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A p-robust mathematical model for a sustainable vaccine supply chain

Mahmoud Pormollaahmad[1], Saeed fazayeli[2]* and and Ali Doniavi[3]

[1] Master of Science in engineering, Urmia University, Urmia, West Azerbaijan Province, Iran
[2]Assistant Professor, Department of Industrial Engineering, Urmia University, Urmia, Iran
[3] Associate Professor, Department of Industrial Engineering, Urmia University, Urmia, Iran

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Abstract

This paper introduces a multi-product, multi-period, and multi-level sustainable supply chain (SC) network problem, including several production centers. It includes stocking technology and different transportation methods in conditions of uncertainty. The increasing demand for vaccines in the conditions of the corona virus epidemic and the existing sensitivities towards the stability characteristics as well as the unique characteristics of the vaccine SC are the reasons for redesigning this network. The economic, environmental and social goals are considered in presented mathematical model in order to achieve organization's sustainability strategy and stakeholder satisfaction. The economic objective function includes two types of tactical and strategic costs to avoid creating sub-optimal solutions. The environmental objective function calculates the total emission of pollution in SC. The social objective is to maximize the social responsiveness of the SC. Three indicators including job opportunity creation (positive effect), employee health and safety (negative effect) and customer health as risk of harm to customer using product (negative effect). LP metric and epsilon limit methods are used to solve the model in small dimensions and Pareto front drawing method is used to draw the conflict of interest diagram. A numerical example has been proposed to evaluate and test the model, and in order to deal with non-deterministic parameters and reduce its impact on the optimal solution, a robust optimization model has been proposed. Finally, the results in deterministic and robust state has been compared.

Keywords:
vaccine supply Chain
sustainability
p-robust model

***Correspondence E-mail**: s.fazayeli@urmia.ac.ir

INTRODUCTION

Governments and societies have concerns about global warming, loss of natural resources, excessive use of non-renewable resources and increasing industrial activities in developed and developing countries caused many managers to consider sustainable businesses [1]. In order to survive in a competitive market, organizations have to reduce operating costs, improve service levels, simultaneous attention to economic, environmental and social aspects of SC. Therefore, organizations are trying to optimize their supply chain network (SCN) considering all elements of sustainability (i.e. economic, environmental and social aspects) [2]. Consequently, a company that is oriented to join global SC, should consider sustainability in its SC [3].

Recently, the world community has faced COVID-19 pandemic, which is the most destructive disease in recent decades. SCs have faced various challenges and this destructive and widespread disease has adversely affected SCs worldwide [4]. Many researchers have investigated the significant effects of COVID-19 on SCs. Productivity, efficiency, and responsiveness of SCs have suffered due to material shortages, delivery delays, disruptions in logistics and transportation systems, facility capacities reduction and other disruption-related harms. The positive point of the occurrence of this disease is the special attention paid to the sustainability of SC [5]. As mentioned, while world focused on developing new vaccines and measuring their effects on humans, the lack of understanding and correct handling of vaccine supply chain issues, can greatly reduce the effectiveness of any vaccine. Therefore, any agency involved in vaccine decision-making should consider vaccine SCs when making key decisions [6]. This disease caused several problems and beside its affection on human lives such as quarantines and other restrictions, industries also had to reduce their activities. This mandatory decision had different economic, social and environmental results such as job loss, revenue reduction, bankruptcy and recycling activity stop [7]. Also, for some SCs, the demand has increased dramatically so that the supply cannot respond and the organization faced shortage. In general, the epidemic of COVID-19 was a test for resilience and sustainability of SCs by impacting on various aspects of the economy and society [8].

This study tries to expand the existing models in the design of the vaccine SC network and the dimensions of sustainability that were less mentioned in the previous researches. The objectives of this research are to identify and examine the dimensions, paradigms and concepts of sustainable SCN design that have been used by academics and experts in the past, and to examine the impact of including sustainability in vaccine SC and how to address it. This study aims to present a mathematical model for the vaccine SC, which includes the SC stability issue. To consider uncertainty in the parameters, a relatively new probabilistic-robust approach is used to overcome the disadvantages of the two probabilistic and robust approaches to gain optimal answers.

The main question of this study is whether it is possible to present a mathematical model for the design of a vaccine SCN that includes location decisions (storage centers, manufacturing centers and packaging centers) and routing decision, where model parameters such as demand and other parameters considered uncertain. Other questions can also be raised as follows: Can sustainability be included in the vaccine supply chain (VSN)? Can providing a sustainable VSC model have better results in the organization's strategic and operational planning? Will considering the problem in a non-deterministic way provide better results? Does considering the probabilistic-robust method for uncertainty in the parameters of the problem produce more realistic results?

LITERATURE REVIEW

Various researchers focused on sustainable SC in recent years. Some researchers paid attention to the uncertainty in the SC. Nayeri et al. presented a multi-objective MIP model to configure a sustainable SC network under uncertainty, while considering flexibility and responsiveness measures. To deal with the uncertainty, they proposed an improved version of the fuzzy stochastic optimization model [2]. Gholipoor et al. stated that companies are creating closed loop SCs to increase their profit and the sustainability. To deal with this, a single-objective, multi-product, multi-period MIP model under fuzzy demand proposed by the authors [9]. Babazadeh et al. designed a SC by modeling a mixed integer nonlinear problem under risk. The aim of this study is to minimize environmental impacts and total costs under supply and demand uncertainties [10]. It is stated in Mousavi et al.'s article that when all three aspects of sustainability are considered, uncertainties are rarely addressed. In this paper, a multi-objective MILP model generated for a robust sustainable SC network problem with uncertainty in all three sustainability objectives including cost and greenhouse gas emission minimization and job creation maximization [11]. Another paper presented by Zahiri et al. introduces an integrated and stable multi-objective MILP model for a pharmaceutical SC under uncertainty. To deal with the uncertainty, a new fuzzy probabilistic-stochastic programming approach is developed [12]. Eskandarpour et al. reviewed 87 articles in the field of SC network design. They believe that the borders of environmental and social researches should move beyond the greenhouse gas emissions to the optimum use of life cycle approaches and new social criteria should be included in the models. More effective inclusion of uncertainty and risk in models with improved multi-objective approaches is also needed [13]. Habib et al. proposed a MILP model to minimize total cost and carbon emissions. In this paper, a robust probabilistic programming approach has been used to address supply and demand uncertainties in the network [14].

Some studies integrated economic and environmental aspects to reduce environmental pollution levels with financial stability. Yu & Solvang developed a closed-loop SCN and modeled a multi-objective optimization problem with fuzzy and stochastic parameters. The main objective of this study was to optimize the trade-off between cost effectiveness and environmental performance [15]. Shen investigated a sustainable SC in an uncertain environment [16]. Sherafati et al. designed an SCN by developing all three dimensions of sustainability while imposing an appropriate carbon regulatory mechanism. The social aspects considered in this study were unemployment rate, corruption, crimes, etc. [17]. The research conducted by Mota et al. generates a multi-objective MILP model which integrates several interconnected decisions including facility location, capacity determination, supplier selection, definition of purchase levels, technology selection and allocation, and defining the transportation network that includes unimodal and intermodal options [18]. Mahmud et al. identified key VSC strategies and their interrelationships under four groups: Intra-organizational, Inter-organizational, Legislative, and Environmental, based on previous literature and the expert opinions of industrial practitioners and policymakers [19]. Gilani and Sahebi presented a mathematical model of a sustainable SC for the COVID-19 vaccine that covers the economic, environmental and social aspects and provides vaccine both domestically and internationally. They also proposed a robust data-driven model based on a polyhedral uncertainty set to address the unjust worldwide vaccine distribution as an uncertain parameter [20]. Tirkolaee et al. developed a novel two-stage decision support framework for configuring multi-echelon VSC, resilient supplier selection, and order allocation under uncertainty. A robust multi-objective optimization model is then built for order allocation considering resiliency scores, reliability of facilities, and uncertain supply and demand [21].

On the other hand, vaccine supply chain should implement as a cold supply chain for health reasons. Gan et al. investigated the cooling performance of vaccine cold storage boxes integrated with phase change material bottles [22]. Khodaee et al. presented a humanitarian cold supply chain distribution model for COVID-19 vaccine distribution in the European Union [23]. Lin et al. considered cold chain transportation decision in the vaccine supply chain [24]. Kumar et al. studied using new cold chain technologies to extend the vaccine cold chain in India [25].

Corporate sustainability metrics are widely available and used by numerous organizations around the world. These metrics are often shared with the public in corporate sustainability reports. Examples of absolute and relative metrics are widely available, including through the Global Reporting Initiative (GRI), which lists more than 90 indicators.

Analysis of criteria based on 13 key features of SSCM proposed by Ahi & Searcy, indicates that more than one-third of the criteria focused on environmental issues, 17% focuses on economic issues and 12.1% focused on social issues. "Air emissions" with 28 repetitions, "energy consumption" with 24 repetitions, and "greenhouse gas emissions" with 24 repetitions are some of the high-frequency environmental measures used. "Cost" (12 times), "return on investment" (11 times) and "operating cost" (11 times) were the most frequently used economic criteria. Examples of social criteria with high frequency are "discrimination" (6 times), "health and safety incidents" (5 times), and "supervisory and public services" (4 times) [26].

According to the Ahi & Searcy, environmental issues, economic issues and social issues are the most frequently used criteria and received most of the attention of researchers. In this study, these 3 sustainability paradigms are used to design a sustainable VSC [26]. Also, by reviewing sustainable SC articles, from the years 2015 to 2022 according to table (1), few of the existing articles have used an integrated approach for strategic and tactical decision-making levels for the design of multi-product and multi-period SC networks.

Table 1: Comparison of sustainability evaluation indicators in articles

papers	uncertainty approach	solving method	transportation	technology level	time period	Case study	Product	Decision		model	
								Strategic	Tactical	Simulation	optimization
[2]	FRS	E	*	*	M	WH	M	*	-	*	*
[3]	F	E	*	*	M	H	M	*	*	-	*
[12]	FS	H	*	*	M	H	M	*	*	-	*
[14]	RPP	H	-	-	M	B	M	*	*	-	*
[27]	-	E	*	*	M	H	M	-	*	-	*
[18]	S	E	*	*	M	EC	M	-	-	-	*
[28]	F	E	*	*	M	EC	S	-	*	-	*
[29]	FS	H	-	*	M	TI	M	-	*	-	*
[30]	F	E	-	-	M	-	M	-	*	*	*
[31]	RPP	H	-	*	S	LB	S	*	*	-	*
[32]	S	H	-	-	-	-	-	*	*	*	-
[33]	S	E	*	-	M	-	M	-	*	-	*
[34]	S	E	-	-	M	-	M	-	*	-	*
[35]	S	E	*	*	M	S	M	-	*	-	*
[36]	-	-	-	-	M	W	S	-	*	*	-
[37]	R	E	-	-	M	E	S	*	*	-	*
[38]	-	E	-	-	M	F	M	*	*	-	*
[39]	S	E	-	-	S	I	S	*	*	-	*
[40]	-	-	-	-	M	-	S	-	*	*	-
[41]	F	E	-	-	M	C	M	*	*	-	*
[42]	S	E	*	-	S	C	M	*	-	-	*
[43]	F	E	-	-	M	E	M	*	*	-	*
[44]	S	E	-	*	M	-	M	*	*	-	*
[45]	FS	E	*	-	M	-	M	*	*	-	*
This study	RPP	E	*	*	M	P	M	*	*	-	*

Note: For time period and product, M stands for "Multi" and S stands for "Single". For uncertainty handling methods: random S, robust R, fuzzy F. (example. FRS: Fuzzy Robust Stochastic, RPP: robust possibility programming). For solution methods, H stands for "heuristic, meta-heuristic", E stands for "exact". For case studies, A: Automotive, C: Apparel, H: Healthcare, E: Energy, P: Pharmaceutical, I: Pipe Industry, F: Food Industry, W: Wood Industry, S: Seaports, TI: Tire Industry, LB: Lignocellulose bioethanol.

