Decision Analytics Journal 4 (2022) 100126

Contents lists available at ScienceDirect

Decision Analytics Journal

journal homepage: www.elsevier.com/locate/dajour

A humanitarian cold supply chain distribution model with equity consideration: The case of COVID-19 vaccine distribution in the European Union

Vahid Khodaee [a], Vahid Kayvanfar [b,*], Alireza Haji [a]

[a] Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran
[b] Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, P.O. Box 34110, Doha, Qatar

ARTICLE INFO

Keywords:
Cold supply chain
Humanitarian
COVID-19 vaccine distribution
Deprivation cost
Equity
Third-party logistics providers (3PLs)

ABSTRACT

This research develops a humanitarian cold supply chain model with equity consideration for COVID-19 vaccine distribution during a pandemic, considering deprivation cost and an important social concept named equity. The proposed comprehensive plan minimizes all incurred costs, including transportation costs, shortage costs, deprivation costs, and holding costs, while aiming at eliminating infection and mortality rates. The proposed three-echelon supply chain model includes suppliers, distributors, and affected regions (ARs), as destinations. We apply the proposed model to the actual vaccine distribution data during the COVID-19 outbreak in Europe. A mixed integer programming (MIP) model is developed to minimize the costs and satisfy the demand goals in the vaccine distribution plan. A sensitivity analysis demonstrates how total and deprivation costs affect each other, helping the managers establish a trade-off between them. The results show that appropriate supply chain planning can minimize logistics and social costs. The proposed model can help policymakers, and decision-makers better understand the importance of equity and implement a fair distribution of vaccines, considering the deprivation cost as a social cost.

1. Introduction

The world has been changed since December 2019 with the pandemic disease from Wuhan city in China. So far, more than six million people have been killed and more than six hundred million infected. SARS-COV2 causes coronavirus disease (COVID-19) and can spread person-to-person by breathing, so attention and efforts to protect different groups of people or reduce transmission should be applied [1]. On the 11 March 2020, the World Health Organization (WHO) eventually announced COVID-19 outbreak as a pandemic ([2], n.d.). COVID-19 virus has negative effect on economic and social community. After the discovery of the COVID-19 vaccine, the challenges and problems of transportation and distribution have gripped governments. The socio-technical essence of logistics is fundamental to this complexity: a collective network of individuals performing a collection of technical acts over a set of support networks [3]. In the beginning, scientists started research with more than 50 potential COVID-19 vaccines around the world. Through the ACT accelerator, WHO is collaborating with scientists, businesses, and global health groups to accelerate pandemic response. COVAX (headed by WHO, GAVI, and CEPI) will promote equity in access and distribution of vaccinations to protect individuals in all countries once a safe and efficient vaccine has been identified. Prioritization will be given to those who are most at danger ([4], n.d.).

Viruses are continuously changing due to mutation, and new varieties are predicted to emerge. Occasionally, new variations occur and then vanish, while new variations emerge at other times. During the COVID-19 pandemic, many strains of the virus that causes COVID-19 are being monitored in the USA and across the world ([5], n.d.). The WHO classifies alpha as a variation of concern, and it was first discovered in Kent, England, in September 2020, sparking the UK's second wave. Beta was the first identified in South Africa in May 2020, and it is also deemed a variation of concern by the WHO. Also, Gamma was first discovered in November 2020 in Manaus, Brazil, and is another variation of worry for WHO. It is still the most common variety in South America at the time of writing. Delta continues to cause a significant surge of cases in Asia, such as India, where it was the first discovered in October 2020 [6].

Vaccination has been the best strategy of preventing illness, reduce transmission, incapacity and death from infections. Based on the literature, every year 2 to 3 million people are saved from death and this amount can increase to 4 to million, if worldwide vaccination coverage could increase farther (*Vaccines and Immunization*, n.d.). In this regard, achieving a vaccine is difficult and requires much effort,

* Corresponding author.
E-mail address: valikayvanfar@hbku.edu.qa (V. Kayvanfar).

https://doi.org/10.1016/j.dajour.2022.100126
Received 29 July 2022; Received in revised form 28 August 2022; Accepted 5 September 2022
Available online 9 September 2022

and its distribution is very sensitive and requires a lot of money and careful planning. One of the most essential roles in distributing vaccines is using the cold supply chain. In cold chains, items must be put away and shipped at low temperatures close or underneath the freezing mark. It requires the utilization of refrigerated distribution centers and trucks, which burn-through enormous amounts of energy for refrigeration [7]. Many potential COVID-19 vaccines have been studied, and a few have been approved for mass production since late 2020 ([8], n.d.). There are some acceptable vaccines in the world, some of them are going to be aptly in the following to explain more about cold chain requirements.

- Pfizer designed packaging and storage improvements that were suited to the location where vaccines were to be used. They use dry ice to sustain appropriate temperature settings of –70 °C ± 10 °C for up to 10 days in specially built, by designing temperature-controlled thermal shippers. They will ship by air to main hubs within a country, and then by ground transportation to dosing sites. Primary efficacy report shows this vaccine to be 95% successful against COVID-19 beginning 28 days following the first dose ([9], n.d.). Moreover, they have three options for storage ([10], n.d.):
    1. Ultra-low-temperature freezers, commercially accessible and can increase shelf life by up to six months.
    2. Units of refrigeration that are often obtainable in hospitals. Holding vaccine at refrigerated 2–8 °C conditions for five days is possible.
    3. Pfizer thermal shippers can be utilized as temporary storage units by refilling them with dry ice and storing them for more than 30 days.
- AstraZeneca was picked as the most appropriate antibody innovation for a SARS-CoV-2 immunization as it has been shown to generate a strong immune response from one dose in other vaccines. It has been hereditarily changed so it cannot grow in humans. This likewise makes it more secure to provide for youngsters, the old and anybody with a previous condition, for example, diabetes ([11], n.d.). In the two various dose schedule vaccine efficacy was 90% in one and 62% in the other, and the vaccine may be simply administered in available healthcare systems, held at 'fridge temperature' (2 °C to 8 °C), and transported using existent operations ([12], n.d.).
- The Johnson & Johnson (J&J)/Janssen vaccine was listed for emergency use by WHO on 12 March 2021. The vaccine has been allowed for use in Europe, the USA and other countries, with the widest experience to date in the United States, where more than 8 million doses of the J&J vaccine had been administered as of 7 May. The vaccine can be kept at 2 °C to 8 °C . Since the only single-dose COVID-19 vaccine licensed for use so far, the vaccine might be a valuable tool for reaching out to hard-to-reach communities and avoiding illnesses and deaths throughout the world ([13], n.d.).
- The Moderna vaccine is based on the mNRA. The WHO's Strategic Advisory Group of Experts determined that it had a 94.1% effectiveness rate based on a two-month median follow-up. Though the vaccine is delivered as a frozen suspension in a multi dose vial at −25 °C to −15 °C, vials can be kept at 2–8 °C for up to 30 days before the first dose is withdrawn, implying that ultra-cold network equipment may not be required to deploy the vaccine ([14], n.d.).
- The Sinopharm COVID-19 (BBIBP-CorV, COVILO) is an inactivated vaccine made of virus particles. This vaccine was developed by China National Pharmaceutical Group Co., Ltd. (Sinopharm) and the Beijing Institute of Biological Products Co in 2020. Studies have shown that it has 79.34% efficacy ([15], n.d.). Cold Chain Requirements Stored between −25 degrees Celsius and −15 degrees Celsius up to expiration date. Refrigerate between 2 degrees Celsius and 8 degrees Celsius for up to 30 days prior to first use ([16], n.d.).

Usually, governments quarantine cities to reduce epidemic and control disease. As a result, they incur many economics costs, including the cost of treatment and the purchase of effective drugs and vaccines. On the other hand, their financial resources and income are reduced. In this way, they are under economic pressure to distribute the vaccine. This issue is particularly articulated in low and middle-income countries (LMICs), where some of the participants to the issue include significant expenses, competing for health preferences, shortage of resources, poor monitoring and surveillance, helpless checking and oversight, and inflexible appropriation structures [17]. Because of the extensive disruptions brought on by this pandemic, such devastating economic setbacks represent a more significant threat to supply chains. The cold supply chain is one of the most significant supply chains that may be more vulnerable to COVID-19 disruptions. Due to the presence of some of the most sensitive products, such as pharmaceuticals and frozen food, in the cold supply chain, disruptions in this supply chain sector can hurt economies and their whole processing networks [18]. Although, vaccine companies are limited and still do not reach mass production for the access of all people in the world, the WHO organized the Expanded Program on Immunization (EPI) in 1974 to give universal access to all paramount vaccines for every children [19]. In the last decade [3] believed that sustaining high class of service in the affected regions might need greater logistical investment than is feasible. In contrast, without taking the implications on the population into account, reducing logistical costs may have a detrimental impact on their health. It is important to determine the prefect mixture of logistic attempt and service level.

Health justice emphasizes ensuring a fair distribution of medical services to vulnerable groups. During the flu pandemic, it can be used as a principle in distributing vaccines to high-priority individuals. Due to COVID-19 effect on sensitive groups and the relationship of groups such as medical staff with sick people, to reduce the harmful effects of the epidemic, an effective mechanism for community vaccination should be used in a way that most effectively reduces the incidence, leads to death, and reduces the vaccination program's cost. Cantillo et al. [20] believed that designing effective models to minimize the social costs of response operations is important in order to deliver essential supplies to communities in need. Social costs contain deprivation costs, which are a growing feature of deprivation of time, derivative from human suffering due to lack of accessing to services or goods, in addition to simply covering the cost of logistics, transportation mode, and humanitarian logistics. The aim of sustainable humanitarian logistics is to provide every human being with a degree of comfort suitable for his or her own and family's health and welfare, especially in catastrophe and crisis [21]. From the viewpoint of Huang et al. [22], both in operational and for modeling purposes, equity can be difficult to describe. The discrepancy between service levels among help receivers, where service levels are defined by pace and quantity of delivery, characterized equity.

In this paper, a new mathematical model for fair distributing COVID-19 vaccine among different ARs is developed and formulated, while the total costs of the whole vaccine chain are minimized, including transportation cost, distribution cost, transportation mode cost, humanitarian logistics costs, deprivation cost, shortage cost, and inventory holding cost. Few studies integrated Humanitarian logistics and cold chain aspect considering equity, deprivation cost, and transportation mode in the pandemic. To the best of the authors' knowledge, for the first time, one of the most important and recent introduced social cost terms (i.e., equity), within a humanitarian cold supply chain in the COVID-19 pandemic is studied in this research, taking budget constraints, cold chain considerations, and real data into account, simultaneously, to provide an optimal plan for the vaccine distribution chain of the COVID-19. Considering deprivation and equity is carried out to minimize human suffering and fatalities in the COVID-19 crisis. The main contributions of this study could summarized as follows:

- Proposing an optimal plan for the COVID-19 vaccine distribution in Europe.
- Developing a new mathematical model for fair distribution of the COVID-19 vaccine.
- Taking equity into account as an essential social factor in humanitarian logistics.
- Considering deprivation cost and equity to minimize fatalities.
- Considering budget constraints and cold chain considerations in a real-world study in Europe.

