance of the mathematical model. The number of indices of the main model (P1) is defined in Table 2, and healthcare managers in Table 3 assign the parameters. They propose the probability of occurrence based on the optimistic, pessimistic, and possible scenarios that are the same. The objective function is 3115731.668 in Table 2, and the final location-allocation is drawn in Figure 4.

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

Problem	$ S' \cdot M \cdot W \cdot P \cdot D \cdot H \cdot V \cdot T \cdot S $	Variables				Constraint	Cost function	Time solution	CO ₂ Emission
		Binary	Positive	Free					
P1	3.3.3.3.5.5.1.3.3	19	531	38	689	3115731.668	66.514	10000	

Table 3. Parameters of the case study.

Parameters	Value	Unit	Parameters	Value	Unit
dd_{vts}	$1000000*((s - 1)*0.1+0.9)$	Num.	ewp_{wpvts}	$U(500,600)/1000/1000*((s - 1)*0.1+0.9)$	Ton
fm_m	$U(33,35)*10000/5$	Dollar	epd_{pdvts}	$U(500,600)/1000/1000*((s - 1)*0.1+0.9)$	Ton
fw_w	$U(33,35)*10000/1.5$	Dollar	edh_{dhvts}	$U(500,600)/1000/1000*((s - 1)*0.1+0.9)$	Ton
fp_p	$U(33,35)*10000/2$	Dollar	$EmMax_t$	10000	Ton
fd_d	$U(33,35)*10000/2.5$	Dollar	pm_m	$U(95,98)$	%
fh_h	$U(33,35)*10000/4$	Dollar	pw_w	$U(95,98)$	%
$vsm_{s'mvts}$	$U(3,4)/1000*((s - 1)*0.1+0.9)$	Dollar	pp_p	$U(95,98)$	%
vmw_{mwvts}	$U(3,4)/1000*((s - 1)*0.1+0.9)$	Dollar	pd_d	$U(95,98)$	%
vwp_{wpvts}	$U(3,4)/1000*((s - 1)*0.1+0.9)$	Dollar	ph_h	$U(95,98)$	%
vpd_{pdvts}	$U(3,4)/1000*((s - 1)*0.1+0.9)$	Dollar	p_s	$1/ S $	%
vdh_{dhvts}	$U(3,4)/1000*((s - 1)*0.1+0.9)$	Dollar	Cm_{mvts}	$10000000*((s - 1)*0.1+0.9)$	Num.
em_m	$U(6,7)*300$	Ton	Cw_{wvts}	$1000000*((s - 1)*0.1+0.9)$	Num.
ew_w	$U(6,7)*40$	Ton	Cp_{pvts}	$1000000*((s - 1)*0.1+0.9)$	Num.
ep_p	$U(6,7)*30$	Ton	Cd_{dvts}	$1000000*((s - 1)*0.1+0.9)$	Num.
ed_d	$U(6,7)*25$	Ton	Ch_{hvts}	$1000000*((s - 1)*0.1+0.9)$	Num.
eh_h	$U(6,7)*15$	Ton	β	50	%
$esm_{s'mvts}$	$U(500,600)/1000/1000*((s - 1)*0.1+0.9)$	Ton	γ	90	%
emw_{mwvts}	$U(500,600)/1000/1000*((s - 1)*0.1+0.9)$	Ton	δ	$900/(M + W + P + D + H)$	%

We used a computer system with this configuration: CPU 3.2 GHz, 8.00 GB RAM, Processor Core i3-3210, 64-bit operating system. Finally, we solve the main model by GAMS-CPLEX solver. We determine VM, warehouse, PW, DW, and HC (cf. Figure 3). After solving the model, we activate VM, warehouse, PW, DW, and HC and assign the location and the quantity of VVSCND components (cf. Table 4).

Figure 3. Potential location for the VVSCND facility.

Figure 4. Final location for VVSCND facility.

Table 4. Binary variable for the VVSCND facility.

Problem	Location variable	Location
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P1	xm_m	Tabriz 0	Tehran 1		Sabzevar 0	
	xw_w	Ghazvin 0	Tehran 1		Isfahan 0	
	xp_p	Yasoj 1	Kashmar 1		Kerman 0	
	xd_d	Tabriz 0	Ilam 1	Shiraz 1	Kashmar 0	Kerman 1
	xh_h	Tabriz 1	Mashhad 1	Abadan 1	Lar 1	Iranshahr 1

4.1. Comparing proposed model

Eventually, we compare the main model with the situation that consider without risk and worst case in Table 5. By employing worst-case and risk, we can see that the cost function is almost 0.04% greater than without risk and worst-case for VVSCND.