Table 2: Model review table of the most relevant researches

papers	Sustainability										
	Economic		Environmental issue			Social issue					
	Total cost	Net present value	CO2 emission	Resource waste	Life cycle analysis	Product responsibility	Labor payment	Job creation	Social anxious	Deprivation	GDP
[2]	*	-	*	-	-	-	-	*	*	-	-
[3]	*	-	*	-	-	-	-	*	*	*	-
[12]	*	-	*	-	-	-	-	*	-	-	-
[14]	*	-	*	-	-	-	-	-	-	-	-
[27]	-	*	-	-	*	-	-	-	-	-	*
[18]	-	*	-	-	*	-	-	-	-	-	*
[28]	*	-	*	-	-	*	*	*	-	-	-
[29]	*	-	-	-	*	-	-	*	*	-	-
[30]	*	-	*	-	-	-	-	*	-	-	-
[31]	-	*	-	-	*	*	-	*	*	-	-
[32]	*	-	-	-	*	-	-	*	-	-	-
[33]	*	-	*	-	-	-	-	-	-	-	-
[34]	*	-	*	-	-	-	-	-	-	-	-
[35]	*	-	*	-	-	-	-	-	-	-	-
[36]	*	-	*	-	-	-	-	-	-	-	-
[37]	*	-	-	-	-	-	-	-	-	-	-
[38]	*	-	*	-	-	-	-	-	-	-	-
[39]	*	-	*	*	-	*	*	*	-	-	-
[40]	*	-	*	*	-	-	-	-	-	-	-
[41]	*	-	*	-	-	-	-	-	-	-	-
[42]	*	-	*	*	-	*	*	*	-	-	-
[43]	*	-	-	-	-	-	-	-	-	-	-
[44]	*	*	-	-	-	-	-	-	-	-	-
[45]	*	-	*	-	-	-	-	*	*	*	-
This study	*	-	*	-	-	*	*	*	*	-	-

In the presented model, cost indicates economic aspect; emission of greenhouse gases (carbon dioxide gas and refrigerant gas) indicates environmental aspect and number of lost working days due to work injuries as well as the number of created jobs indicates the social aspect of sustainable SC management. According to sustainable SC and VSC literature review, only few studies considered the integration of sustainability in the VSC. Also, in dealing with the uncertainty in VSC, this research is one of the first studies. It is a relatively new probabilistic approach that uses the advantages of both stochastic and robust optimization approaches to deal with uncertainties. Also, considering the harmful effects of other greenhouse gases, especially the HFC refrigerant gases used in industrial refrigerators in the cold SC, this study discusses the harmful effects of HFC gases and their role in global warming along with CO2 emissions in the environment.

MATHEMATICAL MODEL

problem description

The production and distribution processes are two main features of VSC, which is important to safe and healthy communities, requires special attention for design and planning. Figure 1 shows a VSC including domestic and foreign manufacturers, international packaging centers, storage and distribution centers and provincial health centers as demand points. Due to limited capacity of domestic vaccines producer, main producer in a foreign country transfers products to international packaging centers, and sends and stores them in the destination country after packaging. Finally, vaccines are transferred to provincial medical centers as demand points by internal transportation. Vaccines can be stored in production, packaging and distribution centers, and this model determines the optimal storage level during the planning time horizon. It is possible to store the vaccine with cold storage and freezing, and it is possible to build storage and distribution centers based on each of them. products are moved between SC echelons by road/rail modes for domestic transport and sea/air modes for external transport. In the proposed SC, strategic and tactical decisions are taken into account at the same time. It should be noted that the present model is written by adapting the model presented by Gilani & Sahebi, 2022.

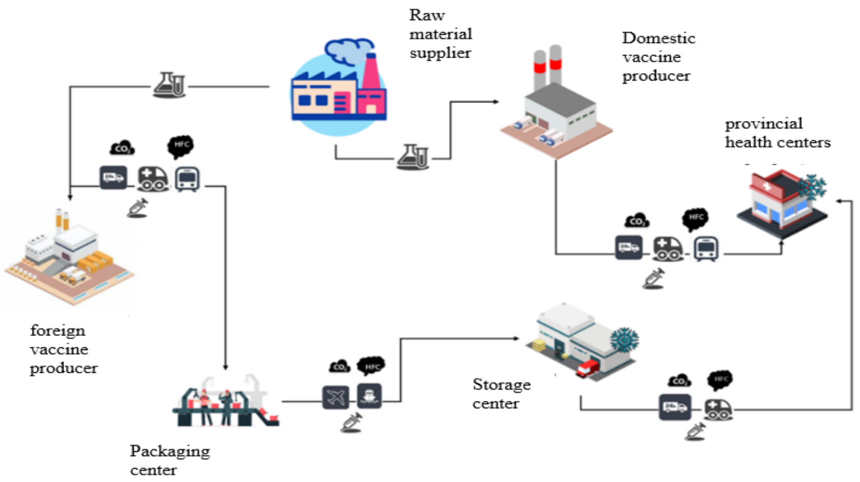

Fig. 1. VSC

Assumptions

The model is multi-level, multi-product and multi-period. The flow of products exists only between different consecutive facilities and the flow of products between similar facilities is not possible. The location of foreign production factories and suppliers is fixed and known. Shortage is possible according to customer demand and a cost is considered for unsatisfied customer demand. The locations of potential domestic production and distribution centers are known. Inventory in domestic and foreign production centers, distribution and packaging centers for products is considered. Only one storage center should be assigned to each customer area. No shipping from foreign factory to customer areas is possible. Transport streams and vaccine storage facilities emit CO2 and HFC-based pollutants.

Symbols

Sets

I	Set of foreign producers	L	Set of transportation modes
J	Set of potential foreign packaging centers	P	Set of vaccines
K	Set of potential for domestic storage centers	M	Set of vaccine holding technology
R	Set of provincial health centers	T	Set of time periods
V	Set of potential domestic producer centers	S	Set of scenarios

Parameters

FIXP_j	Fixed cost of developing packaging center j
FIXD_{km}	Fixed cost of developing distribution center k with holding technology m
FIXI_{pv}	Fixed cost of developing domestic producer p in location v
VCM_{ipt}	Variable cost of foreign producer for vaccine p in location i and time period t
VCP_{jpt}	Variable cost of packaging center j for vaccine p and time period t
VCD_{kpmt}	Variable cost of distribution center k with holding technology m for vaccine p and time period t
VCI_{pvt}	Variable cost of domestic producing vaccine p in location v and time period t
${PCM_{ipt}}^s$	Variable cost of foreign producing vaccine p in factory i and time period t under scenario s
${PCI_{pvt}}^s$	Variable cost of domestic producing vaccine p in factory v and time period t under scenario s
PCD_{kmpt}	Distribution cost per foreign vaccine for distribution center k with holding technology m and time period t
$PCDI_{pvt}$	Distribution cost per domestic vaccine for producer v and time period t
PCP_{jpt}	Packaging cost per foreign vaccine p in packaging center j and time period t
ICM_{ipt}	Holding cost per foreign vaccine p for foreign producer i and time period t
ICP_{jpt}	Holding cost per foreign vaccine p for foreign producer i and time period t
ICD_{kpmt}	Holding cost per foreign vaccine p for distribution center k with holding technology m and time period t
ICI_{pvt}	Holding cost per domestic vaccine p for domestic producer v and time period t
$CTRV_{ijpl}$	Transportation cost per foreign vaccine p from foreign producer i to packaging center j with mode l
$CTRP_{jkpl}$	Transportation cost per foreign vaccine p from packaging center j to distribution center k with mode l
$CTRH_{krpl}$	Transportation cost per foreign vaccine p from distribution center k to provincial health center r with mode l
$CTRI_{pvrl}$	Transportation cost per domestic vaccine p from domestic producer v to provincial health center r with mode l
$CCEM_{ipt}$	Capacity increase cost per foreign vaccine p for foreign producer i in time period t
$CCEP_{jpt}$	Capacity increase cost per foreign vaccine p for packaging center j in time period t
$CCED_{kpmt}$	Capacity increase cost per foreign vaccine p for distribution center k with holding technology m in time period t
$CCEI_{pvt}$	Capacity increase cost per domestic vaccine p for domestic producer v in time period t
MV_l	Market value of vehicle l
IR	Interest rate
NT	Number of time periods
$SUMAX_{pt}$	Maximum order size of raw materials used for foreign vaccine p production in time period t
$SUIAX_{pt}$	Maximum order size of raw materials used for domestic vaccine p production in time period t

$PRN_{ipt}{}^{s}$	Raw material cost for foreign vaccine p produced in foreign producer i in time period t under scenario s
$PRI_{pvt}{}^{S}$	Raw material cost for domestic vaccine p produced in domestic producer v in time period t under scenario s
INR_{l}	Transportation cost per mode l (truck only)
$CMLO_{ip}$	Minimum capacity for foreign vaccine p in foreign producer i
$CILO_{vp}$	Minimum capacity for domestic vaccine p in domestic producer v
$CPLO_{jp}$	Minimum capacity for foreign vaccine p in packaging center j
$CDLO_{kpm}$	Minimum capacity for foreign vaccine p in distribution center k with holding technology m
$CMMX_{ip}$	Maximum capacity for foreign vaccine p in foreign producer i
$CIMX_{vp}$	Maximum capacity for domestic vaccine p in domestic producer v
$CPMX_{jp}$	Maximum capacity for foreign vaccine p in packaging center j
$CDMX_{kpm}$	Maximum capacity for foreign vaccine p in distribution center k with holding technology m
COV_{p}	Raw material to foreign vaccine p exchange rate
COI_{p}	Raw material to domestic vaccine p exchange rate
PCK_{p}	Packaging coefficient for vaccine p
$DH_{rt}{}^{s}$	Demand of customer region r in time period t under scenario s
CTS_{lt}	Vehicle capacity l in time period t
$FJOV_{v}$	Number of jobs created by developing a domestic producer v
$FJOJ_{j}$	Number of jobs created by developing a packaging center j
$FJOK_{km}$	Number of jobs created by developing a distribution center k with holding technology m
PCY^{S}	Shortage cost under scenario s
$EEID_{kpm}$	Total CO2 emission resulted from holding a foreign vaccine p at storage center k with holding technology m
$IMMAX_{ip}$	Maximum inventory for foreign vaccine p at foreign producer i
$IPMAX_{jp}$	Maximum inventory for foreign vaccine p at packaging center j
$IDMAX_{kpm}$	Maximum inventory for foreign vaccine p at distribution center k with holding technology m
$IVMAX_{pv}$	Maximum inventory for domestic vaccine p at domestic producer v
$EETV_{ijpl}$	Total CO2 emission resulted from foreign vaccine p transportation between foreign producer i and packaging center j with mode l
$EHFCI_{ijpl}$	Total refrigerant gas (HFC) emission leaked from vehicle l transporting foreign vaccine p between foreign producer i and packaging center j
$EETP_{jkpl}$	Total CO2 emission resulted from foreign vaccine p transportation between packaging center j and distribution center k with mode l
$EHFCJ_{jkpl}$	Total refrigerant gas (HFC) emission leaked from vehicle l transporting foreign vaccine p between packaging center j and distribution center k