In Section 2, the relevant literature is extensively reviewed. In Section 3, a new mathematical model of distributing vaccine supply chain is proposed to minimize the total cost of considered cold chain. In Section 4, the data collection is comprehensively explained, including comparative results, such as sensitive analysis and managerial insights. Finally, Section 5 concludes this research.

2. Literature review

Studies have focused on and researched the vaccine supply chain from different viewpoints because of the essential role of vaccines in hindering outbreaks of infectious diseases. Vaccines are sensitive materials and they should preserve in low temperatures; they need to distribute in a cold chain under international policies. The cold supply chain is made up of temperature-sensitive operations that begin with the provision of raw materials, continue through manufacturing, and end with the transit of finished items to final customers. Pandemics like COVID-19 threaten the functioning of the cold supply chain. Khan and Ali [18] ensure the sustainable functioning of the cold supply chain by recommending resilience strategies via a Fuzzy QFD technique. Ibrahim et al. [23] implemented a new framework that supports the planning and delivery of vaccination campaigns by segmenting and prioritizing target populations, estimating vaccination timeframe and workforce requirements, and predicting logistics costs and facilitating the distribution of vaccines from manufacturing plants to vaccination centers. Lin et al. [24] developed a mathematical model of the distributor's cold chains transportation decision for vaccines, and scrutinized how the retailer's control policy influences the decision of distributer. Moreover, two common control policies were compared to look into few purposeful insights and their result showed that the impact is less effective in the two-step inspection policy that tends to be more stringent than the single-step one. Duijzer et al. [25] reviewed the literature on vaccine chains by integrating the WHO preferences with an OR/OM supply chain view. They divided the second WHO (Immunization Supply Chain Efficiency) priority into three sections, namely, production, allocation, and distribution, each of which contributes to the efficiency of the supply system. In the OR/OM community, supply chains' environmental effect has received little attention and addressed where appropriate within their supply chain context.

A recent study by Govindan et al. [26] extended a profitable decision support system (DSS) for COVID-19 healthcare supply chain based on fuzzy inference system (FIS) and physicians' knowledge to help with the demand management. Based on the immune system's risk level, the community is separated into four groups, including very susceptible, susceptible, slightly susceptible, and normal. This category can include high-risk age groups and people with underlying diseases like heart disease, diabetes, and cancer. A Mamdani FIS is utilized to identify the society inhabitants, so demand can be handled in a healthcare supply chain under the crisis emerging from COVID-19. The model aims to monitor epidemic prevalence of this disease and to reduce supply chains disturbances that appertain to healthcare supply chains. Many studies have been conducted to control the prevalence of epidemics. He and Liu (2015) improved a model that took into account the spatial interactions between epidemic regions. A modern emergency medical logistics model for quick response to public health crises was proposed, including the time-varying prediction of demand for medical relief and relief distribution. Saif and Elhedhli [7] studied cold supply chain design and provided a mathematical model to represent its economic and environmental effects. The problem was formulated as a concave mixed-integer programming (MIP) problem to minimize the expected cost of the supply chain such as capacity, transportation and inventory holding costs.

The importance of using a cold supply chain in the distribution of vaccine is critical [24]. It is essential for such items as vaccines to understand and analyze each stage of the cold supply chain to provide the most appropriate and safe cooling level. To prevent errors along the chain, it is also critical to comprehend how all the facilities, tools, equipment, and materials are related [27]. Among some of the vaccine supply chain literatures, coordinating the worldwide interests of the entire supply chain and the corporative (local interests of apart stakeholders, such as distributors and clinics) is one of the main strategical planning problems in vaccine supply chain management [28]. Büyüktahtakın et al. [29] introduced a new integrated epidemics-logistics model to optimize logistics activities. The model takes into account treatment capacity, migration, and spatial transmission rates, and its projections closely match the real-world case and death data from the 2014–2015 Ebola outbreak. It may also be used to forecast and manage other infectious illnesses. The aim of the model is to minimize the total number of infections and casualties over a multi-period planning horizon under a restricted budget. Yang et al. [17] addressed the plan of WHO-EPI vaccine distribution in low and middle-income countries. A MIP model was developed, and for solving very large problems, an MPI-based algorithm was built. Numerical tests using data obtained from many various countries in sub-Saharan Africa were performed to study the efficiency of the algorithm. Duijzer et al. [25] planned the critical step of distribute vaccines from the manufacture to the end-users. when choosing where vaccine stocks should be kept, inventory management decisions occur. There are logistical problems relating to location, staffing levels, and the layout of fixed distribution points.

Many studies have been done to increase productivity, maintain quality and reduce transportation time for temperature-sensitive products. Consumer preference for freshness is increasing in the cold supply chain, which motivates investment in preservation technology to enhance the freshness of perishable products [30]. Turan and Ozturkoglu [27] demonstrated that packaging, transportation and shipping, storage specifications and handling practices, inventory management, technical issues, and delivery delay are the elements primarily influencing the effectiveness of the sustainable cold supply chain. Goodarzian et al. [31] Developed a new responsive-green-cold vaccine supply chain network during the COVID-19 pandemic. Challenges in the COVID-19 pandemic in the supply chain demonstrated the necessity of combination and interactivity of resilience and sustainability [32]. Gilani and Sahebi [33] presented a multi-level, multi-period COVID-19 vaccine distribution supply chain MILP model, which addresses internal and external supplies to create a sustainable model. Qian et al. [34] developed an improved food cold chain management system utilizing the internet of things and blockchain technology to provide a novel solution to improve traditional food cold chain management and thus solve the issues connected to the COVID-19 pandemic.

Since vaccines are perishable products, they must distribute in the cold supply chain [35]. Products such as drugs and vaccines are too sensitive, require different temperature area. The article looked at truck scheduling at a cold-chain cross-docking facility that deals with two types of perishable goods. One of their contributions was introducing cross-docking truck scheduling problem to the logistics of cold chain. The transport and storage of two kinds of goods require different inbound/outbound trucks and finite capacity storage areas, and that is why they proposed a mixed-integer linear programming model for handling such a problem to minimize total operational costs of the goods in the cross-docking terminal. Georgiadis and Georgiadis [36] Developed a novel mixed-integer linear programming model to optimize daily vaccination plans in clinics.

Some items, such as medications and blood products, are prone to deterioration and their rate of deterioration changes with time, which is notable. In fact by increasing the interval time in the network between factory and customers, deterioration rate will also increase. The degradation of such items puts significant expenses on cold supply chain. Momeni and Bagheri [37] examined how wholesalers from two separate supply chains collaborate with each other to utilize a common warehouse and how it affects product degradation over time. Furthermore, a novel method are given, and cooperative game theory is employed to be involved in the some advantages of distributor collaboration. The findings show that the recommended method is effective in lowering costs and preventing supply chain degradation.

Global transport from suppliers and to markets around the world results in higher prices and longer travel times, rendering global development a major challenge in the management of logistics. The problem is also the activities linked to international trade, such as providing sufficient transport and storage, bringing goods through customs, supplying them to foreign locations in a timely manner at a reasonable cost [38]. Also, time is a critical issue in transporting vaccines, and they should transport as soon as possible by faster facilities. On the other hand, using transportation modes is too costly, so it might has adverse impacts on the vaccine programs. Murphy and Farris [39] addressed the time-based approach and its effect on the choice of transport to decide how logistics managers need to change so as to resolve a time-based business focus. Their research is significant because it extended the stream's perspective to include the company's other functional areas and concentrate on integrating carriers through improved information technologies such as electronic data interchange (EDI). Murphy and Farris found that timeliness and reliability should be included in models used for transportation option and recommended that the problem should be restructured so that all considerations are specified in terms of cost, including timeliness and reliability.

In this paper, we used third-party logistics providers (3PLs) to transport vaccines among users. "3PL" services refer to outsourcing a company's logistics operations to a specialized firm. In order to focus their financial and human resources on the growth of their primary business activities and to provide flexibility to combine services in response to shifting business demands, many organizations are refusing internal logistics divisions. "3PL" companies perform a wide range of operations. Deliveries of commodities, storage, revenue, assembly, loading, labeling, repackaging, and distribution are all handled by them. Their task is to optimize the logistical procedures, where operational expenses depend on several factors [40]. A 3PL can reduce expenditures by optimizing resource usage and providing better service quality for consumers owing to knowledge experts [41]. Heydari and Bakhshi [42] considered an e-channel where an e-retailer has a small in-house shipping fleet and can hire additional shipping services from a 3PL to deal with demand volatility as they addressed freight shipment fulfillment policies. Moreover, a multi-objective multi-echelon supply–distribution model was suggested to optimize interactions of entities located using a 3PL-managed supply–demand hub in the industrial cluster [43].

In the literature, the notion of equity is usually split into two categories: horizontal and vertical equity. Horizontal equity is characterized as "equal treatment of equals", implying that every individual or group of persons in need has equal access to the same resources with the objective of satisfying that need. Vertical equity, on the contrary, is described as "the unequal, but equitable, treatment of unequal". The emphasis in this form of equity is on giving an amount of resources commensurate to need [44]. Vertical equity may be implemented using an objective function that includes an evaluation of the overall well-being, such as "deprivation costs" [3] However, the exact definition of equity is challenging, equitable supply chain of critical resources in crisis situation is serious. Enayati and Özaltın [45] optimized vaccine distribution in a population composed of subgroups. They used a compartmental model for influenza transmission, and devised a mathematical program to reduce the amount of vaccine doses distributed to effectively extinguish an epidemic in its initial phase. In this way, when deciding on vaccine delivery, they suggest an equity limitation that helps to understand fairness. Moreover, they proposed an exact solution approach that returns a vaccine distribution strategy with the quality assurance of solutions. In fact, there is no universal definition for measuring fairness in the distribution of vital items [46]. Tavana et al. [47] presented a mixed-integer linear programming model to distribute equitable COVID-19 vaccines in developing countries. Manupati et al. [48] designed a mixed-integer linear programming model for locating and allocating cold storage facilities for bulk vaccine production, considering equitable distribution, storage and transportation requirements.

In fact, vaccine distribution chain considering equity concept and other affecting cost terms simultaneously has not been studied in the literature in the COVID-19 pandemic situation so far.

The growing inequality in resource distribution has drew attention in Europe, upon the idea and exact definition of 'deprivation' [49]. Holguín-Veras et al. [3] described deprivation costs as the economic assessment of human suffering related to a lack of access to a service/product. Identifying the features that deprivation cost functions should have, addressing the conceptual and economic dimensions of deprivation cost estimation are among the main purposes of this research. Holguín-Veras et al. [50] assessed a procedure for deprivation cost functions to apply it econometrically so as to gain a deprivation cost functions for drinkable water. Their goal is to plan and test a process encompassing experimental pattern, data collection, and econometric modeling to compute deprivation cost functions for crucial supplies and services. It has been shown that deprivation costs have a non-linear relation with deprivation times. Cantillo et al. [20] used discrete choice model to estimate deprivation costs because of the time waiting for basic supplies.