Figure 5. Comparing proposed model.

Table 5. Comparing P1- VVSCND and VVSCND without risk and worst case.

Model	P1- VVSCND	P1- VVSCND without risk and worst case	Gap
P1	3115731.668	3114437.480	-0.04%

4.2. Variation on the conservative coefficient

In this section, we vary the conservative coefficient (β) as a parameter of conservative decision-makers. By changing between 0%-100%, if the conservative coefficient moves to 100%, the cost function grows in Table 6, Figure 6, and Figure 7. It means that if the conservative coefficient rises to 50%, the cost function will increase to 0.04%, but the time solution changes a little.

Table 6. Variation of conservative coefficient.

Problem	Conservative coefficient (β)	Cost function	Time solution	Cost variation	CO ₂ Emission
P1	0%	3114437.48	40.263	-0.04%	10000
P1	25%	3115129.13	64.821	-0.02%	10000
P1-main model	50%	3115731.668	66.514	0.00%	10000
P1	75%	3116334.21	62.193	0.02%	10000
P1	100%	3116936.75	86.172	0.04%	10000

Figure 6. Cost function for different conservative coefficient. **Figure 7.** Time solution for for different conservative coefficient.

4.3. Variation on agility coefficient

We vary the agility coefficient (γ) as a customer response parameter in this section. When the agility coefficient grows, it increases the response level and the cost function (cf. Table 7 and Figure 8). By raising 10% for agility coefficient, the cost function increased 0.34%.

Table 7. Variation of the agility coefficient.

Problem	Agility coefficient (γ)	Cost function	Time solution	Cost variation	CO ₂ Emission
P1	80%	3034725.38	49.363	-2.60%	10000
P1	85%	3111796.34	74.05	-0.13%	10000
P1-main model	90%	3115731.67	66.514	0.00%	10000
P1	95%	3119861.37	30.724	0.13%	10000
P1	100%	3126383.41	25.829	0.34%	10000

Figure 8. Effects of the agility coefficient.

4.4. Variation on resiliency coefficient

This section changes the resiliency coefficient (δ) as a parameter of resiliency against disruption. The cost function increases when the resiliency coefficient grows (cf. Figure 8 and Table 8). Increasing resiliency coefficient makes to activate facilities. As a result, the cost function increase, too.

Table 8. Changing resiliency coefficient.

Problem	Resiliency coefficient (δ)	Cost function	Time solution	Cost variation	CO ₂ Emission
P1-main model	47%	3115731.67	66.514	0.0%	10000
P1	63%	3242869.47	1.354	4.1%	10000
P1	68%	3374925.63	0.482	8.3%	10000
P1	74%	3542893.68	0.352	13.7%	10000

P1	79%	3764246.787	0.318	20.8%	10000
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Figure 9. Variation on resiliency coefficient for the cost function.

4.5. Variation on the scale of the main model

We define the several large-scale problems in Table 9. As we can see, by increasing the scale of problems, the time solution and cost function increase in Figure 10 and Figure 11. Therefore, the main model is NP-hard and shows exponential behavior on a large scale. Eventually, we can utilize a heuristic, metaheuristic, and new exact solution to solve this model in minimum time for large scale.

Table 9. Cost and time solution for medium scale.

Problem	$ S' \cdot M \cdot W \cdot P \cdot D \cdot H \cdot V \cdot T \cdot S $	Variables			Constraint	Cost function	Time solution	CO ₂ Emission
		Binary	Positive	Free				
P1	3.3.3.3.5.5.1.3.3	19	531	38	689	3115731.67	66.514	10000
P2	3.3.3.3.5.5.1.3.5	19	885	54	1139	3129533.844	100.815	10000
P3	4.4.4.4.4.6.1.3.5	22	1095	54	1559	3429027.874	1000.379	10000
P4	4.4.4.6.6.6.2.5.5	26	5650	80	6760	-	>9800	-

Figure 10. Cost function for medium scale.

Figure 11. Time solution for medium scale.