$EETH_{krpl}$	Total CO2 emission resulted from foreign vaccine p transportation between distribution center k and provincial health center r with mode l
$EHFCK_{krpl}$	Total refrigerant gas (HFC) emission leaked from vehicle l transporting foreign vaccine p between distribution center k and provincial health center r
$EETI_{pvrl}$	Total CO2 emission resulted from domestic vaccine p transportation between domestic producer v and provincial health center r with mode l
$EHFCV_{pvrl}$	Total refrigerant gas (HFC) emission leaked from vehicle l transporting domestic vaccine p between domestic producer v and provincial health center r
$EEPM_{ip}$	Total CO2 emission resulted from foreign vaccine p production at foreign producer i
$EEPI_{pv}$	Total CO2 emission resulted from domestic vaccine p production at domestic producer v
$EEPG_{jp}$	Total CO2 emission resulted from foreign vaccine p production at packaging center j
$EEFP_{j}$	Total CO2 emission resulted from packaging center building j
$EEFD_{km}$	Total CO2 emission resulted from distribution center building k with holding technology m
$BHFC_{km}$	Total refrigerant gas (HFC) emission leaked from distribution center building k with holding technology m per year
$EEFI_{pv}$	Total CO2 emission resulted from domestic vaccine p at producer v
$EEIM_{ip}$	Total CO2 emission resulted from holding of foreign vaccine p at producer i
$EHFCM_{ip}$	Total refrigerant gas (HFC) emission leaked from holding of foreign vaccine p at producer i
$EEIP_{jp}$	Total CO2 emission resulted from holding of foreign vaccine p at packaging center j
$EHFCD_{kpm}$	Total refrigerant gas (HFC) emission from holding of foreign vaccine p at distribution center k with technology m
$EEII_{pv}$	Total CO2 emission resulted from holding of domestic vaccine p at producer v
$EHFCII_{pv}$	Total refrigerant gas (HFC) emission from holding of domestic vaccine p at producer v
$ESTV_{ijpl}$	Total jobs created by sending foreign vaccine p from producer I to packaging center j with mode l
$ESTP_{jkpl}$	Total jobs created by sending foreign vaccine p from packaging center j to distribution center k with mode l
$ESTH_{krpl}$	Total jobs created by sending foreign vaccine p from distribution center k to provincial health center r with mode l
$ESTI_{pvrl}$	Total jobs created by sending domestic vaccine p from producer v to provincial health center r with mode l
$ESMM_{ip}$	Total yearly local jobs created by producing foreign vaccine p at producer i
$ESMI_{pv}$	Total yearly local jobs created by producing domestic vaccine p at producer v
$ESPG_{jp}$	Total yearly local jobs created by packaging foreign vaccine p at packaging center j
$ESPD_{kpm}$	Total yearly local jobs created by distributing foreign vaccine p at distributer k with technology m
$ESDI_{pv}$	Total yearly local jobs created by distributing domestic vaccine p at producer v
$LSTV_{l}$	Average number of days lost per year in the vaccine transportation process by transportation mode l

$LSMM$	Average number of days lost per year in the vaccine production
$LSPG$	Average number of days lost per year in the vaccine packaging
$LSDS$	Average number of days lost per year in the vaccine distribution
$HSMM_{ip}$	The average fraction of dangerous foreign vaccines p in the foreign vaccine production center i
$HSMI_{vp}$	The average fraction of dangerous domestic vaccines p in the domestic vaccine production center v
$TETA_1$	Weighted coefficient of the total number of local jobs created
$TETA_2$	Weighted coefficient of the total number of days lost due to work injuries
$TETA_3$	Weighted coefficient of the total number of potentially dangerous vaccines
π_S	The probability of each existing scenarios
$EHFCP_{jp}$	Total refrigerant gas (HFC) emission leaked from holding of foreign vaccine p at packaging center j

Variables

RTS_l^s	The number of vehicles l purchased to transport materials (trucks only) under scenario s
$CAPM_{ipt}{}^s$	The capacity designed to produce foreign vaccine p at producer i in time period t under scenario s
$CAPP_{jpt}{}^s$	The capacity designed to pack foreign vaccine p at packing center j in time period t under scenario s
$CAPD_{kpmt}{}^s$	The capacity designed to store foreign vaccine p in the distribution and storage center k with technology m in period t under scenario s
$CAPI_{pvt}{}^s$	The designed capacity for domestic vaccine p at the domestic manufacturing facility v in time period t under scenario s
$PROM_{ipt}{}^s$	The amount of foreign vaccine p produced in manufacturing plant i in period t under scenario s
$PROI_{pvt}{}^s$	The amount of domestic vaccine p produced in manufacturing plant v in period t under scenario s
$PPROD_{kpmt}{}^s$	Amount of foreign vaccine p distributed from distribution center k with technology m in period t under scenario s
$PROP_{jpt}{}^s$	Amount of foreign vaccine p packed in packing center j in period t under scenario s
$SUPN_{ipt}{}^s$	The amount of foreign vaccine raw materials of type p purchased at foreign vaccine factory i in period t under scenario s
$SUPI_{pvt}{}^s$	The amount of domestic vaccine raw materials of type p purchased at domestic vaccine factory v in period t under scenario s
$SV_{ijplt}{}^s$	The amount of foreign vaccine p transferred from foreign vaccine production center i to packaging center j with transportation mode l in period t under scenario s
$SP_{jkplt}{}^s$	The amount of foreign vaccine p transported from packaging center j to distribution center k with transportation mode l in period t under scenario s
$SH_{krplt}{}^s$	The amount of foreign vaccine p transferred from distribution center k to provincial health centers r with mode l in period t under scenario s
$SI_{vrplt}{}^s$	The amount of domestic vaccine p transferred from the domestic production of vaccine v to provincial medical centers r by method l in period t under scenario s

$INVM_{ipt}{}^{s}$	Inventory of foreign vaccine p in foreign vaccine production center i in period t under scenario s
$INVP_{jpt}{}^{s}$	Inventory of foreign vaccine p in packing center j in period t under scenario s
$INVD_{kpmt}{}^{s}$	Inventory of foreign vaccine p in distribution center k with storage technology m in period t under scenario s
$INVI_{pvt}{}^{s}$	Inventory of domestic vaccine p in the domestic vaccine production center v in period t under scenario s
$CAPEM_{ipt}{}^{s}$	Capacity increase for production of foreign vaccine p in producer i in period t under scenario s
$CAPEP_{jpt}{}^{s}$	Capacity increase for packaging foreign vaccine p in packaging center j in period t under scenario s
$CAPED_{kpmt}{}^{s}$	Capacity increase for distribute foreign vaccine p in distribution and storage centers k with technology m in period t under scenario s
$CAPEI_{pvt}{}^{s}$	Capacity increase for producing domestic vaccine p at producer v in period t under scenario s
$NNS_{rt}{}^{s}$	Vaccine shortage rate in customer areas (provincial health centers r) in period t under scenario s
ZP_{j}	If packing center j is opened takes 1 otherwise 0
ZD_{km}	If packing center k with maintenance technology m is opened, takes 1 otherwise 0
ZI_{v}	If domestic vaccine production center v is opened, takes 1 otherwise it is 0

. Objective functions in non-deterministic mode

The presented model includes three objective functions: minimizing total costs, minimizing environmental effects, and maximizing social effects of the SC. The first objective function (economic objective function) includes two types of costs: tactical and strategic costs. Strategic costs include establishment (factories and warehouses while tactical costs include purchasing, production, inventory (holding and shortages), and transportation (between SC entities) costs. The objective is as described in equatio (1):

$$
\begin{aligned}
&Z_1 = \sum_{j} ZP_{j}.FIXP_{j} + \sum_{k}\sum_{m} ZD_{km}.FIXD_{km} + \\
&\sum_{v}\sum_{p} ZI_{v}.FIXI_{vp} + \sum_{i}\sum_{p}\sum_{t} CAPM_{ipt}{}^{s}.VCM_{ipt}.\pi_{s} \\
&+\sum_{j}\sum_{p}\sum_{t} CAPP_{jpt}{}^{s}.VCP_{jpt}.\pi_{s} + \\
&\sum_{k}\sum_{p}\sum_{m}\sum_{t} CAPD_{kpmt}{}^{s}.VCD_{kpmt}.\pi_{s} + \\
&\sum_{v}\sum_{t}\sum_{p} CAPI_{vtp}{}^{s}.VCI_{vtp}\,\pi_{s} \\
&+\sum_{i}\sum_{p}\sum_{t} INVM_{ipt}{}^{s}.ICM_{ipt}.\pi_{s} + \\
&\sum_{j}\sum_{p}\sum_{t} INVP_{jpt}{}^{s}.ICP_{jpt}.\pi_{s} + \\
&\sum_{k}\sum_{p}\sum_{m}\sum_{t} INVD_{kpmt}{}^{s}.ICD_{kpmt}.\pi_{s} \\
&+\sum_{v}\sum_{t}\sum_{p} INVI_{vtp}{}^{s}.ICI_{vtp}.\pi_{s} + \\
&\sum_{i}\sum_{p}\sum_{t} PROM_{ipt}{}^{s}.PCM_{ipt}{}^{s}.\pi_{s} + \\
&\sum_{v}\sum_{t}\sum_{p} PROI_{pvt}{}^{s}.PCI_{pvt}{}^{s}.\pi_{s} + \\
&\sum_{k}\sum_{p}\sum_{m}\sum_{t} PROD_{kpmt}{}^{s}.PCD_{kpmt}.\pi_{s} + \\
&\sum_{v}\sum_{t}\sum_{p} PROI_{vpt}{}^{s}.PCDI_{vpt}.\pi_{s} + \\
&\sum_{j}\sum_{p}\sum_{t} PROP_{jpt}{}^{s}.PCP_{jpt}.\pi_{s} + \\
&\sum_{r}\sum_{t} PCY^{s}.NNS_{rt}{}^{s}.\pi_{s} + \\
&\sum_{i}\sum_{p}\sum_{t} CAPEM_{ipt}{}^{s}.CCEM_{ipt}.\pi_{s} + \\
&\sum_{j}\sum_{p}\sum_{t} CAPEP_{jpt}{}^{s}.CCEP_{jpt}.\pi_{s} \\
&+\sum_{k}\sum_{p}\sum_{m}\sum_{t} CAPED_{kpmt}{}^{s}.CCED_{kpmt}.\pi_{s} + \\
&\sum_{v}\sum_{p}\sum_{t} CAPEI_{vpt}{}^{s}.CCEI_{vpt}.\pi_{s} + \\
&\sum_{i}\sum_{j}\sum_{p}\sum_{l}\sum_{t} SV_{ijplt}{}^{s}.CTRV_{ijplt}.\pi_{s} \\
&+\sum_{j}\sum_{k}\sum_{p}\sum_{l}\sum_{t} SP_{jkplt}{}^{s}.CTRP_{jkplt}.\pi_{s} + \\
&\sum_{k}\sum_{r}\sum_{p}\sum_{l}\sum_{t} SH_{krplt}{}^{s}.CTRH_{krplt}.\pi_{s} + \\
&\sum_{p}\sum_{v}\sum_{r}\sum_{l}\sum_{t} SI_{pvrlt}{}^{s}.CTRI_{pvrlt}.\pi_{s} + \\
&\sum_{i}\sum_{p}\sum_{t} SUPN_{ipt}{}^{s}.PRN_{ipt}{}^{s}.\pi_{s} + \\
&\sum_{v}\sum_{p}\sum_{t} SUPI_{vpt}{}^{s}.PRI_{vpt}{}^{s}.\pi_{s} + \sum_{l} RTS_{l}{}^{s}.INR_{l}.\pi_{s} - \\
&\sum_{l=1} \frac{RTS_{l}{}^{s}.MV_{l}}{(1+IR)^{nt}}.\pi_{s}
\end{aligned}
\tag{1}
$$