Humanitarian aid in disasters is essential to preserving lives and reducing human suffering [57]. Changes in the wellbeing of persons impacted by catastrophes are assessed as discrete choices. Their models take into account the impact of a person's socioeconomic traits as well as random influences on discrete choice. The results of this research are practical for estimating the social costs of humanitarian relief operations. From the author's viewpoint, one of the main goals of humanitarian logistics is to assurance the timely supply of supplies to people affected by disasters throughout the response process.

Recently, by introducing the concept of deprivation cost, some advances have been made in the mathematical modeling of humanitarian operations [51,56]. In order to minimize the social costs, which include deprivation costs and the cost of procurement and planning, [51] move towards a global optimal model for optimizing humanitarian logistics. In this regard, providing an optimal plan for the distribution of the COVID-19 vaccine among countries, is a very important research gap which has been covered in this research. In planning for disasters [52] suggested a facility location model for prepositioning supplies. Their model specifically considers the deprivation costs and minimizes the social costs, as the sum of deprivation costs and private costs through actual knowledge. As an example of various main methods, several papers discussed about different optimization approaches and mathematical models. The adopted approaches include MIP [29,58,59], bi-criteria integer linear programming [60], linear programming [61], case study and simulation [62,63], generalized Benders' decomposition [64], heuristics based on Benders' decomposition or Lagrangian relaxation [65,66].

In this regard, epidemic outbreaks have a particular effect on supply chain distribution. The rapid spread of these diseases, including MERS, SARS, Swine flu, Ebola, and the last one, coronavirus, have many effects on supply chain components such as supply and demand, population, and distribution infrastructure [26].

Table 1 provides a comparative literature analysis by organizing the related studies on the vaccine supply chain according to their key characteristics, which helps to further define the research gap and the contributions of this study. As already mentioned in previous section,

Table 1
Summary of the literature related to vaccine supply chain.

Author/year	Cold supply chain	Typo of Mathematical Model	Single/multi Objective	Transportation Mode	Equity	Deprivation cost	Case study
Holguín-Veras et al. [3]		NLP	S		✔	✔	
Hovav and Tsadikovich [28]	✔	MIP	S				✔
Saif and Elhedhli [7]	✔	MIP	S	✔			
Gutjahr and Fischer [51]		NLP	S		✔	✔	✔
Cotes and Cantillo [52]		MIP	S			✔	✔
Larimi and Yaghoubi [53]		MIP	M				✔
Lin et al. [24]	✔	–	S	✔			✔
Enayati and Özaltın [45]	✔	MIP	S		✔		
Zheng et al. [35]	✔	MIP	S				
Al Theeb et al. [54]	✔	MIP	S				✔
Yang et al. [17]	✔	MIP	S				✔
Sazvar et al. [55]		MIP	M	✔		✔	✔
Malmir and Zobel [56]		MIP	S	✔	✔	✔	✔
Goodarzian et al. [31]	✔	MINLP	M		✔		✔
Gilani and Sahebi [33]	✔	MILP	M	✔			✔
Sun et al. [57]		MIP	M			✔	✔
Vali-Siar and Roghanian [32]		MILP	M				✔
Current research	✔	MIP	S	✔	✔	✔	✔

to the best of the authors' knowledge, one of the most important and recent introduced social cost terms (i.e., equity), for the first time, within a humanitarian cold supply chain in the COVID-19 pandemic in Europe is studied in this research, considering cold chain considerations, budget limitations, and real data, at the same time, to provide an optimal plan for the vaccine distribution chain of the COVID-19 in Europe. The lack of these items in the literature is a serious research gap which has been covered in this research. Also, considering deprivation and equity is carried out to minimize human suffering and fatalities in the COVID-19 crisis

3. Problem statement

In this study, a mathematical model is developed to minimize the overall cost of a vaccine supply chain, involving different cost terms that pay special attention to social costs to reduce human mortality and suffering of infected people. Furthermore, the distribution of vaccines in pandemic and critical conditions, such as what we see in the crisis of COVID-19, requires speed and accuracy in distribution, deprivation, and equitable distribution. In this study, special attention has been paid to the last two issues. In fact, we do not mean equity in the sense of equal distribution and an equal amount to the points of demand, but equity distribution to one proportion of the affected region (AR). That is two points of demand benefit equally from the distribution of the vaccine. In the meantime, point A may have more population than point B, but taking the equity limitations into account, these two points should be vaccinated in the almost same proportion within a given tolerance. To ensure the rapid distribution of the vaccine in the chain, we use the concept of deprivation cost, which is time-dependent, and is calculated from the period of ordering the point of demand to the delivery of these items to it.

Distribution is not feasible for a variety of reasons (as one can see in the real world), and usually, the demand of an AR is divided into several parts and satisfied in different periods. These reasons include limited production capacity, limited storage capacity of distributors, restricted machine capacity, etc., existing perishable items, requiring special maintenance equipment. Therefore, it is not possible to store high volume of products for a long time.

As mentioned earlier, the items considered, i.e., vaccines, are perishable. However, due to the special conditions in the COVID-19 pandemic, special care is taken in its consumption, maintenance, and distribution. So far, there has been no specific report of spoilage of a significant amount of vaccines in the world. On the other hand, since the need of whole world exceeds from the production rate of vaccine manufacturers in upcoming months and even years, and this means that no item will be deteriorated due to storage in the warehouse, the deterioration cost has not been considered in this research, accordingly. In the vaccine chain problem considered in this research, there are some entities, including suppliers, distributors, and ARs, which play a significant role in the cold supply chain. Also, only a single item as a vaccine is considered, however, there are some different COVID-19 vaccines, approved by WHO. In this paper, an effort is made that the manufacturers distribute the vaccines in an equal manner to the possible extent using equity concept.

3.1. Sets

I-*index for suppliers* $(i = 1, 2, \ldots., I)$;
J-*index for distributors* $(j = 1, 2, \ldots, J)$;
K-*index for affected regions* $(k = 1, 2, \ldots, K)$;
V-*index for refrigerated trucks* type "v" $(v = 1, 2, \ldots, V)$;
V' -*index for refrigerated trucks* type "v′" $\left(n = 1, 2, \ldots, V'\right)$;
T-*index for period* $(t = 1, 2, \ldots, T)$;

Fig. 1 illustrates a generic depiction of the interaction between different entities in the considered vaccine supply chain. It is assumed that local governments manage each AR, and vaccines are generally transported from suppliers to distributors, which are managed by 3PLs, and then, to the ARs. Moreover, refrigerated trucks that transport vaccines from suppliers to distributors are different from those refrigerated trucks transporting vaccines from distributors to affected regions (transportation mode is allowed). Because distributors are 3PLs, they might have different infrastructure. Each region may receive different amounts of dissimilar types of vaccines according to their demands. The proposed model describes how to distribute various vaccines from suppliers to distributors and then parcel out different vaccines to several ARs. In each part, a specific truck is utilized to preserve vaccines in cold space.

3.2. Assumptions

1. There are different type of refrigerated trucks, each of which can ship different amount of vaccines to the distributors and ARs (transportation mode is allowed).
2. There is no bound on the number of refrigerated trucks and all available routes are accessible.
3. The production capacity of each supplier is restricted.
4. Because of the crisis and excess global demand, shortage is not allowed.
5. Each distributor can serve more than one AR.
6. Suppliers can serve each distributor; moreover, they can serve ARs directly.

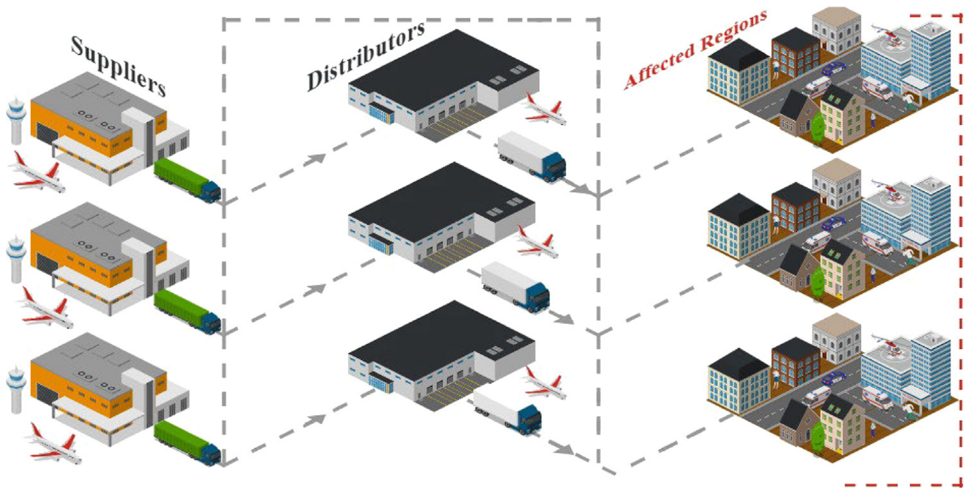

Fig. 1. The considered cold supply chain.

7. There is multi type of vaccines, each of which is approved by WHO.
8. Each suppliers can produce one type of vaccine.
9. No lead time is considered.
10. In each period, the demand of AR is independent and prearranged.
11. The distributors are each managed by a 3PL.

3.3. Parameters

D_k^t = *Demand of* kth *AR in period t.*

C_{ij}^{v} = *cold transportation cost per unit of vaccine by* refrigerated truck *v from supplier i to distributor j.*

$C_{jk}^{v'}$ = cold *transportation cost per unit of vaccine by* refrigerated truck *v' from distributor j to* kth AR.

C_{ik}^{v} = cold *transportation cost per unit of vaccine by* refrigerated truck *v from supplier i to* kth AR.

C_v = *fixed cost of utilizing* refrigerated truck *v*.

$C_{v'}$ = *fixed cost of utilizing* refrigerated truck *v'*.

H_j = *Average Inventory cost of vaccines.*

P_k = *Penalty cost of unmet demand of* kth AR.