4.6. Discussion

As can be seen, we show a VSCND with a viability approach that integrates resiliency, sustainability, and agility in vaccine production and distribution for the first time. Because we add agility constraints (satisfaction demand), resiliency constraints (flexible and scenario-based capacity and redundancy network), and sustainability constraints (maximum allowed emission), this model has a novel contribution and cannot compare with another model. As shown in

Table 1, only these researchers (Alizadeh et al., 2020; Alizadeh et al., 2021; de Carvalho et al., 2019; Sazvar et al., 2021) pay attention to only closed-loop, sustainable, and resiliency. Therefore, gap research integrates viability (resiliency, sustainability, and agility).

This research includes a VSCND that contains suppliers, VM, warehouse, PW, DW, and HC. We want to locate a resilience facility and determine flow quantity. Finally, we compare our model with a situation that we do not consider risk and worst-case. We found that the cost function is approximately 0.04% greater than without risk and worst case by considering risk and worst case. In addition, we run sensitivity analysis on essential parameters. A variation on the conservative coefficient shows us that increasing the conservative coefficient; it makes to increases the cost function. A variation on agility coefficient results by increasing the agility coefficient shows that responding and the cost function will increase. At the same time, a variation on the resiliency coefficient makes to increase resiliency and cost, too. Therefore, considering leveling

conservative, agility and resiliency make to robust mathematical model against conservative decision-makers, responding citizen in minimum time and resilience against disruption and fluctuation.

5. Managerial insights and practical implications

This research suggests novel insights and practical implications for healthcare managers. We suggest a VVSCND for the first time to consider sustainable, resiliency and agility requirements. These requirements include CO₂ emission, flexible capacity with reliable facilities and responsive SCND. As a result, we, as researchers and designers of SC, try to apply this type of VSCND to delivering vaccines on time because it causes to face pandemics and epidemics like COVID-19 as well as possible. It is possible to consider viability to increase cost, but we complied with sustainable, resiliency, and agility requirements. Effect of this form designing is a long time and decrease CO₂ emissions, improve the level of responding to citizen and customers. Therefore, as a designer of VVSCND, we suggest to healthcare managers to use and apply comprehensive designing like VVSCND.

6. Conclusions and Outlook

This research suggests sustainability, agility, and resiliency for VSCND by considering risk and robustness for the first time. We applied a hybrid robust stochastic optimization and worst-case for robustness in the objective function. We minimize the weighted expected and maximum cost function and suggest robustness against demand fluctuation. Finally, we located VM, warehouse, PW, DW, and HC. Eventually, we assigned flow on the forward VSCND.

The findings are as follows:

1. We compare VVSCND with conditions that do not consider risk and worst case in Table 5. By employing risk and worst case, we can see that the cost function is almost 0.04% greater than without risk and worst case.
2. If the conservative coefficient increases to 100%, the cost function grows in Table 6, Figure 6, and Figure 7. If the conservative coefficient increases 50%, the cost function will increase to 0.04%, but the time solution changes slightly.

3. If the agility coefficient grows, we can see that the response level and cost function will increase (cf. Table 7 and Figure 8). By raising 10% for agility coefficient, the cost function increased 0.34%.
4. If the resiliency coefficient grows, we can see that the cost function will increase (cf. Figure 9 and Table 8). Increasing resiliency coefficient makes to activate facilities. As a result, the cost function increase.
5. When the problem scale rises, we see that the cost function and time solution rise in Figure 10 and Figure 11. Therefore, the main model is NP-hard and shows exponential behavior on a large scale. Eventually, we can solve the model by heuristic, metaheuristic, and new exact solution in minimum time on a large scale.

The limitation of this research is solving the large-scale in minimum time. It is better to use exact algorithms like Benders decomposition, meta-heuristic algorithms, branch-and-cut, and branch and price (Fakhrzad & Lotfi, 2018; Lotfi, Mehrjerdi, & Mardani, 2017). Eventually, other resilience methods and sustainable strategies like backup suppliers and node complexity increase resiliency and sustainability.