In the cold SC, products must be stored and transported at near or below freezing temperatures. This requires the use of refrigerated warehouses and trucks that consume large amounts of energy for refrigeration. More energy consumption is associated with more carbon dioxide (CO2) emissions in power generation

facilities. In addition, refrigeration systems use large amounts of hydrofluorocarbon (HFC) gases, which have a high global warming potential and long lifetime in the atmosphere. The regular and catastrophic leakage of HFC gases from the cold SC, constitutes a significant part of global warming impact. Therefore, these gases must be considered in design and operation of a cold SC.
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The second objective function calculates the total emission of pollution resulting from all traverses in SC. In this objective function, it is tried to minimize the environmental effects that have adverse effects on the environment. Facilities and flow transfer between facilities have an important effect on environmental pollution. It was observed in the literature review, most of the previous researches have considered the minimization of carbon dioxide gas emission as the objective function. But in the cold SC, due to the high energy consumption and leakage of refrigerant gases, which leads to high levels of greenhouse gas emissions, it is necessary to pay attention to refrigerant greenhouse gases (HFC) in addition to carbon dioxide gas. Equation number (2) is the mathematical representation of environmental goal. This goal should be minimized to design an environmentally friendly (green) SC.

$$
\begin{gathered}
Z_2 = \sum_{\mathrm{i}}\sum_{\mathrm{j}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SV}_{\mathrm{ijplt}}{}^{\mathrm{S}}.\,\mathrm{EETV}_{\mathrm{ijpl}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{j}}\sum_{\mathrm{k}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SP}_{\mathrm{jkplt}}{}^{\mathrm{S}}.\,\mathrm{EETP}_{\mathrm{jkpl}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{k}}\sum_{\mathrm{r}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SH}_{\mathrm{krplt}}{}^{\mathrm{S}}.\,\mathrm{EETH}_{\mathrm{krpl}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{v}}\sum_{\mathrm{p}}\sum_{\mathrm{r}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SI}_{\mathrm{vprlt}}{}^{\mathrm{S}}.\,\mathrm{EETI}_{\mathrm{vprl}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{i}}\sum_{\mathrm{j}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SV}_{\mathrm{ijplt}}{}^{\mathrm{S}}.\,\mathrm{EHFCI}_{\mathrm{ijpl}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{j}}\sum_{\mathrm{k}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SP}_{\mathrm{jkplt}}{}^{\mathrm{S}}.\,\mathrm{EHFCJ}_{\mathrm{jkpl}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{k}}\sum_{\mathrm{r}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SH}_{\mathrm{krplt}}{}^{\mathrm{S}}.\,\mathrm{EHFCK}_{\mathrm{krpl}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{v}}\sum_{\mathrm{p}}\sum_{\mathrm{r}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SI}_{\mathrm{vprlt}}{}^{\mathrm{S}}.\,\mathrm{EHFCV}_{\mathrm{vprl}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{i}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{PROM}_{\mathrm{ipt}}{}^{\mathrm{S}}.\,\mathrm{EEPM}_{\mathrm{ip}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{v}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{PRPI}_{\mathrm{vpt}}{}^{\mathrm{S}}.\,\mathrm{EEPI}_{\mathrm{vp}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{j}} \mathrm{ZP}_{\mathrm{j}}.\,\mathrm{EEFP}_{\mathrm{j}}+\sum_{\mathrm{k}}\sum_{\mathrm{m}} \mathrm{ZD}_{\mathrm{km}}.\,\mathrm{EEFD}_{\mathrm{km}}+\sum_{\mathrm{v}}\sum_{\mathrm{p}} \mathrm{ZI}_{\mathrm{v}}.\,\mathrm{EEFI}_{\mathrm{vp}}+ \\
\sum_{\mathrm{j}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{PROP}_{\mathrm{jpt}}{}^{\mathrm{S}}.\,\mathrm{EEPG}_{\mathrm{jp}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{k}}\sum_{\mathrm{m}} \mathrm{ZD}_{\mathrm{km}}.\,\mathrm{BHFC}_{\mathrm{km}}+\sum_{\mathrm{i}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{INVM}_{\mathrm{ipt}}{}^{\mathrm{S}}.\,\mathrm{EEIM}_{\mathrm{ip}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{j}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{INVP}_{\mathrm{jpt}}{}^{\mathrm{S}}.\,\mathrm{EEIP}_{\mathrm{jp}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{k}}\sum_{\mathrm{p}}\sum_{\mathrm{m}}\sum_{\mathrm{t}} \mathrm{INVD}_{\mathrm{kpmt}}{}^{\mathrm{S}}.\,\mathrm{EEID}_{\mathrm{kpm}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{v}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{INVI}_{\mathrm{vpt}}{}^{\mathrm{S}}.\,\mathrm{EEII}_{\mathrm{vp}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{i}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{INVM}_{\mathrm{ipt}}{}^{\mathrm{S}}.\,\mathrm{EHFCM}_{\mathrm{ip}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{j}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{INVP}_{\mathrm{jpt}}{}^{\mathrm{S}}.\,\mathrm{EHFCP}_{\mathrm{jp}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{k}}\sum_{\mathrm{p}}\sum_{\mathrm{m}}\sum_{\mathrm{t}} \mathrm{INVD}_{\mathrm{kpmt}}{}^{\mathrm{S}}.\,\mathrm{EHFCD}_{\mathrm{kpm}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{v}}\sum_{\mathrm{p}}\sum_{\mathrm{t}} \mathrm{INVI}_{\mathrm{vpt}}{}^{\mathrm{S}}.\,\mathrm{EHFCII}_{\mathrm{vp}}.\,\pi_{\mathrm{s}}
\end{gathered}
\tag{2}
$$

According to equation (3), the third objective function is to maximize the social responsiveness of the SC. This objective function includes the indicators of creating job opportunities (positive effect), lost working days due to illness and accidents (negative effect; related to health and safety of employees) and risk of using products for customers (negative effect; related to customer health). Job opportunities are classified into two fixed and variable categories. Permanent job opportunities, such as managerial jobs, are not dependent on capacity of facilities, but variable jobs, such as workers' job, are different depends on facility’s capacity and rate of production. In this objective function fixed and variable job opportunities are model separately. Regarding the health and safety of employees, the average number of working days lost due to injury is used.

$$
\begin{gathered}
Z_3 = \theta_1 *(\sum_{\mathrm{v}} \mathrm{FJOV}_{\mathrm{v}}.\,\mathrm{ZI}_{\mathrm{v}}+\sum_{\mathrm{j}} \mathrm{FJOJ}_{\mathrm{j}}.\,\mathrm{ZP}_{\mathrm{j}}+\sum_{k}\sum_{m} \mathrm{FJOK}_{\mathrm{km}}.\,\mathrm{ZD}_{\mathrm{km}}+\sum_{\mathrm{i}}\sum_{\mathrm{j}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SV}_{\mathrm{ijplt}}{}^{\mathrm{s}}.\,\mathrm{ESTV}_{\mathrm{ijpl}}.\,\pi_{\mathrm{s}}+ \\
\sum_{\mathrm{j}}\sum_{\mathrm{k}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SP}_{\mathrm{jkplt}}{}^{\mathrm{s}}.\,\mathrm{ESTP}_{\mathrm{jkpl}}.\,\pi_{\mathrm{s}}+\sum_{\mathrm{k}}\sum_{\mathrm{r}}\sum_{\mathrm{p}}\sum_{\mathrm{l}}\sum_{\mathrm{t}} \mathrm{SH}_{\mathrm{krplt}}{}^{\mathrm{s}}.\,\mathrm{ESTH}_{\mathrm{krpl}}.\,\pi_{\mathrm{s}}+
\end{gathered}
$$

$$
\begin{gathered}
\sum_v \sum_p \sum_r \sum_l \sum_t \mathrm{SI}_{\mathrm{vprlt}}{}^{s}.\mathrm{ESTH}_{\mathrm{vprl}}.\pi_s+\sum_i \sum_p \sum_t \mathrm{PROM}_{\mathrm{ipt}}{}^{s}.\mathrm{ESMM}_{\mathrm{ip}}.\pi_s+\sum_v \sum_p \sum_t \mathrm{PRPI}_{\mathrm{vpt}}{}^{s}.\mathrm{ESMI}_{\mathrm{vp}}.\pi_s+ \\
\sum_j \sum_p \sum_t \mathrm{PROP}_{\mathrm{jpt}}{}^{s}.\mathrm{ESPG}_{\mathrm{jp}}.\pi_s+\sum_k \sum_p \sum_m \sum_t \mathrm{PROD}_{\mathrm{kpmt}}{}^{s}.\mathrm{ESPD}_{\mathrm{kpmt}}.\pi_s+\sum_v \sum_t \sum_p \mathrm{PROI}_{\mathrm{vpt}}{}^{s}.\mathrm{ESDI}_{\mathrm{vpt}}.\pi_s) \\
-\theta_2*(\sum_l(\sum_i \sum_j \sum_p \sum_l \sum_t \mathrm{SV}_{\mathrm{ijplt}}{}^{s}.\mathrm{ESTV}_{\mathrm{ijpl}}.\pi_s+\sum_j \sum_k \sum_p \sum_l \sum_t \mathrm{SP}_{\mathrm{jkplt}}{}^{s}.\mathrm{ESTP}_{\mathrm{jkpl}}.\pi_s+ \\
\sum_k \sum_r \sum_p \sum_l \sum_t \mathrm{SH}_{\mathrm{krplt}}{}^{s}.\mathrm{ESTH}_{\mathrm{krpl}}.\pi_s+\sum_v \sum_p \sum_r \sum_l \sum_t \mathrm{SI}_{\mathrm{vprlt}}{}^{s}.\mathrm{ESTH}_{\mathrm{vprl}}.\pi_s).\mathrm{LSTV}_l+ \\
(\sum_i \sum_p \sum_t \mathrm{PROM}_{\mathrm{ipt}}{}^{s}.\mathrm{ESMM}_{\mathrm{ip}}.\pi_s+\sum_v \sum_p \sum_t \mathrm{PRPI}_{\mathrm{vpt}}{}^{s}.\mathrm{ESMI}_{\mathrm{vp}}.\pi_s).\mathrm{LSMM}+ \\
(\sum_j \sum_p \sum_t \mathrm{PROP}_{\mathrm{jpt}}{}^{s}.\mathrm{ESPG}_{\mathrm{jp}}.\pi_s).\mathrm{LSPG}+(\sum_k \sum_p \sum_m \sum_t \mathrm{PROD}_{\mathrm{kpmt}}{}^{s}.\mathrm{ESPD}_{\mathrm{kpmt}}.\pi_s+ \\
\sum_v \sum_t \sum_p \mathrm{PROI}_{\mathrm{vpt}}{}^{s}.\mathrm{ESDI}_{\mathrm{vpt}}.\pi_s).\mathrm{LSDS})-\theta_3*(\sum_i \sum_p \sum_t \mathrm{PROM}_{\mathrm{ipt}}{}^{s}.\mathrm{HSMM}_{\mathrm{ip}}.\pi_s+ \\
\sum_v \sum_p \sum_t \mathrm{PRPI}_{\mathrm{vpt}}{}^{s}.\mathrm{HSMI}_{\mathrm{vp}}.\pi_s)
\end{gathered}
\tag{3}
$$

All social effects of SC are formulated by giving weight to each component. θ1 with (+) sign used to maximize the number of jobs, θ2 with a (-) sign used to minimize number of days lost due to work-related injuries, θ3 with a sign (-) used to minimize environmental risks.