M = A *large custom number.*

PC_i = *Maximum production capacity of supplier i.*

S_j = *Maximum storage capacity of distributor j.*

α = *Consumption coefficient of each vehicle's storage capacity to transport each box of vaccine.*

CAP_v = *Capacity of vehicle type v for transferring boxes of vaccine from supplier to distributor and AR.*

$CAP_{v'}$ = *Capacity of vehicle type v' for transferring boxes of vaccine from supplier to AR.*

3.4. Variables

ij^{vt} = *Amount of vaccines transported by vehicle v from supplier i to distributor j in period t.*

$x_{jk}^{v't}$ = *Amount of vaccines that are transported by vehicle v' from distributor j to* kth *AR in period t.*

x_{ik}^{vt} = *Amount of vaccines transported directly by vehicle v from supplier* i to kth *AR in period t.*

y_v^t = 1; *if vehicle v delivers vaccine from supplier i to distributor j in period t*;0, *otherwise.*

$y_{\prime v}^{t}$ = 1; *if vehicle v delivers vaccine from supplier i to* kth *AR in period t*;0*otherwise.*

$y_{v'}^{\prime\prime t}$ = 1; *if vehicle v' delivers vaccine from distributor j to* kth *AR in period t*;0, *otherwise.*

z_k^t = 1; *if the* kth *AR is supplied in period t*;0, *otherwise.*

R_k^t = *Unmet demand at* kth *AR in period t.*

Inv_j^t = *Average Inventory level of vaccines in distributor j in period t.*

Num_i^{vt} = *Number of vehicle type v transports vaccine from supplier i in time period t.*

$Num_j^{v't}$ = *Number of vehicle type v' transports vaccine from distributor j in time period t.*

3.5. Objective function

The following is the mathematical expression of the economic factor:

$$\boldsymbol{Min\ Z} = \sum_{i,j,v,t} C_{ij}^{v} x_{ij}^{vt} + \sum_{j,k,v',t} C_{jk}^{v'} x_{jk}^{v't} + \sum_{i,k,v',t} C_{ik}^{v} x_{ik}^{vt}$$
$$+ \sum_{v,t} C_v y_{ij}^{vt} + \sum_{v,t} C_v y'^{vt}_{ik} + \sum_{v',t} C_n y''^{v't}_{jk} + \sum_{k,t} P_k R_k^t + \sum_{j,t} H\,Inv_j^t$$
$$+ \textit{deprivation cost} \tag{1}$$

$$\textbf{deprivation cost} = \sum_{t} r(t) \left[\sum_{k} D_k^t \left(1 - z_k^t\right) + \sum_{k} \left(z_k^t \left(D_k^t - \left(\sum_{i,v} x_{ik}^{vt} + \sum_{j,v'} x_{jk}^{v't}\right)\right)\right)\right] \tag{1a}$$

The proposed objective function, Eq. (1), includes nine terms that should be minimized: total cold transportation costs in the considered network, the cost of utilizing transportation mode, penalty cost of unmet demand, inventory holding cost, and deprivation cost.

Eq. (1)a calculates the cost of deprivation. In fact, this term tries to fairly distribute the vaccines among ARs to the possible extent. The cost of deprivation is a quantitative assessment of the extent of human harm due to lack of access to crucial items, such as vaccines, in a critical situation, considered as a function of time. The deprivation cost function in a vaccine supply chain is defined in terms of time and can play a decisive role in the objective function. In fact, deprivation cost can be estimated as a function of time required for the ARs to access the vaccine in the distribution network in the form of the function, r(t). It is worth mentioning that $r(t) = 3t$ in this research according to [56]. It is obvious that the cost of deprivation for some shipments could be computed as $\sum_t r(t)$, where this function is a particular form of a quadratic function $g(t) = 0.4t^2$ [51]. When the need of the ARs is sufficiently met, this value reaches zero and is recalculated until the next need is met and naturally increases linearly.

The constrains of this model are as follows:

Subject to

$$\sum_{i,v} x_{ij}^{vt} \geq \sum_{k,v'} x_{jk}^{v't} \qquad \forall j,t \tag{2}$$

Constraint (2) ensures that in each period, the amount of vaccines delivered from the distributor j to the kth AR should be at most equal to the amount of vaccines sent from the supplier i to distributor j.

$$\sum_{i,v} x_{ij}^{vt} + Inv_j^{t-1} = \sum_{k,v'} x_{jk}^{v't} + Inv_j^t \qquad \forall j,t \tag{3}$$

Eq. (3) instates the balance inventory in each period.

$$D_k^t - \left\{ \sum_{j,v'} x_{jk}^{v't} + \sum_{i,v} x_{ik}^{vt} \right\} = R_k^t \qquad \forall t,k \tag{4}$$

Eq. (4) calculates the amount of shortage belonging to the kth AR in each period.

$$\sum_{i,v} x_{ij}^{vt} + Inv_j^{t-1} \leq S_j \qquad \forall j,t \tag{5}$$

Constraint (5) shows the storage capacity of each distributor in each period.

$$\sum_{i,j} x_{ij}^{vt} \leq M y_v^t \qquad \forall v,t \tag{6}$$

$$\sum_{i,k} x_{ik}^{vt} \leq M {y'}_v^t \qquad \forall v,t \tag{7}$$

$$\sum_{j,k} x_{jk}^{v't} \leq M {y''}_{v'}^t \qquad \forall v',t \tag{8}$$

Eqs. (6)–(8) guarantee that if a truck is used to transport vaccines to a given destination, some amounts of products may be carried to that destination; otherwise, no vaccine will be delivered.

$$\sum_{i,j,v} x_{ij}^{vt} + \sum_{i,k,v} x_{ik}^{vt} \leq PC_i \qquad \forall t \tag{9}$$

Constraint (9) ensures that the amount of vaccines, which transported to distributors or directly to ARs, does not violate the production capacity of supplier i.

$$\sum_{i,v} x_{ik}^{vt} + \sum_{j,v'} x_{jk}^{v't} \leq M z_k^t \qquad \forall k.t \tag{10}$$

The minimal rate of demand should be met, so Eq. (10) represents the relative justice of delivering vaccines to particular ARs.

$$D_k^t + R_k^{t-1} = \left\{ \sum_{j,v'} x_{jk}^{v't} + \sum_{i,v} x_{ik}^{vt} \right\} + R_k^t \qquad \forall t,k \tag{11}$$

Because the whole amount of vaccines requested by all ARs may not be supplied in any of the periods, the unmet demand is backlogged. Eq. (11) establishes a balance in vaccine inventory levels taking such backlog into account, so that the demand in each period plus the backordered amount from the previous period should be equal to the total amount of sent vaccines to ARs plus those quantities which will be backordered in that period.

$$\left\{ \sum_{j,v'} x_{jk}^{v'T} + \sum_{i,v} x_{ik}^{vT} \right\} = D_k^T + R_k^T \qquad \forall k \tag{12}$$

Eq. (12) ensures that in the last period all backordered amount of vaccines must be satisfied.

$$\alpha . \left[\sum_{i,j,t} x_{ij}^{vt} + \sum_{i,k,t} x_{ik}^{vt} \right] \leq \sum_{i,t} Num_i^{vt}.Cap_v \qquad \forall v \tag{13}$$

$$\alpha . \left[\sum_{j,k,t} x_{jk}^{v't} \right] \leq \sum_{j,t} Num_j^{v't}.Cap_{v'} \qquad \forall v' \tag{14}$$

Constraint (13) determines how much vaccines are delivered altogether from a supplier to a distributor and/or AR in each period by what type of refrigerated trucks. Similarly, constraint (14) specifies how much vaccines are directly delivered from a distributor to a AR in each period by what type of refrigerated trucks.

$$\left| \frac{\left(\sum_{i,v} x_{ik}^{vt} + \sum_{j,v'} x_{jk}^{v't}\right)}{D_k^t} - \frac{\left(\sum_{i,v} x_{ik'}^{vt} + \sum_{j,v'} x_{jk'}^{v't}\right)}{D_{k'}^t} \right| \leq \lambda \qquad \forall k,k',t \tag{15}$$

The equity concept is applied through constraint (15) as horizontal equity, which could be extended to humanitarian issues, ensuring that a certain amount of vaccine is delivered to each AR in COVID-19 outbreak [56]. As already pointed out, equity constraints set ensure equitable distribution. By applying the equity constraint, one can make sure that the difference in satisfying different AR's demands should be less or equal than a predetermined threshold, λ [56].

$$x_{ij}^{vt}, x_{jk}^{v't}, x_{ik}^{vt}, R_k^t, Inv_j^t, Num_i^{vt}, Num_j^{v't} \epsilon \mathbb{N} \qquad \forall i,j,k,v,v',t \tag{16}$$
$$y_v^t, {y'}_v^t, z_k^t \epsilon \{0,1\}$$

Table 2
The needed parameter values of case study.

Parameter	Value
α	6 cubic foot
PC_i	Uniform (50000,60000)
S_j	Uniform (5000,6000)
C_v	Uniform (100,110)
$C_{v'}$	Uniform (50,60)
H_j	Uniform (0.7,1.3)
P_k	Uniform (30,35)
CAP_v	Uniform (350,360)
$CAP_{v'}$	Uniform (320,350)

4. Experimental results and sensitivity analysis

All sample problems are coded in GAMS 24.1.2 and solved by the OLOG CPLEX on a PC with a 2.6 GHz Intel® Core ™ i7-4720HQ CPU processor and 8 GB RAM memory.

4.1. Data and case study

Since we are focusing on the COVID-19 case, we have considered the actual data on vaccine distribution in Europe. Data includes the cost parameters of transportation between target points and the production amount of vaccine factories. Accordingly, this model can adapt to different data and scales applicable in critical situations, such as pandemics and/or epidemics for sending essential items or conditions such as floods and earthquakes. It also can be used in different geographical locations.

As mentioned, the used data in this research encompass parts of Europe, where some pharmaceutical factories are currently producing vaccine, such as Pfizer, Moderna, AstraZeneca, and J&J, respectively are made in Germany, Switzerland, the United Kingdom, and Netherlands. The number of ARs in the Europe considered in this research are 10. The production capacity of the producers/factories (based on their capacity and the needs of ARs) can be seen in Table 3. The capacity of the distributors, working as a hub and are located near the pharmaceutical companies, are shown in Table 2, as well. These distributors gather vaccines from all pharmaceutical companies, and then forward it to the ARs. The rest of other parameters are shown in Table 2.

The refrigerated trucks considered in this research have 40 ft ^{3}-refrigerated containers. Each period includes fifteen days, because of the critical and sensitive situation, and the total time is 6 periods, which equals 90 days. The population of the target countries is shown in Table 4, which is measured according to the number of used vaccine doses.

Table 3
The positions of suppliers and distributors.

Pharmaceutical companies	Suppliers	Distributors
AstraZeneca	United kingdom	United kingdom
Pfizer	Germany	Germany
Johnson and Johnson	Netherland	Netherland
Moderna	Switzerland	Switzerland

Table 4
The positions of ARs and vaccine demands.

ARs	Population (million)	Demand (million doses)	Demand (boxes)
United kingdom	66.65	133.3	27344
Germany	83.02	166.04	34060
Netherland	17.28	34.56	7090
Switzerland	8.545	17.09	3506
Sweden	10.23	20.46	4197
Italy	60.36	120.72	24764
Spain	46.94	93.88	19258
Greece	10.72	21.44	4398
Poland	17.28	34.56	7090
Austria	8.859	17.718	3635

Though, it is assumed that all vaccines are double-dose, the Johnson and Johnson vaccine is a single dose. It should be pointed out that vaccines are preserved in the special boxes holding up to 4875 doses of vaccine, where the weight of shipping box is 80 pounds ([67], n.d.). The positions of the suppliers and distributors as well as ARs are listed in Tables 3 and 4, respectively.