Further, applying other risk criteria like the Conditional β -mean approach (Ghaffarinasab & Kara, 2022) is useful to consider the risk method (Lotfi, Kargar, et al., 2021; Zare Mehrjerdi & Lotfi, 2019). Other uncertainty methods like stochastic programming and robust optimization (convex) make it close to the real world (Lotfi, Sheikhi, et al., 2021). In addition, we propose to use another uncertainty method like robust fuzzy optimization and a data-driven approach for a robustness model against disruption and resiliency (Krebs, Müller, & Schmidt, 2022). Eventually, RFID and blockchain improve SC's agility and viability by applying Internet-of-Thing (IoT) (De Vass, Shee, & Miah, 2021).

7. Declarations

7.1. Ethics approval and consent to participate

Not applicable.

7.2. Consent for publication

Not applicable.

7.3. Availability of data and material

The data and code supporting this study's findings are openly available in VVSCND at <http://dx.doi.org/10.17632/yxfr8jyr5t.1>, (Lotfi, 2022).

7.4. Competing interests

The authors declare that they do not have any competing interests.

7.5. Funding

The authors did not receive any funding for this research work.

7.6. Authors' contributions

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

Reza Mohammad Shafiei: methodology, software, formal analysis, data curation, writing original draft, writing review and edit, visualization.

Masoumeh Ghavami Komeleh: methodology, validation.

Fatemeh Gholizadeh Pasha: validation, writing review and edit.

Mohammad Ferasat: validation, writing review and edit.

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References

- Adobor, H. (2019). Supply chain resilience: a multi-level framework. *International Journal of Logistics Research and Applications*, 22(6), 533-556.
- Alizadeh, M., Makui, A., & Paydar, M. M. (2020). Forward and reverse supply chain network design for consumer medical supplies considering biological risk. *Computers & Industrial Engineering*, 140, 106229.
- Alizadeh, M., Paydar, M. M., Hosseini, S. M., & Makui, A. (2021). Influenza vaccine supply chain network design during the COVID-19 pandemic considering dynamical demand. *Scientia Iranica*.
- Chen, S.-I. (2012). *Modeling the WHO-EPI vaccine supply chain in low and middle income countries*. University of Pittsburgh.
- de Carvalho, M. I., Ribeiro, D., & Barbosa-Povoa, A. P. (2019). Design and Planning of Sustainable Vaccine Supply Chain *Pharmaceutical Supply Chains-Medicines Shortages* (pp. 23-55): Springer.
- Fakhrzad, M.-B., & Lotfi, R. (2018). Green vendor managed inventory with backorder in two echelon supply chain with epsilon-constraint and NSGA-II approach. *Journal of Industrial Engineering Research in Production Systems*, 5(11), 193-209.
- Georgiadis, G. P., & Georgiadis, M. C. (2021). Optimal planning of the COVID-19 vaccine supply chain. *Vaccine*, 39(37), 5302-5312.
- Ghaffarinasab, N., & Kara, B. Y. (2022). A conditional β -mean approach to risk-averse stochastic multiple allocation hub location problems. *Transportation Research Part E: Logistics and Transportation Review*, 158.