Model constraints in non-deterministic mode

$\mathrm{PROM}_{\mathrm{ipt}}{}^{s} \le \mathrm{CAPM}_{\mathrm{ipt}}{}^{s}$	$\forall ipts$	1	4
$\mathrm{PROI}_{\mathrm{vpt}}{}^{s} \le \mathrm{CAPI}_{\mathrm{vpt}}{}^{s}$	$\forall vpts$		5
$\mathrm{PROP}_{\mathrm{jpt}}{}^{s} \le \mathrm{CAPP}_{\mathrm{jpt}}{}^{s}$	$\forall jpts$		6
$\mathrm{PPROD}_{\mathrm{kpmt}}{}^{s} \le \mathrm{CAPD}_{\mathrm{kpmt}}{}^{s}$	$\forall kpmts$		7
$\mathrm{CMLO}_{\mathrm{ip}} \le \mathrm{CAPM}_{\mathrm{ipt}}{}^{s} \le \mathrm{CMMX}_{\mathrm{ip}}$	$\forall ipts$	2	8
$\mathrm{CILO}_{\mathrm{vp}}.\mathrm{ZI}_{\mathrm{v}} \le \mathrm{CAPI}_{\mathrm{vpt}}{}^{s} \le \mathrm{CIMX}_{\mathrm{vp}}.\mathrm{ZI}_{\mathrm{v}}$	$\forall vpts$		9
$\mathrm{CPLO}_{\mathrm{jp}}.\mathrm{ZP}_{\mathrm{j}} \le \mathrm{CAPP}_{\mathrm{jpt}}{}^{s} \le \mathrm{CPMX}_{\mathrm{jp}}.\mathrm{ZP}_{\mathrm{j}}$	$\forall jpts$		10
$\mathrm{CDLO}_{\mathrm{kpm}}.\mathrm{ZD}_{\mathrm{km}} \le \mathrm{CAPD}_{\mathrm{kpmt}}{}^{s} \le \mathrm{CDMX}_{\mathrm{kpm}}.\mathrm{ZD}_{\mathrm{km}}$	$\forall kpmts$		11
$\sum_{T} \mathrm{INVM}_{\mathrm{ipt}}{}^{s} \le \mathrm{IMMAX}_{\mathrm{ip}}$	$\forall ipts$	3	12
$\sum_{T} \mathrm{INVP}_{\mathrm{jpt}}{}^{s} \le \mathrm{IPMAX}_{\mathrm{jp}}.\mathrm{ZP}_{\mathrm{jp}}$	$\forall jpts$		13
$\sum_{T} \mathrm{INDV}_{\mathrm{kpmt}}{}^{s} \le \mathrm{IDMAX}_{\mathrm{kpm}}.\mathrm{ZD}_{\mathrm{km}}$	$\forall kpmts$		14
$\sum_{T} \mathrm{INVI}_{\mathrm{vpt}}{}^{s} \le \mathrm{IVMAX}_{\mathrm{vp}}.\mathrm{ZI}_{\mathrm{v}}$	$\forall pvts$		15
$\sum_{i} \mathrm{SUPN}_{\mathrm{ipt}}{}^{s} \le \mathrm{SUMMX}_{\mathrm{pt}}$	$\forall pts$	4	16
$\sum_{v} \mathrm{SUPI}_{\mathrm{vpt}}{}^{s} \le \mathrm{SUIMX}_{\mathrm{pt}}$	$\forall pts$		17
$\mathrm{CAPM}_{\mathrm{ipt}}{}^{s} = \mathrm{CAPM}_{\mathrm{ipt-1}}{}^{s} + \mathrm{CAEM}_{\mathrm{ipt}}$	$\forall ipts$	5	18
$\mathrm{CAPP}_{\mathrm{jpt}}{}^{s} = \mathrm{CAPP}_{\mathrm{jpt-1}}{}^{s} + \mathrm{CAEP}_{\mathrm{jpt}}$	$\forall jpts$		19
$\mathrm{CAPD}_{\mathrm{kpmt}}{}^{s} = \mathrm{CAPD}_{\mathrm{kpmt-1}}{}^{s} + \mathrm{CAED}_{\mathrm{kpmt}}$	$\forall kpmts$		20
$\mathrm{CAPI}_{\mathrm{vpt}}{}^{s} = \mathrm{CAPI}_{\mathrm{vpt-1}}{}^{s} + \mathrm{CAEI}_{\mathrm{vpt}}$	$\forall vpts$		21
$\sum_{p} \mathrm{SV}_{\mathrm{ijplt}}{}^{s} \le \mathrm{RTS}_{\mathrm{l}}{}^{s}.\mathrm{CTS}_{\mathrm{l}}$	$\forall ijtsl \in \{1,2\}$	6	22
$\sum_{p} \mathrm{SH}_{\mathrm{kprlt}}{}^{s} \le \mathrm{RTS}_{\mathrm{l}}{}^{s}.\mathrm{CTS}_{\mathrm{l}}$	$\forall krtsl \in \{1,2\}$		23
$\sum_{p} \mathrm{SI}_{\mathrm{pvrlt}}{}^{s} \le \mathrm{RTS}_{\mathrm{l}}{}^{s}.\mathrm{CTS}_{\mathrm{l}}$	$\forall vtsl \in \{1,2\}$		24

$\sum_{p} \mathrm{SP}_{jkplt}{}^{s} \leq \mathrm{RTS}_{l}{}^{s}.\mathrm{CTS}_{l}$	$\forall jktsl \in \{3,4\}$		25
$\mathrm{SUPN}_{ipt}.{}^{s}\,\mathrm{COV}_{p} = \mathrm{PROM}_{ipt}{}^{s}$	$\forall ipts$	7	26
$\mathrm{SUPI}_{vpt}.{}^{s}\,\mathrm{COI}_{p} = \mathrm{PROI}_{vpt}{}^{s}$	$\forall vpts$		27
$\sum_{i} \sum_{l\in\{1.2\}} \mathrm{SV}_{ijplt}{}^{s}.\frac{1}{\mathrm{PCK}_{p}} = \mathrm{PROP}_{jpt}{}^{s}$	$\forall jpts$		28
$\sum_{j} \sum_{l\in\{3.4\}} \mathrm{SP}_{jkplt}{}^{s}.\mathrm{PCK}_{p} = \sum_{m} \mathrm{PROD}_{kpmt}{}^{s}$	$\forall kpts$		29
$\sum_{p}\sum_{v}\sum_{l\in\{1.2\}} \mathrm{SI}_{vprlt}{}^{s} + \sum_{k}\sum_{p}\sum_{l\in\{1.2\}} \mathrm{SH}_{krplt}{}^{s} \geq \mathrm{DH}_{rt}{}^{s}$	$\forall rts$		30
$\mathrm{DH}_{rt}{}^{s} - \sum_{p}\sum_{v}\sum_{l\in\{1.2\}} \mathrm{SI}_{pvrlt}{}^{s} + \sum_{p}\sum_{k}\sum_{l\in\{1.2\}} \mathrm{SH}_{krplt}{}^{s} = \mathrm{NNS}_{rt}{}^{s}$	$\forall rts$		31
$\mathrm{INVM}_{ipt-1}{}^{s} - \mathrm{INVM}_{ipt}{}^{s} + \mathrm{PROM}_{ipt}{}^{s} = \sum_{j}\sum_{l\in\{1.2\}} \mathrm{SV}_{ijplt}{}^{s}$	$\forall ipts$	8	32
$\mathrm{INVP}_{jpt-1}{}^{s} - \mathrm{INVP}_{jpt}{}^{s} + \mathrm{PROP}_{jpt}{}^{s} = \sum_{j}\sum_{l\in\{3.4\}} \mathrm{SP}_{jkplt}{}^{s}$	$\forall jpts$		33
$\sum_{m} \mathrm{INVD}_{kpmt-1}{}^{s} - \sum_{m} \mathrm{INVD}_{kpmt}{}^{s} + \sum_{m} \mathrm{PROD}_{kpmt}{}^{s} = \sum_{r}\sum_{l\in\{1.2\}} \mathrm{SH}_{Kprlt}{}^{s}$	$\forall kpts$		34
$\mathrm{INVI}_{vpt-1}{}^{s} - \mathrm{INVI}_{pvt}{}^{s} + \mathrm{PROI}_{vpt}{}^{s} = \sum_{r}\sum_{l\in\{1.2\}} \mathrm{SI}_{jkplt}{}^{s}$	$\forall vpts$		35
$\sum_{m} \mathrm{ZD}_{km} = 1$	$\forall k$	9	36
$\mathrm{ZP}_{j}.\mathrm{ZD}_{km}.\mathrm{ZI}_{v} \in \{0.1\}$	$\forall jkmv$	10	37
$\mathrm{RTS}_{l}{}^{s} \in \{\mathrm{intejer}\}$	$\forall ls$		38
$\mathrm{CAPM}_{ipt}{}^{s}.\mathrm{CAPP}_{jpt}{}^{s}.\mathrm{CAPD}_{kpmt}{}^{s}.\mathrm{CAPI}_{pvt}{}^{s}.\mathrm{PROM}_{ipt}{}^{s}.\mathrm{PROI}_{pvt}{}^{s}$ $.\mathrm{PPROD}_{kpmt}{}^{s}.\mathrm{PROP}_{jpt}{}^{s}.\mathrm{SUPN}_{ipt}{}^{s}.\mathrm{SUPI}_{pvt}{}^{s}.\mathrm{SV}_{ijplt}{}^{s}.\mathrm{SP}_{jkplt}{}^{s}.\mathrm{SH}_{krplt}{}^{s}$ $.\mathrm{SI}_{vrplt}{}^{s}.\mathrm{INVM}_{ipt}{}^{s}.\mathrm{INVP}_{jpt}{}^{s}.\mathrm{INVD}_{kpmt}{}^{s}.\mathrm{INVI}_{pvt}{}^{s}.\mathrm{CAPEM}_{ipt}{}^{s},$ $.\mathrm{CAPEP}_{jpt}{}^{s}.\mathrm{CAPED}_{kpmt}{}^{s}.\mathrm{CAPEI}_{pvt}{}^{s}.\mathrm{NNS}_{rt}{}^{s} \geq 0$	$\forall ijpkmvlts$		39

Part 1: Capacity constraints to ensure that the capacity of each center is less than or equal to its designed capacity in each period. Part 2: Limits the production of facilities based on its designed capacity. Equations of in this part, try to determine this capacity in a rational way by determining the relevant upper and lower limits in construction and economic dimensions. Part 3: Formulates capacity constraints for centers capable of holding inventory. Part 4: The constraints related to the flow of raw materials to domestic and foreign production centers are in this stage. It must be ensured that the raw materials required for vaccine production are less than or equal to the maximum available amount of supplier raw materials in any time period. Part 5: These constraints develop capacity. To formulate this concept, the capacity designed in each period is used, which is equal to the capacity of the previous period plus the increase of capacity in that period. Part 6: The constraints related to the capacity of the transport fleet as well as the constraints related to access to sufficient number of vehicles are in this part. Part 7: The constraints discussed in this section try to balance vaccine flow in different SC layers. Part 8: This part formulates inventory level in facilities that are capable to maintain the inventory. Part 9: Determines the logical limitation in the choice of

vaccine storage technology in a distribution center. Part 10: Shows the variables sign.

P-robust approach

In real-world problems, we are always faced with uncertainty due to the lack of access to accurate information or the high cost of obtaining it. In the literature, in order to face the uncertainty, researchers have mainly used two approaches: probabilistic planning and robust planning. Stable optimization is looking for a solution that is resistant to changes and does not change. The probabilistic-robust is one of the new methods in mathematical programming that has attracted the attention of many researchers [46]. This method incorporates the advantages of both probabilistic and robust methods to deal with uncertainties. The objective of the probabilistic method is usually to minimize the expected cost or maximize the expected profit considering all scenarios. Although the solution obtained by the probabilistic method is financially optimal in most scenarios, it may lead to losses in other scenarios. On the other hand, the robust method usually aims at minimize maximum cost or maximum regret. However, this is overly conservative as the solution may be implemented for infrequently occurring scenarios. Therefore, the p-robust optimization method combines the benefits of maximum expected profit and minimizing maximum regret [47].