One of the most critical parts of the cost is shipping cost, which is shown in the proposed model as follows:

$$\sum_{i.j.v.t} C_{ij}^{v} x_{ij}^{vt} + \sum_{j.k.v'.t} C_{jk}^{v'} x_{jk}^{v't} + \sum_{i.k.v'.t} C_{ik}^{v} x_{ik}^{vt} \quad (17)$$

The cost of transporting vaccine from the origin (i.e., suppliers) to the distributors or the ARs and also from the distributors to the ARs is calculated based on the distance between two points multiplied by the cold transportation cost per unit distance multiplied by the cost of transporting each vaccine box. This calculation is computed based on the weight of shipping boxes multiplied by cold transportation cost per unit weight. So, we have Eqs. (18) and (19), as follows

$$\mathbf{C = distance\ per\ km \times cold\ transportation\ cost\ per\ km} \\ \mathbf{\times\, cold\ transportation\ cost\ per\ box} \quad (18)$$

$$\mathbf{Transportation\ cost\ per\ box} \\ \mathbf{= shipping\ box\ weight \times cold\ transportation\ cost\ per\ pond} \quad (19)$$

4.2. Illustrative study

The implementation results of the model in the basic state are presented in this section, and the information provided in the previous section is described. Then, different scenarios are analyzed by changing the values of the period, production capacity, and demand.

The study scope of this research focuses on the part of Europe in such a way that while covering a significant population of this continent, it covers vast and decentralized areas. In this way, by examining a large population in an extensive range, it will have the ability to be implemented in models with different sizes and populations.

As the COVID-19 disease is a pandemic, it would be very useful to study continental Europe as a case study with several countries with different populations. Also, the presence of different vaccine production factories in this area creates the conditions for a comprehensive study from the supplier to the consumer. Some regions of the world are deprived of vaccine production factories, or at least a small number of producers are in those regions. On the other hand, there may be fewer countries with a smaller population in a geographical region, while there are none of these negative points in the European region.

Table 5
The primary results.

Total cost	2,221,811,425 €
Deprivation cost	109,668 €
Penalty cost of unmet demand	3,240,893 €
Inventory holding cost	0 €

This study uses real data in such a way that the population of the countries as those in need of the COVID-19 vaccine and the target population, or the distance between the centers of the countries as the distance between the suppliers, distributors, and consumers is specified.

Fig. 2 depicts an information gathering mode of the model implementation for the sixth period ($T = 6$), in which four types of approved vaccines are sent from four sources to the target points. In fact, vaccines, directly or indirectly (through an intermediary point) reach 10 ARs through four distribution centers. Each supplier produces only one type of vaccine and it is assembled at distributors and shipped to ARs. There are two types of refrigerated trucks for carrying vaccines, i.e., transportation mode is considered. The suppliers possess 8 available type "v" refrigerated trucks, while 20 number of this type are available for distributors. In addition, these refrigerated trucks use 40-foot refrigerated containers to carry the vaccine. Based on the optimum output presented in Table 5, the model has used all refrigerated trucks to send vaccines directly and/or indirectly.

As one can observe, the cost of deprivation is only 0.005% of the total cost. Although this amount is negligible compared to the total cost of distribution of 659,768 million doses of vaccine, it has a remarkable effect on the fair distribution of the vaccine. In fact, supply chain managers, such as local governments or global organizations (e.g. WHO), should pay special attention to this concept; since by spending a relatively small cost, a considerable part of one of the main goals, i.e., fair distribution, is achieved.

4.3. Comparative results

In this subsection, different scenarios are examined, and analyzed by changing the values of the parameters. This comparison helps us to anticipate different situations in a pandemic and get ready for action.

Table 6 reports the exact results of the various components of the objective function that have changed in each scenario. According to these results, the total cost in the first scenario has decreased by increasing the time; however, in contrast, the shortage and deprivation costs have increased significantly. It is clear that this increase has occurred, due to the increase in demand response time. Thus, increasing the response period to the demand increases the cost of deprivation, which encourages the model to respond quickly to these needs.

On the other hand, with the reduction in the number of periods in the second scenario, one can observe an increase in the total cost due to the shorter time horizon of the program from 6 periods to 3 periods (total supply in 45 days). Furthermore, in this case, the costs of deprivation and shortage have dramatically decreased. Naturally, as the time between ordering the vaccines and accessing to them decreases, the cost of deprivation also decreases. These results are shown in Figs. 3 and 4.

In the third scenario, with a 10% increase in production capacity, a slight change is occurred in the costs, which indicates an insignificant decrease in the amount of total cost and increase in the deprivation cost Table 6. On the other hand, with the rise in vaccine demand by 50% in the fourth scenario, shown in Table 6, one can perceive a significant increase in the total costs and others. Though such cost increase sounds to be natural, but given the current demand in Europe, which has more than doubled its real demand for vaccines (Safe COVID-19 Vaccines for Europeans | European Commission, n.d.), it is expected that this amount of demand in the current pandemic situation will not only disrupt the vaccine supply chain but also incurs the high costs to the

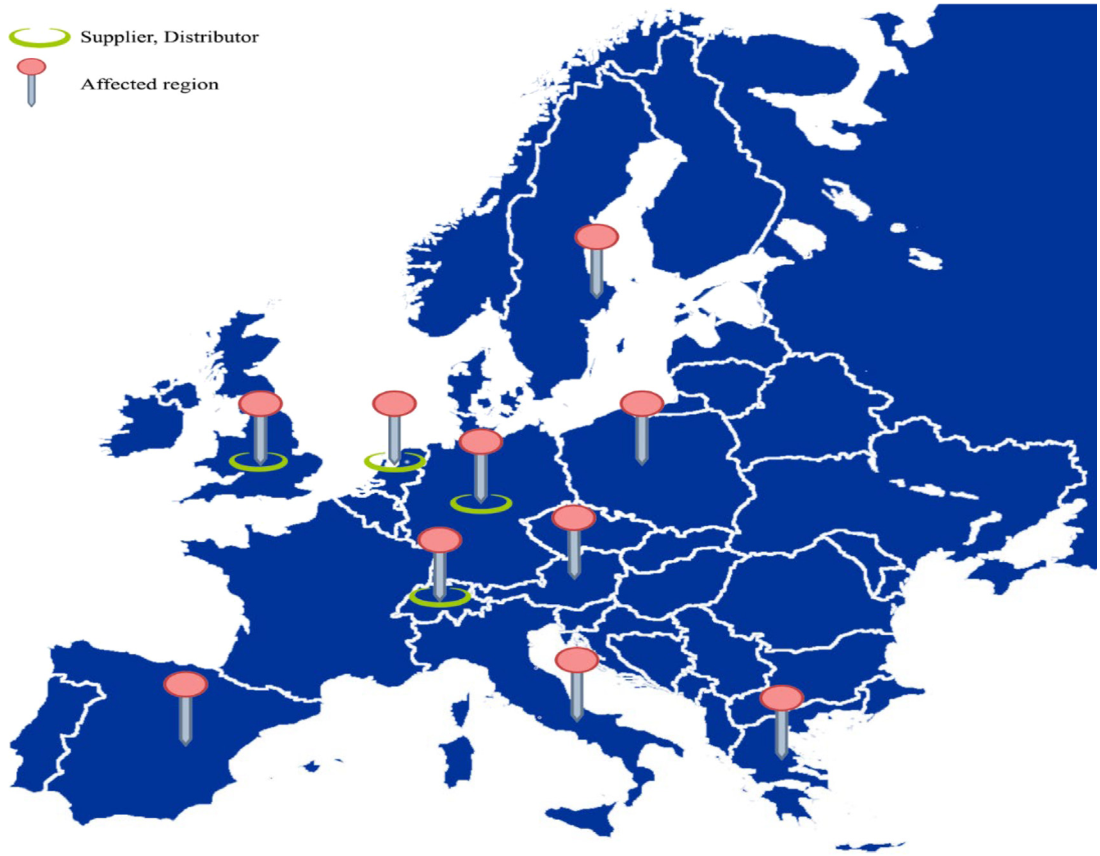

Fig. 2. The location of suppliers, distributors and ARs.

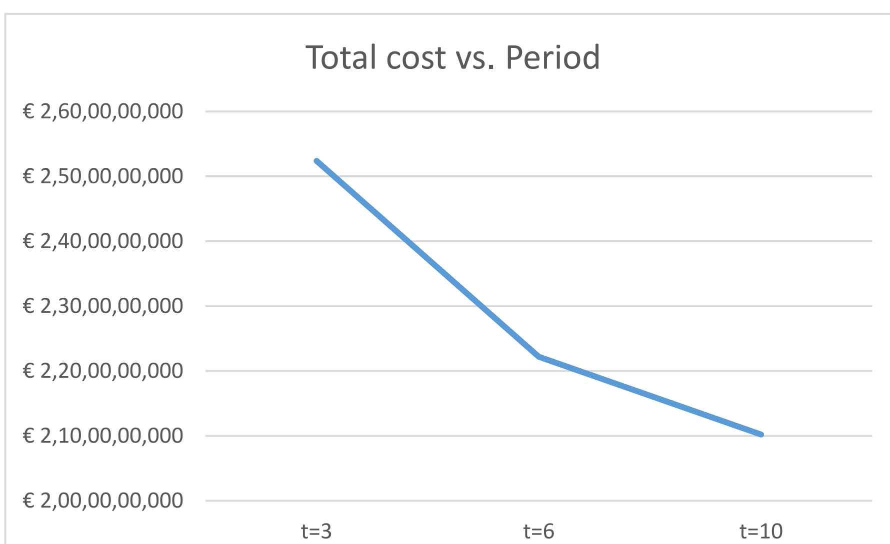

Fig. 3. Fluctuations of total cost by changing the problem size and period.

Table 6
The results of different scenarios.

Scenarios	Different parameters	Total cost	Deprivation cost	Penalty cost of unmet demand
Scenario #1	t = 10	€ 2,102,025,288	€ 538,493	€ 3,017,629
Scenario #2	t = 3	€ 2,523,858,043	€ 13,801	€ 2,629,273
Scenario #3	PC = (55000,65000)	€ 2,221,811,407	€ 109,675	€ 3,240,881
Scenario #4	D*1.5	€ 4,016,280,673	€ 173,290	€ 3,620,366

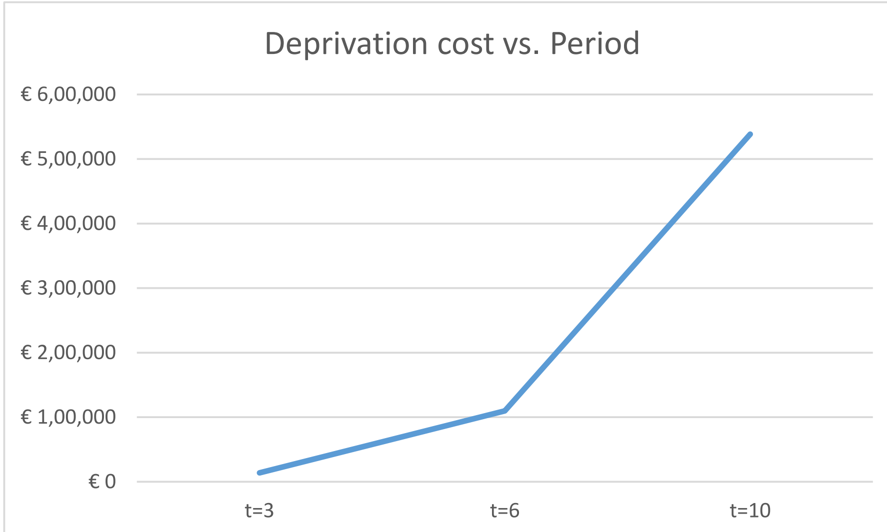

Fig. 4. Fluctuations of deprivation cost by changing the problem size and period.