- Gondal, I. A., & Sahir, M. H. (2013). Model for biomass-based renewable hydrogen supply chain. *International journal of energy research*, 37(10), 1151-1159.
- Hovav, S., & Tsadikovich, D. (2015). A network flow model for inventory management and distribution of influenza vaccines through a healthcare supply chain. *Operations Research for Health Care*, 5, 49-62.
- Jeihoonian, M., Kazemi Zanjani, M., & Gendreau, M. (2020). Dynamic reverse supply chain network design under uncertainty: mathematical modeling and solution algorithm. *International Transactions in Operational Research*.
- Krebs, V., Müller, M., & Schmidt, M. (2022). Γ -robust linear complementarity problems with ellipsoidal uncertainty sets. *International Transactions in Operational Research*, 29(1), 417-441.
- Lim, J., Norman, B. A., & Rajgopal, J. (2022). Redesign of vaccine distribution networks. *International Transactions in Operational Research*, 29(1), 200-225.
- Lotfi, R. (2022). VVSCND. Retrieved from <http://dx.doi.org/10.17632/yxfr8jvr5t.1>
- Lotfi, R., Kargar, B., Hoseini, S. H., Nazari, S., Safavi, S., & Weber, G. W. (2021). Resilience and sustainable supply chain network design by considering renewable energy. *International Journal of Energy Research*.
- Lotfi, R., Mehrjerdi, Y. Z., & Mardani, N. (2017). A multi-objective and multi-product advertising billboard location model with attraction factor mathematical modeling and solutions. *International Journal of Applied Logistics (IJAL)*, 7(1), 64-86.
- Lotfi, R., Safavi, S., Gharehbaghi, A., Ghaboulain Zare, S., Hazrati, R., & Weber, G.-W. (2021). Viable Supply Chain Network Design by considering Blockchain Technology and Cryptocurrency. *Mathematical Problems in Engineering*, 2021.
- Lotfi, R., Sheikhi, Z., Amra, M., AliBakhshi, M., & Weber, G.-W. (2021). Robust optimization of risk-aware, resilient and sustainable closed-loop supply chain network design with Lagrange relaxation and fix-and-optimize. *International Journal of Logistics Research and Applications*, 1-41.
- Lotfi, R., Zare Mehrjerdi, Y., Pishvae, M. S., & Sadeghieh, A. (2019). *A robust optimization approach to Resilience and sustainable closed-loop supply chain network design under risk averse*. Paper presented at the 15th Iran International Industrial Engineering Conference.
- Manupati, V. K., Schoenherr, T., Subramanian, N., Ramkumar, M., Soni, B., & Panigrahi, S. (2021). A multi-echelon dynamic cold chain for managing vaccine distribution. *Transportation Research Part E: Logistics and Transportation Review*, 156, 102542.
- Montoya-Torres, J. R., Muñoz-Villamizar, A., & Mejia-Argueta, C. (2021). Mapping research in logistics and supply chain management during COVID-19 pandemic. *International Journal of Logistics Research and Applications*, 1-21.
- Nagurney, A. (2010). Optimal supply chain network design and redesign at minimal total cost and with demand satisfaction. *International Journal of Production Economics*, 128(1), 200-208.
- PG Petroianu, L., Zabinsky, Z. B., Zameer, M., Chu, Y., Muteia, M. M., Resende, M. G., . . . Draiva, A. (2021). A light-touch routing optimization tool (RoOT) for vaccine and medical supply distribution in Mozambique. *International Transactions in Operational Research*, 28(5), 2334-2358.
- Pishvae, M. S., & Torabi, S. A. (2010). A possibilistic programming approach for closed-loop supply chain network design under uncertainty. *Fuzzy sets and systems*, 161(20), 2668-2683.
- Rastegar, M., Tavana, M., Meraj, A., & Mina, H. (2021). An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic. *Vaccine*, 39(3), 495-504.
- Sadjadi, S. J., Ziaei, Z., & Pishvae, M. S. (2019). The design of the vaccine supply network under uncertain condition: A robust mathematical programming approach. *Journal of Modelling in Management*.
- Sazvar, Z., Tafakkori, K., Oladzad, N., & Nayeri, S. (2021). A capacity planning approach for sustainable-resilient supply chain network design under uncertainty: A case study of vaccine supply chain. *Computers & Industrial Engineering*, 159, 107406.
- Sherali, H. D., & Adams, W. P. (2013). *A reformulation-linearization technique for solving discrete and continuous nonconvex problems* (Vol. 31): Springer Science & Business Media.
- Sinha, P., Kumar, S., & Chandra, C. (2021). Strategies for ensuring required service level for COVID-19 herd immunity in Indian vaccine supply chain. *European Journal of Operational Research*.
- Srivastava, V., Ratna, M., Ray, A., Shukla, S., Shrivastava, V., Kothari, N., . . . Jandu, H. S. (2021). Strengthening the immunization supply chain: A time-to-supply based approach to cold chain network optimization & extension in Madhya Pradesh. *Vaccine*, 39(45), 6660-6670.

- Tseng, M.-L., Ha, H. M., Lim, M. K., Wu, K.-J., & Iranmanesh, M. (2020). Sustainable supply chain management in stakeholders: supporting from sustainable supply and process management in the healthcare industry in Vietnam. *International Journal of Logistics Research and Applications*, 1-20.
- Zare Mehrjerdi, Y., & Lotfi, R. (2019). Development of a mathematical model for sustainable closed-loop supply chain with efficiency and resilience systematic framework. *International Journal of Supply and Operations Management*, 6(4), 360-388.
- Zhang, Z.-H., & Jiang, H. (2014). A robust counterpart approach to the bi-objective emergency medical service design problem. *Applied Mathematical Modelling*, 38(3), 1033-1040.