To express this approach, suppose S is the set of possible scenarios, and it is assumed that the parameters of the problem under each scenario have a certain value and the probability of occurring each scenario has a known value. Ps is a deterministic minimization problem under scenario s (for each scenario s∈S). For each s, suppose that Z_s^* is the optimal value of the objective function of the Ps problem, and also suppose that for all scenarios s Z_s^*≥0.

Definition 1. Suppose that p≥0 be a fixed number and a feasible solution for the problem Ps for all s∈S. And Z_s (X) be the value of the objective function for the feasible solution x. We call the solution x p-robust if for all s∈S:

$$\frac{Z_s(X) - Z_s^*}{Z_s^*} \leq p \quad (40)$$

It is also possible to define a different regret limit of Ps for each scenario s. For example, allow scenarios with a low probability of occurrence to accept a higher amount of regret. In this case, Ps is used instead of P in the mentioned relation. Therfore p vector will be as (P_1…..P_s) (Ghaderi and Khanzadeh, 2018). The probabilistic optimization approach can be combined with the expected cost minimization objective function. In this case we have:

$$MIN \quad \sum_{s \in S} q_s Z_s(X)$$

$$s.t \quad Z_s(X) \leq (1+p) Z_s^*$$

$$x \in X$$

Where S is the set of all possible, q_s is the probability of scenario and X is the set of all possible solutions for all P_s. This method of robust optimization is called the probabilistic-robust approach. In this approach, it is assumed that the data of the problem changes based on the predetermined scenarios. The answer obtained from this approach divide by optimal value of each scenario should not be greater than a factor. By running the mathematical model, for each of the scenarios, the mathematical model will provide an optimal solution, which are respectively known as $Z_1^* \quad Z_2^* \; Z_3^*$ for the first, second and third objective function. In the following, according to the general form of p-robust optimization, the constraints (42), (43), and (44) are added to the model.

P shows the relative regret for each of the available scenarios. The constraints added to the model are as follow. Based on these constraints, the cost of each scenario should not be more than (1+α)% of the optimal cost of that scenario. In other words, these constraints ensure that if we consider the scenarios separately, the answer to the achievement of each scenario does not deteriorate more than (1+α)% of the optimal solution of that scenario. If α=0 is chosen in this relation, then the solution of the problem for each of the scenarios will be optimal in general. With higher values of α, the probability of obtaining a feasible solution answer will be higher.

$$\begin{gathered}
\sum_j ZP_j . FIXP_j + \sum_k \sum_m ZD_{km} . FIXD_{km} + \sum_v \sum_p ZI_v . FIXI_{vp} + \sum_i \sum_p \sum_t CAPM_{ipt}{}^s . VCM_{ipt} + \\
\sum_j \sum_p \sum_t CAPP_{jpt}{}^s . VCP_{jpt} + \sum_k \sum_p \sum_m \sum_t CAPD_{kpmt}{}^s . VCD_{kpmt} + \sum_v \sum_t \sum_p CAPI_{vtp}{}^s . VCI_{vtp} + \\
\sum_i \sum_p \sum_t INVM_{ipt}{}^s . ICM_{ipt} + \sum_j \sum_p \sum_t INVP_{jpt}{}^s . ICP_{jpt} + \sum_k \sum_p \sum_m \sum_t INVD_{kpmt}{}^s . ICD_{kpmt} + \\
\sum_v \sum_t \sum_p INVI_{vtp}{}^s . ICI_{vtp} + \sum_i \sum_p \sum_t PROM_{ipt}{}^s . PCM_{ipt}{}^s + \sum_v \sum_t \sum_p PROI_{pvt}{}^s . PCI_{pvt}{}^s + \\
\sum_k \sum_p \sum_m \sum_t PROD_{kpmt}{}^s . PCD_{kpmt} + \sum_v \sum_t \sum_p PROI_{vpt}{}^s . PCDI_{vpt} + \sum_j \sum_p \sum_t PROP_{jpt}{}^s . PCP_{jpt} + \\
\sum_r \sum_t PCY^s . NNS_{rt}{}^s + \sum_v \sum_p \sum_t CAPEI_{vpt}{}^s . CCEI_{vpt} + \sum_k \sum_p \sum_m \sum_t CAPED_{kpmt}{}^s . CCED_{kpmt} + \\
\sum_i \sum_p \sum_t CAPEM_{ipt}{}^s . CCEM_{ipt} + \sum_j \sum_p \sum_t CAPEP_{jpt}{}^s . CCEP_{jpt} + \sum_i \sum_j \sum_p \sum_l \sum_t SV_{ijplt}{}^s . CTRV_{ijplt} + \\
\sum_j \sum_k \sum_p \sum_l \sum_t SP_{jkplt}{}^s . CTRP_{jkplt} + \sum_k \sum_r \sum_p \sum_l \sum_t SH_{krplt}{}^s . CTRH_{krplt} + \sum_p \sum_v \sum_r \sum_l \sum_t SI_{pvrlt}{}^s . CTRI_{pvrlt} + \\
\sum_i \sum_p \sum_t SUPN_{ipt}{}^s . PRN_{ipt}{}^s + \sum_v \sum_p \sum_t SUPI_{vpt}{}^s . PRI_{vpt}{}^s + \sum_l RTS_l{}^s . INR_l - \\
\sum_{l=1} \frac{RTS_l{}^s . MV_l}{(1+IR)^{nt}} \le (1+p) . Z_1^* \qquad \forall s
\end{gathered} \tag{42}$$

$$\begin{gathered}
\sum_i \sum_j \sum_p \sum_l \sum_t SV_{ijplt}{}^S . EETV_{ijpl} + \sum_j \sum_k \sum_p \sum_l \sum_t SP_{jkplt}{}^S . EETP_{jkpl} + \sum_k \sum_r \sum_p \sum_l \sum_t SH_{krplt}{}^S . EETH_{krpl} + \\
\sum_{v} \sum_{p} \sum_{r} \sum_{l} \sum_{t} SI_{vprlt}{}^S . EETI_{vprl} + \sum_i \sum_j \sum_p \sum_l \sum_t SV_{ijplt}{}^S . EHFCI_{ijpl} + \sum_j \sum_k \sum_p \sum_l \sum_t SP_{jkplt}{}^S . EHFCJ_{jkpl} + \\
\sum_k \sum_r \sum_p \sum_l \sum_t SH_{krplt}{}^S . EHFCK_{krpl} + \sum_v \sum_p \sum_r \sum_l \sum_t SI_{vprlt}{}^S . EHFCV_{vprl} + \sum_i \sum_p \sum_t PROM_{ipt}{}^S . EEPM_{ip} + \\
\sum_v \sum_p \sum_t PRPI_{vpt}{}^S . EEPI_{vp} + \sum_v \sum_p ZI_v . EEFI_{vp} + \sum_k \sum_m ZD_{km} . EEFD_{km} + \sum_j \sum_p \sum_t PROP_{jpt}{}^S . EEPG_{jp} + \\
\sum_j ZP_j . EEFP_j + \sum_k \sum_m ZD_{km} . BHFC_{km} + \sum_i \sum_p \sum_t INVM_{ipt}{}^S . EEIM_{ip} + \sum_j \sum_p \sum_t INVP_{jpt}{}^S . EEIP_{jp} + \\
\sum_k \sum_p \sum_m \sum_t INVD_{kpmt}{}^S . EEID_{kpm} + \sum_v \sum_p \sum_t INVI_{vpt}{}^S . EEII_{vp} + \sum_i \sum_p \sum_t INVM_{ipt}{}^S . EHFCM_{ip} + \\
\sum_j \sum_p \sum_t INVP_{jpt}{}^S . EHFCP_{jp} + \sum_k \sum_p \sum_m \sum_t INVD_{kpmt}{}^S . EHFCD_{kpm} + \sum_v \sum_p \sum_t INVI_{vpt}{}^S . EHFCII_{vp} \le \\
(1+P) . Z_2^* \qquad \forall s
\end{gathered} \tag{43}$$

$$\begin{gathered}
\theta_1 * \Big(\sum_v FJOV_v . ZI_v + \sum_j FJOJ_j . ZP_j + \sum_v \sum_p \sum_r \sum_l \sum_t SI_{vprlt}{}^s . ESTH_{vprl} + \sum_{k} \sum_{m} FJOK_{km} . ZD_{km} + \\
\sum_i \sum_j \sum_p \sum_l \sum_t SV_{ijplt}{}^s . ESTV_{ijpl} + \sum_j \sum_k \sum_p \sum_l \sum_t SP_{jkplt}{}^s . ESTP_{jkpl} + \sum_k \sum_r \sum_p \sum_l \sum_t SH_{krplt}{}^s . ESTH_{krpl} + \\
\sum_i \sum_p \sum_t PROM_{ipt}{}^s . ESMM_{ip} + \sum_v \sum_t \sum_p PROI_{vpt}{}^s . ESDI_{vpt} + \sum_v \sum_p \sum_t PRPI_{vpt}{}^s . ESMI_{vp} + \\
\sum_j \sum_p \sum_t PROP_{jpt}{}^s . ESPG_{jp} + \sum_k \sum_p \sum_m \sum_t PROD_{kpmt}{}^s . ESPD_{kpmt} \Big) - \theta_2 * \\
\Big(\sum_l \big(\sum_i \sum_j \sum_p \sum_l \sum_t SV_{ijplt}{}^s . ESTV_{ijpl} + \sum_j \sum_k \sum_p \sum_l \sum_t SP_{jkplt}{}^s . ESTP_{jkpl} + \sum_k \sum_r \sum_p \sum_l \sum_t SH_{krplt}{}^s . ESTH_{krpl} + \\
\sum_v \sum_p \sum_r \sum_l \sum_t SI_{vprlt}{}^s . ESTH_{vprl} \big) , LSTV_l + \big(\sum_i \sum_p \sum_t PROM_{ipt}{}^s . ESMM_{ip} + \sum_v \sum_p \sum_t PRPI_{vpt}{}^s . ESMI_{vp} \big) . LSMM + \\
\big(\sum_j \sum_p \sum_t PROP_{jpt}{}^s . ESPG_{jp} \big) . LSPG + \big(\sum_k \sum_p \sum_m \sum_t PROD_{kpmt}{}^s . ESPD_{kpmt} + \sum_v \sum_t \sum_p PROI_{vpt}{}^s . ESDI_{vpt} \big) . LSDS \Big) \\
- \theta_3 * \big(\sum_i \sum_p \sum_t PROM_{ipt}{}^s . HSMM_{ip} + \sum_v \sum_p \sum_t PRPI_{vpt}{}^s . HSMI_{vp} \big) \le (1+P) . Z_3^* \qquad \forall s
\end{gathered} \tag{44}$$

SOLUTION APPROACH

Model verification

Table 3: Numerical examples in small dimensions

Example number	period	Holding technology	product type	Transport modes	Domestic factories	customer areas	warehouse	Packaging centers	Foreign factories
١	٤	٢	٢	٢	٢	٣	٢	٢	٢
٢	٤	٢	٢	٢	٤	٤	٤	٣	٢
٣	٦	٢	٤	٣	٣	٦	٥	٢	٣
٤	٧	٢	٣	٤	٤	٧	٤	٣	٣
٥	٤	٢	٢	٤	٤	٨	٣	٤	٤
٦	١٢	٢	٢	٤	٤	١٢	٤	٤	٤

To show the validity of the model in the deterministic state, some small numerical examples with different dimensions are presented. The proposed multi-objective model solved by GAMS software using a personal computer (Intel core i7-7500u, up to 3.5GHz). The CPLEX solver used in deterministic mode.