Table 7
The result of changing by the value of λ.

l	Total cost	Deprivation cost
0.1	€ 2,267,924,137	€ 83,796
0.3	€ 2,221,811,425	€ 109,668
0.7	€ 2,154,778,408	€ 111,219

Table 8
The result of with/without the equity constraint.

Total cost	Deprivation cost
€ 2,221,811,425	€ 109,668
€ 2,109,483,829	€ 28,731

governments. As mentioned earlier, one of the goals of this research is to reduce the total cost of the considered supply chain, due to the lack of governmental budget, specifically after several months of dealing with COVID-19 disease, since according to the existing world condition, no one knows how long does it take.

4.4. Sensitivity analysis

A sensitivity analysis on the total cost as well as the deprivation cost is carried out in this part to offer a better understanding about the acquired results, which could be seen in Table 7 by changing the value of λ.

As can be seen in Fig. 5, by applying strict conditions to the model, which means that pay more attention to the equity constraint by decreasing the value of λ, the total cost amount increases by 2.07%, and the deprivation cost decreases by 23.59%.

Since more attention has been paid to the equity issue in vaccine distribution in the proposed supply chain, the speed of satisfying the ARs' need increases, and therefore the deprivation cost decreases. To reach such a purpose, the cost of other sectors of the model increase. As a result, the total cost increases. As, one can observe in Fig. 6, when the equity is neglected, which equivalently means that λ increases, the model pays less attention to the equity and the total cost decreases by 3.01%, however, the deprivation cost increases by 1.41% (because less attention is paid to equitable distribution). This totally increases the cost of deprivation in the supply chain.

In this paper, we use equity as a constraint that definitely has effect on total cost and deprivation cost. To show the effect of this constraint on the whole model, the model without the constraint of equity is examined and analyzed. In this case, the model is run with primary data and without any restrictions on equity. As can be seen in Table 8, the total cost as well as the deprivation cost have been reduced. Though, minimizing the total cost, including vaccine distribution is one of the main goals, fair vaccine coverage in pandemic conditions is a lofty goal to reduce the rate of infection and mortality, and prevent additional costs in the future. Fig. 7 demonstrates that ignoring such important constraint reduces total cost by only 5.05%, which is not significant compared to the huge amount of upcoming imposed expenditures to the system; accordingly, the healthcare managers are strongly recommended to apply this limitation.

On the other hand, Fig. 8 shows a 73.8% reduction in the deprivation cost reflecting the considerable impact of equity constraint on this part of costs. It is obvious that the two concepts of equity and deprivation are interdependent, where the deprivation cost without the equity constraint will not have a remarkable impact on the vaccine supply chain.

According to information provided by OXFAM Foundation, vaccine doses delivered to the United States, European Union, and the United Kingdom in the six weeks ending December 24, 2021, were more than the total vaccine doses delivered to African countries since the beginning of 2021. The detailed statistics of this international organization show that between November 11 and December 21, 2021, the European Union, the United Kingdom, and the United States received 513 million vaccines. On the other hand, African countries received only 500 million doses of vaccines in the whole of 2021 ([68], n.d.). These terrible statistics show the wrong behavior of health care systems, lack of attention to humanitarian logistics, and equity distribution of vaccines.

4.5. Managerial insights

The used data and obtained results and conducted analyses demonstrate some significant and practical managerial insights. Providing an appropriate and high-quality decision support tool for government and health managers would be very useful which is carried out in this part. Thus, they can deal with potential barriers and make the best possible decisions/reactions in such circumstances and crises.

Since human life is more important than other cost terms in the vaccine distribution chain and generally in humanitarian supply chains. Therefore, an appropriate plan is the one in which social costs, including deprivation cost and mortality rate, are reduced to the possible extent, while the other cost terms, may be increased, such as logistics

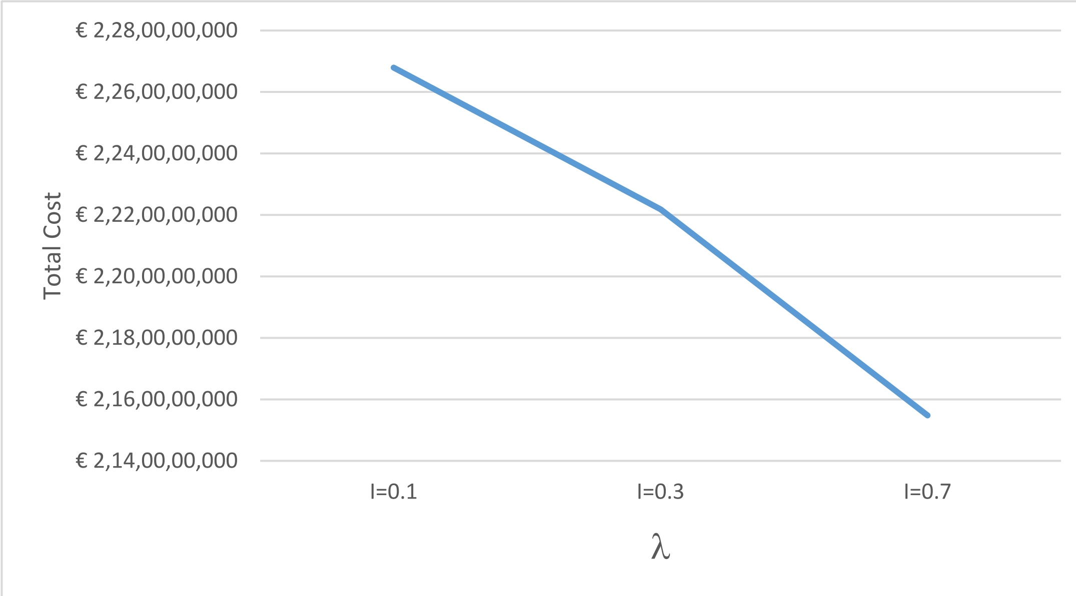

Fig. 5. Changing the total cost by changing the value of λ.

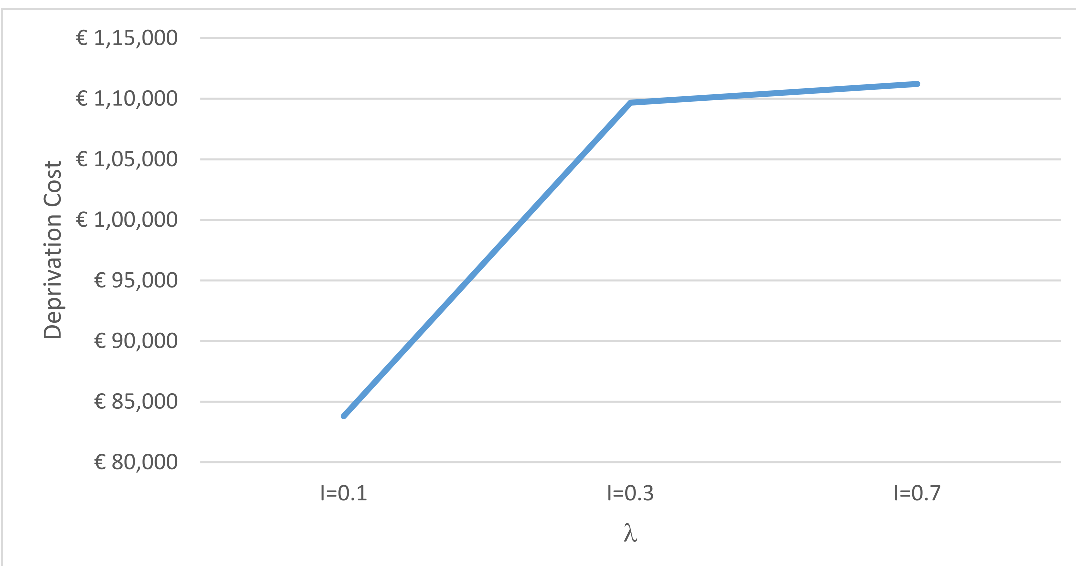

Fig. 6. Changing the deprivation cost by changing the value of λ.

costs, due to frequent dispatching refrigerated trucks to supply the vaccine for the ARs.

In the fourth scenario, by 50% increase in demand, a significant increase is observed in total costs, however, the deprivation cost increased less. This signifies that the growth rate of deprivation costs is much lower than the growth rate of total costs in confronting with demand increase. Accordingly, as an important insight, managers need to focus on fast maximum coverage. According to the obtained results, as the equity constraint is neglected, so does the total cost, while the deprivation cost increases. On the other hand, as the monitoring over equal vaccine distribution reduces, the total cost decreases, while the deprivation cost increases. So, it could be crucial for governments and managers to take the COVID-19 conditions into account, legislate some rules to make sure about effectively equity implementation. In this regard, the proposed planning in this research could be very helpful for establishing equity in the vaccine distribution throughout the world under the COVAX program, through fairly distributing the vaccine among the countries with fairness and without considering the regional superiority, nationality, racism, etc.

5. Conclusions, limitations and future research

The heavy burden and costs of COVID-19 pandemic on health organizations and governments is indescribable. This crisis has caused the illness of hundreds of millions and the death of millions of people all around the globe, and the involvement of all social and cultural aspects of human life.

The cost of treating, purchasing, and distributing vaccines is costly for governments and requires precise planning in government budgets. Therefore, with careful planning, fair distribution of vaccines must be accelerated, because with fast vaccination, the COVID-19 crisis will be eradicated. On the other hand, the high efficacy of the vaccine in preventing an increase in mortality rate among infected people requires us to cover the target population as quickly as possible.