The optimal values of the objective functions for the sample instances are shown in table 4. It can be seen that the proposed model is applicable for sample problems with different dimensions and reports the optimal values of the objective functions.

Table 4: Optimal values of objective functions for numerical examples

Example number	$\boldsymbol{Z_1^*}$	$\boldsymbol{Z_2^*}$	$\boldsymbol{Z_3^*}$	$\boldsymbol{Z_{NAHAEI-LP}^*}$
١	٥,٤٩٨E+٨	١٥٢٧٧٣,٧٩٢	٤٩٧٥٣,١١٧	٠,٤٥٨
٢	٦,٦٤٣E+٨	١٨٧٣٨٨,٨٧٢	١٣٤٩٠,٣٩٩	٠,٩٣٥
٣	٩,٣٢٠E+٨	٣٧٩١٥٦,٠٧٤	٧٨٨٦٩,١٠١	٥,٦٣٠
٤	١,٤٣٣E+٩	٥٦١٤٢٤,١٠٢	١١٩١٥٦,٦٣٣	١٢,٠٣٨
٥	١,٥٧١E+٩	٣٢٢١٨٨,٧٠٦	٦١٩١٢,٩٧٦	١,٧٤١
٦	١,٩٦٦E+٩	١٧٠٥٥٦٣,٢٨٨	٥٦١٦٩٥,٤٦٥	٢,٣٥٩

Compare between epsilon constraints and LP metric methods in the deterministic state

One of the well-known approaches to face multi-objective problems is the epsilon constraint method. In this method, the problem is solved by transferring all the objective functions except one of them to the constraints. The small problem with the set of indexes according to table number 5 has been solved by Games software.

Table 5: set of indices for the small instance

SETS	I	J	K	R	V	L	P	M	T
SIZE	2	2	2	3	4	2	2	2	24

Table 6: Optimal values for a small example of the LP metric method

solution method	W_1	W_2	W_3	Z_1^*	Z_2^*	Z_3^*	$Z_{NAHAEI-LP}^*$
LP metric	٠/٣٣	٠/٣٣	٠/٣٣	١/١٩٠E+٩	٨٧٩٥٣٨/٩٥٣	٢١٨٧٢٩/١٣٢	٠/٢٣٥
	W_1	W_2	W_3	Z_1	Z_2	Z_3	Z_{NAHAEI}^*
	٠/٣٣	٠/٣٣	٠/٣٣	١/٢٣٩E+٩	١٣٥۶٥٧٨/۶٧٢	٢۴۶٢٩۶/٣٨٢	٠/٢٣٥

Table 7: Optimal values of the objective functions for the ε-Constraint method

PAYOFF TABLE	solution time	$\boldsymbol{W_1}$	$\boldsymbol{W_2}$	$\boldsymbol{W_3}$	$\boldsymbol{Z_1^*}$	$\boldsymbol{Z_2^*}$	$\boldsymbol{Z_3^*}$
١	٢٧ :٠۴ :٢٢	٠/٣٣	٠/٣٣	٠/٣٣	١/١٩٠E+٩	١٠٧۴٠٢٣/٨۵	٣٨۴۴٠٠/٠١
٢		٠/٣٣	٠/٣٣	٠/٣٣	١/۵٠٧E+٩	٨٧٩۵٣٨/٩۵٣	٣٧٣٨۶٠/۶٧
٣		٠/٣٣	٠/٣٣	٠/٣٣	١/۶٢٣E+٩	١٢٠۵٧٧١/۴٨	٢١٨٧٢٩/١٣٢

According to table number 7 and due to the long time need for solving the model using ε-Constraint method, only a small size instance is solved. The optimal values of the objective functions are reported in table number 6. In each step, by placing an objective function as the main objective function and other objective functions as model constraints, it can be seen that the optimal values of the main objective function are equal to LP metric method results in table number 4. Therefore, LP metric method is used in the continuation of this research.

CASE STUDY

By conducting a case study in Iran's pharmaceutical sector, a suitable SC network for influenza vaccine is proposed to contribute to social and environmental sustainability in addition to being cost-effective. Therefore, based on the data of the health sector and previous researches, a sustainable SC plan for influenza vaccine has been presented. Due to lack of information, potential demand points and other needed information about the VSC and influenza disease were identified from the literature [3]. For the rest of the data and parameters, random numbers are generated in GAMS software. In this regard, 20 cities in Iran were considered as customer areas. A representation of potential domestic influenza vaccine production sites,

candidate sites for central warehouses, and customer regions is demonstrated in Figure number 1. According to Figure number 2, China, India, Japan and Turkey are selected as the foreign vaccine production areas. According to the proposed model, packaging centers can be

built in one of the candidate cities of Ankara, Beijing, Tokyo, and Delhi, Pusan. Product flow from these packaging centers to storage centers inside Iran is conducted by one of the air or sea transportation modes.

explanation	symbol
Domestic factories	🟥
warehouse (distribution centers)	△
Provincial treatment areas	●

explanation	symbol
Packaging centers (Ankara, Beijing, Tokyo, Delhi, Busan)	
Foreign production centers (China, India, Japan and Turkey)	
central warehouses (in Iran)	

Fig. 3. Geographic map of chain levels (international)

There are three types of influenza vaccines, namely, recombinant influenza vaccine (RFV), acellular influenza vaccine (CFV) and finally, egg-based influenza vaccine (EFV). Current research implements model for influenza vaccine with domestic and foreign suppliers using random data in Iran. In the presented model, a time planning horizon of 12 months is considered.

Table 8:The set of indices for example at the real level

SETS	**I**	**J**	**K**	**R**	**V**	**L**	**P**	**M**	**T**
SIZE	4	5	5	20	6	4	3	2	**12**

5.1. Examining the changes of the problem with changes in the weights of the objective function (changes in the weights of the LP-Metric method).

Table 9: Optimal values of objective functions with weight changes

objective function	W_1	W_2	W_3	Z_1	Z_2	Z_3	Z_{LP}^*
values	۰	۰	۱	۹/۸۴۶E+۹	۱/۹۷۳E+۷	۱/۲۳۵E+۷	۱۴/۰۹۴
	۱	۰	۰	۳/۸۵۰E+۹	۷۰۸۳۱۷۰/۲۷۷	۳۸۲۰۰۸۰/۱۷۵	۰/۱۸۰
	۰	۱	۰	۶/۷۶۶E+۹	۲۹۵۹۴۸۵/۹۰۸	۱۱۳۲۰۴۳/۰۵۶	۰/۰۸۰
	۰/۵	۰/۵	۰	۴/۸۴۶E+۹	۸۹۵۶۱۸۷/۷۹۷	۵۰۹۷۸۴۰/۳۶۴	۱/۳۷۶
	۰/۵	۰	۰/۵	۶/۰۰۸E+۹	۲/۱۵۹E+۷	۱/۳۳۸E+۷	۸/۰۹۶
	۰	۰/۵	۰/۵	۹/۶۵۸E+۹	۱/۵۴۶E+۷	۱/۱۴۷E+۷	۸/۸۳۰
	۰/۳۳	۰/۳۳	۰/۳۳	۴/۶۸۱E+۹	۶۲۵۲۹۴۳/۶۳۷	۳۱۷۲۹۱۲/۶۳۷	۱/۵۴۴
	۰/۵	۰/۲۵	۰/۲۵	۴/۵۸۹E+۹	۷۸۶۵۵۲۵/۳۶۲	۴۲۵۴۵۴۲/۹۵۲	۱/۷۲۰
	۰/۲۵	۰/۵	۰/۲۵	۴/۷۷۴E+۹	۷۲۳۸۰۶۲/۱۲۴	۴۲۵۴۵۴۳/۵۹۷	۱/۹۸۶
	۰/۲۵	۰/۲۵	۰/۵	۴/۹۹۴E+۹	۹۸۶۵۷۷۹/۳۵۳	۶۶۹۰۷۵۱/۲۰۸	۴/۳۷۰

Considering the importance of the objective functions, this question is answered here: Can the change in the weight of the objective functions change the structure of the network or not? In general, it is concluded that the importance of each objective function strongly affects the value and structure of the SC network. Hence, managers should carefully select the importance of each objective function.

Based on results for case study, Turkey and India are selected as foreign production centers and Tehran, Isfahan and Tabriz are selected for domestic companies.

5.2. Pareto diagrams (conflict of functions)

To illustrate the trade-off between each pair of objective functions, Pareto frontiers are drawn in the following diagrams. The trade-off between the total cost and the environmental objective function shown in the Figure number 4. It demonstrates that less environmental effects can be achieved with the following items. By investing more on high-level holding technology for vaccine storage, transportation with new vehicles, creating more storage, packaging and production centers to reduce the distance of transportation, which leads to less emission of environmental pollutants, including carbon dioxide and refrigerant gases.

Figure number 5 shows the trade-off between social objective functions and total cost. It implies that creating more job satisfaction and creating more safety for employees and customers (social goal) is also achieved with more investment and more cost. The conflict between the goals is also fully evident.

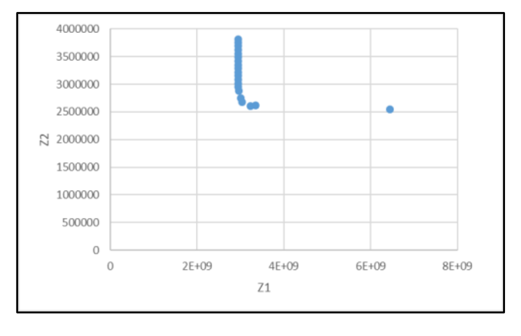

Fig. 4. Pareto front diagram of environment objective functions and cost

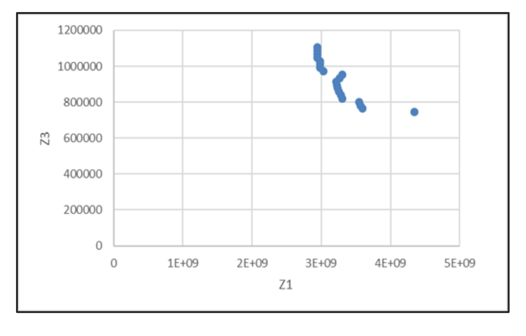

Fig. 5. Pareto front diagram of social objective functions and cost

SENSITIVITY ANALYSIS

The effect of uncertainty in parameters is recently measured in models in the form of probabilistic models or sensitivity analysis. Also, to determine the parameters effects on model, sensitivity analysis is performed on it. The objective functions of the problem have been measured for different values of the parameters. It should be noted that only two parameters were changed each time and the other parameters remained constant.

Table 10: Parameters change (production capacity)

number	parameter	Initial value	Change percentage	New value	Z1	Z2	Z3	Final objective function	Deficiency cost amount
1	$CILO_{vp}$	U(100000,500000)	0%	U(100000,500000)	3.2659E+9	2740407.146	818338.439	1.544	2.4816E+8
	$CIMX_{vp}$	U(600000,700000)		U(600000,700000)					
2	$CILO_{vp}$	U(100000,500000)	5%	U(105000,525000)	3.2639E+9	2737982.248	809433.836	3.323	5.7339E+8
	$CIMX_{vp}$	U(600000,700000)		U(630000,735000)					
3	$CILO_{vp}$	U(100000,500000)	-5%	U(95000,475000)	3.3857E+9	2745057.271	831311.710	2.759	4.6184E+8
	$CIMX_{vp}$	U(600000,700000)		U(570000,635000)					
4	$CILO_{vp}$	U(100000,500000)	15%	U(115000,575000)	3.1944E+9	2733800.091	792645.731	2.375	4.0341E+8
	$CIMX_{vp}$	U(600000,700000)		U(690000,805000)					
5	$CILO_{vp}$	U(100000,500000)	-20%	U(80000,400000)	3.5674E+9	2756273.051	864877.451	2.598	4.7026E+8
	$CIMX_{vp}$	U(600000,700000)		U(480000,560000)					

It can be seen that by increasing the parameters of the minimum and maximum production capacity of domestic factories with a step of 5%, the amount of the economic objective function of the model (total cost) decreases. Also, with the increase of capacities, the number of factories required for construction decreases, instead, the cost of shortage increases. By reducing the capacity limits with a step of 5%, the number of domestic factories has been built, and as a result, the amount of the cost objective function has increased and the amount of the shortage cost has decreased. The fourth stage, compared to the second stage, with a 10% increase in the capacities, the number of manufacturing plants to be built increases and the amount of shortage cost is significantly reduced, which is our desire. In the fifth stage, with a 20% reduction in the capacity limits compared to the first stage, the number of production factories required for construction compared to the first stage (5% increase), the value of the cost function has increased due to the fixed construction costs, as well as the social objective function due to the increase in the number Jobs increase. To check the uncertainty in the parameters of the problem, by changing the value of 6 parameters with uncertainty, 5 scenarios are produced with the specified probability of occurrence, which is as follows.

The answer obtained for each scenario that has been solved in deterministic state, is presented in table number 12 as follow.

Table 11: Generated scenarios for the non-deterministic state

Scenario	$\mathbf{PCY}^{S}$	$\mathbf{PCI}_{pvt}{}^{s}$	$\mathbf{PCM}_{ipt}{}^{s}$	$\mathbf{PRI}_{pvt}{}^{S}$	$\mathbf{PRN}_{ipt}{}^{s}$	$\mathbf{DH}_{rt}{}^{s}$
١	U(١٠،٢٠)	U(١,٣)	U(١،٤)	U(٢،٨)	U(١،٥)	**U(١٢٠٠٠٠،٤٢٠٠٠٠)**
٢	U(٢٠،٣٠)	U(٢,٣)	U(٢ ،٤)	U(٢،٤)	U(١،٤)	**U(١١٠٠٠٠،٤٠٠٠٠٠)**
٣	U(١٥,٤٥)	U(٢,٧)	U(١,٦)	U(٣,٨)	U(٢،٦)	**U(١٠٠٠٠٠،٣٨٠٠٠٠)**

٤	U(٢٥,٥٥)	U(٣,٥)	U(٢,٣)	U(٢،٤)	U(٣,٨)	**U(٩٠٠٠٠،٣٦٠٠٠٠)**
٥	U(٢٠,٤٠)	U(١,٣)	U(١,٣)	U(٢,٥)	U(٢,٧)	**U(١٣٠٠٠٠،٤٤٠٠٠٠)**

Table 12: The answer obtained for each scenario in the deterministic state

scenario	**probability of each scenario π_S**	**Optimal value of objective function 1**	**Optimal value of objective function 2**	**Optimal value of objective function 3**	**Optimal value of final objective function**
1	٠/٢	٣/٢٦٦ E+٩	٢٧٤٠٤٠٧/١٤٦	٨١٨٣٣٨/٤٣٩	**١/٥٤٤**
2	٠/٢	٣/٠٤٧E+٩	٢٥٨٨٤٣٩/٥٣٤	٧٦٣٩٩٩/٩٩٢	**٠/٣٥٤**
3	٠/٢	٣/٢٧٤E+٩	٢٤٣٦٧٨١/٤٨٥	٧١٠١٥١/٠٤٣	**٠/٣٤٩**
4	٠/٢	٢/٩٨٩E+٩	٢٢٨٥٤٥٤/٤٩٩	٦٥٦٧٠٣/١٣٧	**٢/٠٨٢**
5	٠/٢	٣/٣٠٥E+٩	٢٨٩٣٠٣٥/٠٩٦	٨٧٣٣٨٦/٩٩٧	**١/٨٤١**

The problems solved for single-scenario modes and they are all in deterministic state. The purpose of the model presented in this research is to solve the problem simultaneously for all scenarios. P-robust problem solves all presented scenarios in the form of one problem. The value of the objective functions obtained for the P-robust problem and its optimal answer is described in table number 13. It should be mentioned that the P value considered to solve this problem was 0.5.

Table 13: Comparison of the optimal value of the objective functions

Problem type	Z_1	Z_2	Z_3	Z_{LP}^*
P-robust	4.100E+9	۳۷۸۱۲۹۳,۴۲۹	۲۰۵۷۴۹۹,۱۴۱	۱,۷۱۰
Deterministic state	3/563E+9	۲۷۴۰۴۰۷/۱۴۶	۸۱۸۳۳۸/۴۳۹	۱/۵۴۴

As we can see in the above tables, the answer for P-robust problem has more cost, environmental, and social objective functions than the deterministic state. The mentioned cost is the cost of uncertainty that is imposed on the problem under the variable parameters of each of the scenarios. In fact, the answer to the probability problem is the answer that considers all the scenarios at the same time, so that the distance from the optimal state of each of scenario should not exceed a certain amount.

Table 14: Optimal value of the objective functions for different values of the (p) parameter

number	**(p)parameter**	Z_1	Z_2	Z_3	Z_{LP}^*
۱	$P = 0$	-	-	-	**Unjustified**
۲	$P = 0.1$	-	-	-	**Unjustified**
۳	$P = 0.2$	۳,۵۲۰۳۲۲E+9	۳۱۰۵۳۶۹,۴۶۷	۷۰۹۰۲۵,۶۷۶	**۰,۳۹۹**
۴	$P = 0.3$	۳,۵۶۲۹۹۶E+9	۳۳۶۳۲۲۱,۰۳۵	۸۱۶۴۸۱,۹۴۴	**۰,۵۳۱**
۵	$P = 0.4$	۳,۹۰۰۹۶۵E+9	۳۴۶۲۰۶۹,۴۹۵	۱۶۳۸۴۶۶,۰۹۵	**۱,۲۸۶**
۶	$P = 0.5$	۴,۰۹۹۹۲۸E+9	۳۷۸۱۲۹۳,۴۲۹	۲۰۵۷۴۹۹,۱۴۱	**۱,۷۱۰**
۷	$P = 0.6$	۴,۹۱۵۸۲۳E+9	۴۰۳۳۰۴۵,۶۲۶	۲۲۵۴۶۰۹,۹۱۵	**۱,۹۹۹**
۸	$P = 0.7$	۴,۶۳۰۹۷۰E+9	۴۲۹۹۹۳۲,۹۵۲	۲۵۳۶۶۹۶,۰۹۲	**۲,۲۴۸**
۹	$P = 0.8$	۴,۵۴۱۱۷۸E+9	۴۵۴۳۰۱۰,۶۰۱	۳۰۳۴۸۶۲,۰۱۱	**۲,۶۹۹**
۱۰	$P = 0.9$	۴,۸۵۶۰۶۴E+9	۴۷۷۷۵۵۴,۱۱۲	۳۱۲۷۲۲۲,۴۴۱	**۲,۸۴۳**
۱۲	$P = 1$	4.941513E+9	5010986.050	۳۸۸۵۱۶۰,۰۴۱	**۳,۵۳۵**

In order to reduce the maximum regret, it is necessary to increase the average planning costs and vice versa. In other words, reducing the distance from the optimal value of each scenario requires spending more money. Because meeting the constraints of the problem in the worst possible scenario is provided with a higher cost. The sensitivity analysis of the model has been carried out and the results are reported in Table number 14.

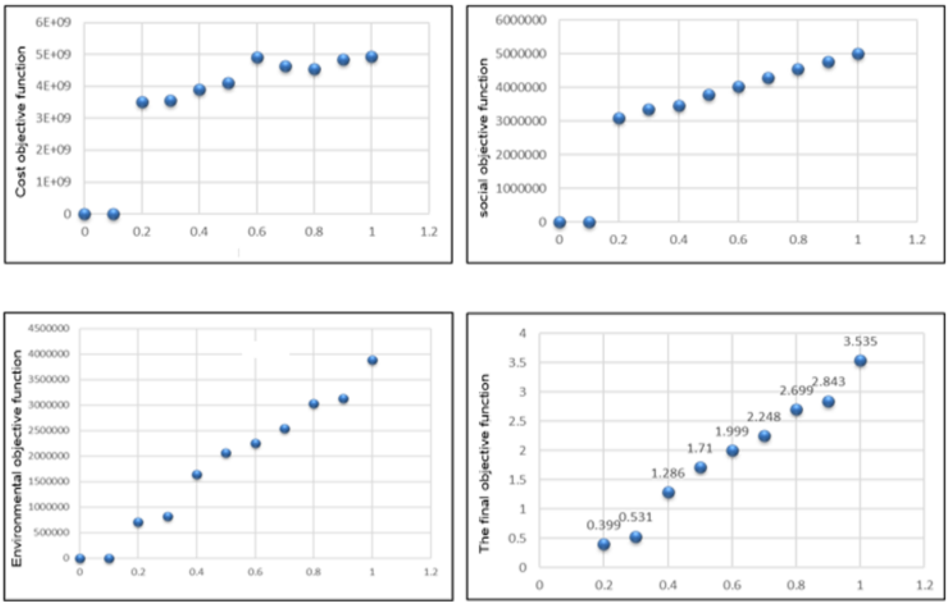

Fig. 6. changes of the objective function 1, 2 and 3 according to the P parameter

A solution for the optimization model is called a robust solution when it remains (close to) optimal under all scenarios. Also, when a model is a robust model that is almost feasible under all scenarios.

The role of cold transportation in vaccine supply chain is considering cold equipment in shipment and effects on transportation costs. long-term passive device (LTPD The transportation costs can be considered as follow:

C= distance per km × cold transportation costs per km × cold transportation cost per box.

CONCLUSION

In this research, a three-objective model for the design of a sustainable VSC with multi-products, multi-cycle, and multi-level is presented that includes supplier centers, producers, distributors, and customer areas. The objectives are total cost in SC, environmental issues and social goals and the model decides about locations, allocation and inventory control on the network. The conflict of interests between sustainability indicators in the VSC has been investigated with the Pareto front method. The results of Pareto Front diagram drawn for the environmental objective function and the economic objective function, indicate that less environmental effects can only be achieved by investing more in using advanced technologies for maintenance and new vehicles and creating more facilities to reduce distance. The different weights of the objective functions of the sustainable SC have been solved by the LP-metric method, and the results show that the importance of each objective function strongly affects the value and structure of the vaccine sustainable SC network. Hence, managers should carefully choose the importance of each objective function.

To determine the effectiveness of the model due to changes in parameters of the problem, a sensitivity analysis was performed. For example, a sensitivity analysis was performed on the vehicle carrying capacity parameter. The results show that with the reduction of the vehicle capacity, the number of trucks required for purchase increases, and as a result, the cost objective function is also slightly increases.

In order to deal with the uncertainty in the VSC, p-robust approach has been used to reach a robust answer and a robust model to encompass probabilistic and robust approaches. In robust approach a moderate scenario is chosen besides its probability to occur. Also in probabilistic approach it is probable that the worst scenario is selected and have differences with what happens in reality. The model of this study has always been feasible against the uncertainty of parameters, and the model's answer for the objective functions remains close to optimal under all scenarios. Comparing the optimal values of the objective functions in the deterministic state and the robust state shows that the solution obtained from the robust state has more objective functions than the deterministic state. Also, the results of model for different values of parameters shows that reducing the distance between the optimal values of each scenario requires spending more money, because calculating the limits of the problem in the worst possible scenario is more expensive. Also the model's sensitivity analysis has been performed with respect to P values and the results shows a proper behave for model.

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