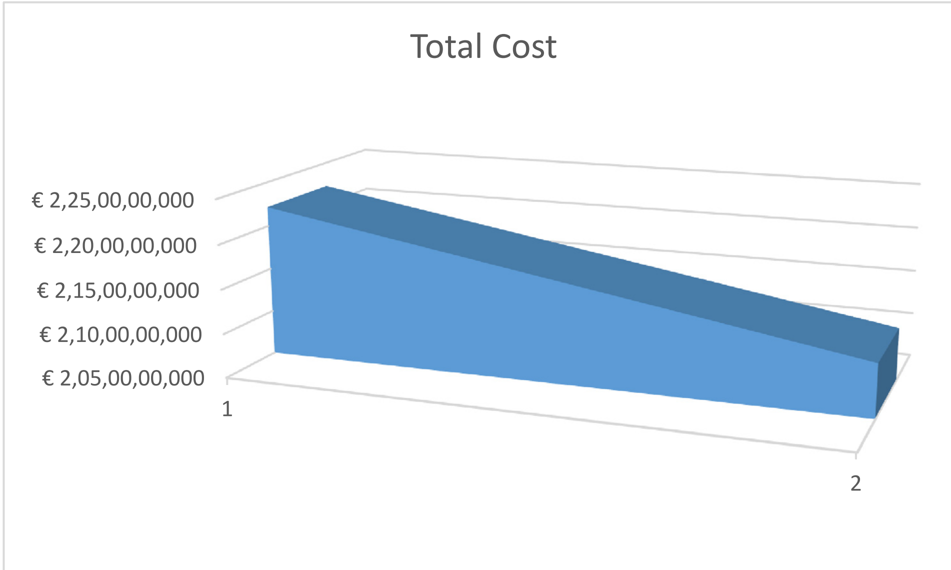

Fig. 7. Different values of total cost with/without the equity constraint.

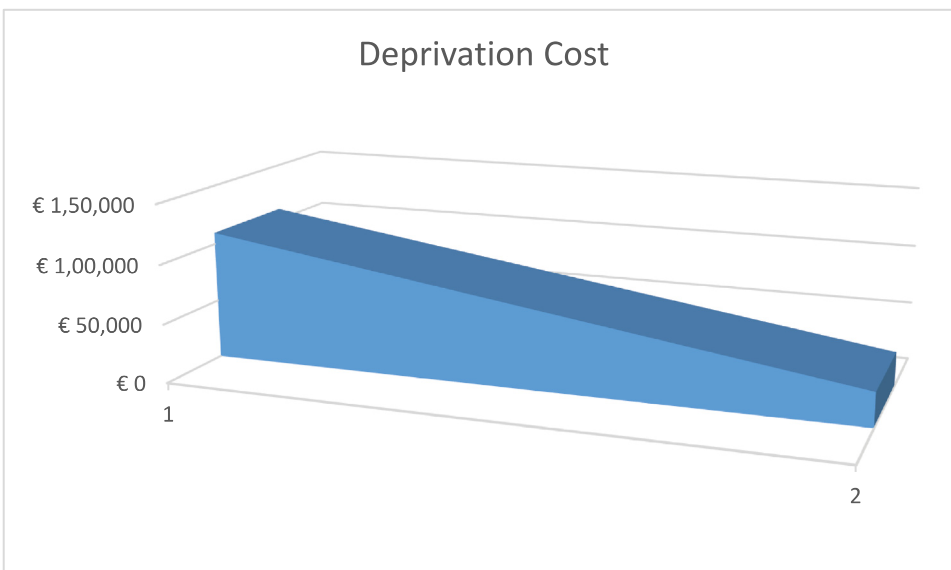

Fig. 8. Different values of deprivation cost with/without the equity constraint.

Thus, one of the most critical challenges is the rapid distribution of vaccines or health items to the affected areas (ARs), including Personal Protective Equipment (PPE) such as scrubs, hand sanitizer, alcohol, mask, etc. On the other hand, equity limitation has been used to ensure fair distribution among the ARs. The PPE items and taking the equity concept into account simultaneously is of paramount importance and may prevent the spread of the disease in any way. Due to human problems in the absence of vaccines or health items, the concept of deprivation cost has been considered a module for measuring the social cost of human suffering.

In this study, a cold supply chain model for vaccine distribution in the COVID-19 pandemic is proposed to optimize different aspects of the whole system. These aspects include minimizing total costs, including distribution, inventory, and deprivation costs. However, by doing so, the infection and therefore, mortality rates will be reduced. To enhance delivery speed and accuracy, third-party logistics providers (3PLs) handle the distribution process. Furthermore, one of the most relevant social cost variables in a humanitarian cold supply chain in the COVID-19 outbreak, i.e., equity, is examined for the first time. In case of not paying attention to equity, the cost of the entire supply chain will be reduced by 5.05%. This cost reduction is not significant compared to the costs of compensating for the lack of attention to the equity that will plague the system in the future. On the other hand, the deprivation cost becomes meaningless due to the connection between the cost of deprivation and justice. In this planning, two types of refrigerated trucks in different parts of the supply chain are considered, which will make supply chain management more controllable and faster.

The obtained results include three significant outcomes/insights: (i) The ratio of the cost of deprivation to the total cost is small, so it is worthwhile to pay attention to this issue, because it avoids additional costs in the future significantly, such as the cost of handling a large amount of infected people and their treatment, (ii) Increasing or decreasing the time horizon has the greatest impact on the deprivation cost. As the time horizon increases, one may have more time to satisfy the ARs' demand, however, time is one of the most important factors influencing the reduction of the infection rate of the COVID-19 disease and prevention of human death. Thus, with an increasing time horizon, the social costs of the system, comprising deprivation cost, are almost five times. On the other hand, by reducing the time horizon, transportation costs will increase, because the needs must be met in a shorter period of time with more refrigerated trucks, but social costs will be drastically reduced due to the reduction of the destructive social effects on the ARs, and reduction in infection and death rates. (iii) An increase fifty percent in demand increases the total cost amount 80 percent, but the rate of increase in the deprivation cost is less than such a growth in the total cost, so it is wisely and beneficial from both social and economic perspectives to pay more attention to the social term of the objective function, i.e., equity. By doing so, the upcoming expenditures imposed to the whole system will be reduced to a large extent.

Changing the amount of λ in the equity constraint affects the total cost and the cost of deprivation and can help managers in decision-making. In a way, determining the level of equity (or equivalently determining the amount of λ) will affect the total cost of the supply chain and the effectiveness of the vaccination program. The equity constraint, which plays a key role in the fair distribution of vaccines, directly impacts on costs. In this way, by paying more attention to the equity constraint, the total cost amount increases by 2.07%, and the deprivation cost decreases by 23.59%. On the contrary, when the model pays less attention to the equity, the total cost decreases by 3.01%, however, the deprivation cost increases by 1.41%. In the COVID-19 pandemic, vaccination is the only permanent way to prevent the widespread outbreak and death of thousands of people. Thus, establishing equity in the distribution among the ARs gets us closer to this goal. Also, the additional costs imposed on the whole supply chain are negligible compared to the costs of treatment of infected people and human suffering from disease and death. This consequence demonstrates the importance of taking equity into account.

One of the limitations existing in this research was access to real information from suppliers and distributors, which would make the results closer to reality. Some information such as the spoilage and/or deterioration rate of vaccines is not currently so high, probably because the high demand rate throughout the world, which makes the governments to particularly attention to the vaccine distribution and provide accessibility for all eligible individuals. However, with the normalization of world conditions and controlling the COVID-19 outbreak, the deterioration rate of vaccines is expected to increase and could be considered as one of the essential cost terms in such supply chains. In the proposed model in this research, all used parameters were considered definitive, however, with the goal of approaching to real-world situation, one may consider them as uncertain parameters as a future research, such as demand, deterioration rate. In fact, stochastic approaches could be used for handling such an uncertain problem. Future studies should therefore follow the lead of scholars like [69] and consider any potential uncertainty in parameters. In addition, taking some objectives simultaneously into account could be another future stream, through employing Pareto-optimal fronts. Moreover, simulation tools could be applied for more effective analysis over the results, such as finding chain bottlenecks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H.A. Rothan, S.N. Byrareddy, The epidemiology and pathogenesis of coronavirus disease (COVID-19) outbreak, J. Autoimmun. (2020) 102433.

[2] WHO/Europe | Coronavirus disease (COVID-19) outbreak, https://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-19.

[3] J. Holguín-Veras, N. Pérez, M. Jaller, L.N. Van Wassenhove, F. Aros-Vera, On the appropriate objective function for post-disaster humanitarian logistics models, J. Oper. Manage. 31 (5) (2013) 262–280.

[4] COVID-19 vaccines, Retrieved February 5, 2021, from https://www.who.int/emergencies/diseases/novel-coronavirus-2019/covid-19-vaccines.

[5] What You Need to Know about Variants | CDC, Retrieved August 23, 2021, from https://www.cdc.gov/coronavirus/2019-ncov/variants/variant.html.

[6] E. Mahase, COVID-19: How many variants are there, and what do we know about them? BMJ 374 (2021) n1971, http://dx.doi.org/10.1136/BMJ.N1971.

[7] A. Saif, S. Elhedhli, Cold supply chain design with environmental considerations: A simulation–optimization approach, European J. Oper. Res. 251 (1) (2016) 274–287.

[8] Coronavirus disease (COVID-19): Vaccines, https://www.who.int/news-room/q-a-detail/coronavirus-disease-(covid-19)-vaccines?adgroupsurvey=%7Badgroupsurvey%7D&gclid=CjwKCAiA5IL-BRAzEiwA0lcWYiqQNibsR4uWHIHUMCjwDHv6yI7peYfr67Fnu9dTtOTAe3Nor0yf5RoCyNAQAvD_BwE.

[9] Pfizer and BioNTech Conclude Phase 3 Study of COVID-19 Vaccine Candidate, Meeting All Primary Efficacy Endpoints | Pfizer, https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-conclude-phase-3-study-covid-19-vaccine.

[10] COVID-19 Vaccine U.S. Distribution Fact Sheet | Pfizer, https://www.pfizer.com/news/hot-topics/covid_19_vaccine_u_s_distribution_fact_sheet.

[11] About the Oxford COVID-19 vaccine | Research | University of Oxford, https://www.research.ox.ac.uk/Article/2020-07-19-the-oxford-covid-19-vaccine.

[12] Oxford University breakthrough on global COVID-19 vaccine | Research | University of Oxford, https://www.research.ox.ac.uk/Article/2020-11-23-oxford-university-breakthrough-on-global-covid-19-vaccine.

[13] Statement of the COVID-19 subcommittee of the WHO Global Advisory Committee on Vaccine Safety (GACVS) on safety signals related to the Johnson & Johnson/Janssen COVID-19 vaccine, Retrieved July 3, 2021, from https://www.who.int/news/item/19-05-2021-statement-gacvs-safety-johnson-johnson-janssen-covid-19-vaccine.

[14] WHO lists Moderna vaccine for emergency use, Retrieved July 3, 2021, from https://www.who.int/news/item/30-04-2021-who-lists-moderna-vaccine-for-emergency-use.

[15] Sinopharm COVID-19 Vaccine (BBIBP-CorV) — Precision Vaccinations, Retrieved August 27, 2022, from https://www.precisionvaccinations.com/vaccines/sinopharm-covid-19-vaccine-bbibp-corv.

[16] COVID-19 Vaccine Characteristics | ViewHub, Retrieved August 27, 2022, from https://view-hub.org/covid-19/characteristics/.

[17] Y. Yang, H. Bidkhori, J. Rajgopal, Optimizing vaccine distribution networks in low and middle-income countries, Omega 99 (2021) 102197, http://dx.doi.org/10.1016/j.omega.2020.102197.

[18] A.U. Khan, Y. Ali, Enhancement of resilience and quality of cold supply chain under the disruptions caused by COVID-19: A case of a developing country, Aust. J. Manag. (2022) 03128962221095596.

[19] J. Bland, C.J. Clements, Protecting the world's children: The story of WHO's immunization programme, World Health Forum 19 (2) (1998) 162–173, 1998.

[20] V. Cantillo, I. Serrano, L.F. Macea, J. Holguín-Veras, Discrete choice approach for assessing deprivation cost in humanitarian relief operations, Socio-Econ. Plan. Sci. 63 (2018) 33–46.

[21] M. Klumpp, S. De Leeuw, A. Regattieri, R. De Souza, Humanitarian Logistics and Sustainability, Springer, 2015.

[22] M. Huang, K. Smilowitz, B. Balcik, Models for relief routing: Equity, efficiency and efficacy, Transp. Res. E 48 (1) (2012) 2–18.

[23] D. Ibrahim, Z. Kis, K. Tak, M.M. Papathanasiou, C. Kontoravdi, B. Chachuat, N. Shah, Model-based planning and delivery of mass vaccination campaigns against infectious disease: Application to the COVID-19 pandemic in the UK, Vaccines 9 (12) (2021) 1460.

[24] Q. Lin, Q. Zhao, B. Lev, Cold chain transportation decision in the vaccine supply chain, European J. Oper. Res. 283 (1) (2020) 182–195.

[25] L.E. Duijzer, W. van Jaarsveld, R. Dekker, Literature review: The vaccine supply chain, European J. Oper. Res. 268 (1) (2018) 174–192.

[26] K. Govindan, H. Mina, B. Alavi, A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19), Transp. Res. E 138 (2020) 101967.

[27] C. Turan, Y. Ozturkoglu, Investigating the performance of the sustainable cold supply chain in the pharmaceutical industry, Int. J. Pharmaceutical Healthcare Mark. (2022) ahead-of-print. Vaccines and immunization. (n.d.). https://www.who.int/health-topics/vaccines-and-immunization#tab=tab_1.

[28] S. Hovav, D. Tsadikovich, A network flow model for inventory management and distribution of influenza vaccines through a healthcare supply chain, Oper. Res. Health Care 5 (2015) 49–62.

[29] İ.E. Büyüktahtakın, E. des Bordes, E.Y. Kıbış, A new epidemics–logistics model: Insights into controlling the Ebola virus disease in West Africa, European J. Oper. Res. 265 (3) (2018) 1046–1063.

[30] X. Ma, Y. Zhao, Q. Luo, Q. Bai, Preservation technology investment and carbon abatement strategies in a supplier-retailer cold chain based on a differential game, Comput. Ind. Eng. 172 (2022) 108540, http://dx.doi.org/10.1016/j.cie.2022.108540.

[31] F. Goodarzian, A. Navaei, B. Ehsani, P. Ghasemi, J. Muñuzuri, Designing an integrated responsive-green-cold vaccine supply chain network using Internet-of-Things: Artificial intelligence-based solutions, Ann. Oper. Res. (2022) 1–45.
[32] M.M. Vali-Siar, E. Roghanian, Sustainable, resilient and responsive mixed supply chain network design under hybrid uncertainty with considering COVID-19 pandemic disruption, Sustain. Prod. Consumpt. 30 (2022) 278–300, http://dx.doi.org/10.1016/j.spc.2021.12.003.
[33] H. Gilani, H. Sahebi, A data-driven robust optimization model by cutting hyperplanes on vaccine access uncertainty in COVID-19 vaccine supply chain, Omega 110 (2022) 102637, http://dx.doi.org/10.1016/j.omega.2022.102637.
[34] J. Qian, Q. Yu, L. Jiang, H. Yang, W. Wu, Food cold chain management improvement: A conjoint analysis on COVID-19 and food cold chain systems, Food Control 137 (2022) 108940, http://dx.doi.org/10.1016/j.foodcont.2022.108940.
[35] F. Zheng, Y. Pang, Y. Xu, M. Liu, Heuristic algorithms for truck scheduling of cross-docking operations in cold-chain logistics, Int. J. Prod. Res. (2020) 1–22.
[36] G.P. Georgiadis, M.C. Georgiadis, Optimal planning of the COVID-19 vaccine supply chain, Vaccine 39 (37) (2021) 5302–5312.
[37] M.A. Momeni, M. Bagheri, Shared warehouse as an inter-supply chain cooperation strategy to reduce the time-dependent deterioration costs, Socio-Econ. Plan. Sci. (2021) 101070.
[38] M.M. J, N. Mario, A review of the transportation mode choice and carrier selection literature, Int. J. Logist. Manag. 19 (2) (2008) 183–211, http://dx.doi.org/10.1108/09574090810895951.
[39] D.J. Murphy, M.T. Farris, Time-based strategy and carrier selection, J. Bus. Logist. 14 (2) (1993) 25.
[40] N. Batarliene, A. Jarašūnienė, 3PL service improvement opportunities in transport companies, Procedia Eng. 187 (2017) 67–76, http://dx.doi.org/10.1016/j.proeng.2017.04.351.
[41] V. Kayvanfar, S.M.M. Husseini, Z. NengSheng, B. Karimi, M.S. Sajadieh, A practical supply–demand hub in industrial clusters: A new perspective, Manag. Res. Rev. (2019).
[42] J. Heydari, A. Bakhshi, Contracts between an e-retailer and a third party logistics provider to expand home delivery capacity, Comput. Ind. Eng. 163 (2022) 107763, http://dx.doi.org/10.1016/j.cie.2021.107763.
[43] V. Kayvanfar, M.S. Sajadieh, S.M.M. Husseini, B. Karimi, Analysis of a multi-echelon supply chain problem using revised multi-choice goal programming approach, Kybernetes (2018).
[44] K.T. Joseph, K. Rice, C. Li, Integrating equity in a public health funding strategy, J. Public Health Manag. Pract.: JPHMP 22 (Suppl 1) (2016) S68.
[45] S. Enayati, O.Y. Özaltın, Optimal influenza vaccine distribution with equity, European J. Oper. Res. 283 (2) (2020) 714–725.
[46] D. Stone, Policy Paradox: The Art of Political Decision-Making, W.W. Norton & Company, New York, 2002.
[47] M. Tavana, K. Govindan, A.K. Nasr, M.S. Heidary, H. Mina, A mathematical programming approach for equitable COVID-19 vaccine distribution in developing countries, Ann. Oper. Res. (2021) 1–34.
[48] V.K. Manupati, T. Schoenherr, N. Subramanian, M. Ramkumar, B. Soni, S. Panigrahi, A multi-echelon dynamic cold chain for managing vaccine distribution, Transp. Res. E 156 (2021) 102542.
[49] Townsend P., Deprivation, J. Soc. Policy 16 (2) (1987) 125–146.
[50] J. Holguín-Veras, J. Amaya-Leal, V. Cantillo, L.N. Van Wassenhove, F. Aros-Vera, M. Jaller, Econometric estimation of deprivation cost functions: A contingent valuation experiment, J. Oper. Manage. 45 (2016) 44–56.
[51] W.J. Gutjahr, S. Fischer, Equity and deprivation costs in humanitarian logistics, European J. Oper. Res. 270 (1) (2018) 185–197, http://dx.doi.org/10.1016/j.ejor.2018.03.019.
[52] N. Cotes, V. Cantillo, Including deprivation costs in facility location models for humanitarian relief logistics, Socio-Economic Planning Sciences 65 (2019) 89–100.
[53] N.G. Larimi, S. Yaghoubi, A robust mathematical model for platelet supply chain considering social announcements and blood extraction technologies, Comput. Ind. Eng. 137 (2019) 106014.
[54] N. Al Theeb, H.J. Smadi, T.H. Al-Hawari, M.H. Aljarrah, Optimization of vehicle routing with inventory allocation problems in cold supply chain logistics, Comput. Ind. Eng. 142 (2020) 106341.
[55] Z. Sazvar, K. Tafakkori, N. Oladzad, S. Nayeri, A capacity planning approach for sustainable-resilient supply chain network design under uncertainty: A case study of vaccine supply chain, Comput. Ind. Eng. 159 (2021) 107406.
[56] B. Malmir, C.W. Zobel, An applied approach to multi-criteria humanitarian supply chain planning for pandemic response, J. Humanit. Logist. Supply Chain Manag. (2021).
[57] H. Sun, J. Li, T. Wang, Y. Xue, A novel scenario-based robust bi-objective optimization model for humanitarian logistics network under risk of disruptions, Transp. Res. E 157 (2022) 102578, http://dx.doi.org/10.1016/j.tre.2021.102578.
[58] I. Correia, S. Nickel, F. Saldanha-da Gama, Single-assignment hub location problems with multiple capacity levels, Transp. Res. B 44 (8–9) (2010) 1047–1066.
[59] J. Kratica, M. Milanović, Z. Stanimirović, D. Tošić, An evolutionary-based approach for solving a capacitated hub location problem, Appl. Soft Comput. 11 (2) (2011) 1858–1866.
[60] M. da Graça Costa, M.E. Captivo, J. Clímaco, Capacitated single allocation hub location problem—A bi-criteria approach, Comput. Oper. Res. 35 (11) (2008) 3671–3695.
[61] T.K. Dasaklis, N. Rachaniotis, C. Pappis, Emergency supply chain management for controlling a smallpox outbreak: The case for regional mass vaccination, Int. J. Syst. Sci.: Oper. Logist. 4 (1) (2017) 27–40.
[62] D. Ivanov, Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case, Transp. Res. E 136 (2020) 101922.
[63] D. Ivanov, Viable supply chain model: Integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic, Ann. Oper. Res. 1 (2020).
[64] R.S. de Camargo, G. Miranda, Single allocation hub location problem under congestion: Network owner and user perspectives, Expert Syst. Appl. 39 (3) (2012) 3385–3391.
[65] I. Contreras, J.A. Díaz, E. Fernández, Lagrangean relaxation for the capacitated hub location problem with single assignment, OR Spectrum 31 (3) (2009) 483–505.
[66] R.S. De Camargo, G. de Miranda Jr., R.P.M. Ferreira, A hybrid outer-approximation/benders decomposition algorithm for the single allocation hub location problem under congestion, Oper. Res. Lett. 39 (5) (2011) 329–337.
[67] COVID vaccine distribution: First Pfizer shipments to arrive Monday, Retrieved August 10, 2021, from https://www.usatoday.com/story/news/health/2020/12/12/covid-vaccine-distribution-first-pfizer-shipments-arrive-monday/6521379002/.
[68] Rich countries have received more vaccines in run-up to Christmas than African countries have all year | Oxfam International, Retrieved December 27, 2021, from https://www.oxfam.org/en/press-releases/rich-countries-have-received-more-vaccines-run-christmas-african-countries-have-all.
[69] V. Kayvanfar, S.M. Moattar Husseini, B. Karimi, M.S. Sajadieh, Supply–demand hub in industrial clusters: A stochastic approach, Eng. Optim. 50 (9) (2018) 1561–1577.