RESEARCH ARTICLE OPEN ACCESS

Solutions from Operations Research for the Covid-19 Vaccination Challenge

Vrinda Sharma*, Vidhit Mehta**, YajwinDaga***, Yash Dhairyawan****, Yashvardhan Jain*****

*(Student at NMIMS University, V.L. Mehta Road, Ville Parle, Mumbai
Email:vrindasharma8512@gmail.com)
**(Student at NMIMS University, V.L. Mehta Road, Ville Parle, Mumbai
Email: vidhitmehta14@gmail.com)
***(Student at NMIMS University, V.L. Mehta Road, Ville Parle, Mumbai
Email: dagayajwin@gmail.com)
****(Student at NMIMS University, V.L. Mehta Road, Ville Parle, Mumbai
Email: ysd0302@gmail.com)
*****(Student at NMIMS University, V.L. Mehta Road, Ville Parle, Mumbai
Email: yvj1308@gmail.com)

--************************----------------------------------

Abstract:

The economic and social disruption in the wake of the Covid-19 pandemic is unprecedented. Even as the world is slowly returning to pre-pandemic normalcy, the war against this malady will not be over until a large majority of the global population is vaccinated against it. This paper explores previous work on the applications of operations research in mass vaccination in general. However, not much of this literature is focused on epidemiology. This paper proposes solutions to ensure equitable distribution of the vaccine across the globe and optimize production to minimize vaccine wastage. Although the models are elementary and do not factor in the subjective complexities of the real world, they can be the basis for more detailed models with multiple inputs.

Keywords **—Mass Vaccination, Covid-19 Vaccination, Vaccine Allocation, Inventory Control, Affordability of Vaccines.**

--************************----------------------------------

I.INTRODUCTION

In 2020, the novel coronavirus took the world by storm. In one of the deadliest pandemics in human history, over 225 million people were infected with the virus and over 4.5 million people lost their lives to it. The world was fighting a lost war against the lethal virus until scientists and academicians across the world rose to the occasion. By the end of 2020, a few vaccines were in the pipeline while some others were already being administered. The war against the coronavirus is far from over, even as vaccination numbers soar to over 5.5 billion administered doses.(WHO Coronavirus (COVID-19), 2021.) Developed economies are swiftly vaccinating large masses of their population, while low-income countries are awaiting their turn to do the same. Of the 5.5 billion doses administered globally, only 15.02 million have been allocated to low-income countries. The distribution of the vaccine is highly inequitable and the economic implications of delays in vaccination are very grave.

The novelty of the problem lies in the fact that the vaccination process is extremely time-sensitive and is happening on an unprecedentedly large scale. Countries must vaccinate 60% of their populations by mid-2022, to not suffer economic losses of massive proportions. (Vaccine Inequality Could Cost the Global Economy Trillions: Report, 2021) While literature exists that aims to solve the problem of vaccine inequity, few papers employ operations research techniques to do the same. Most papers are suggestive of what governments and bodies like the World Health Organization should do to ensure equitable distribution of the vaccine. The suggestions are geared towards the socio-political and economic environment.

The previous work in the area of mass vaccination has been studied through a literature review along the four dimensions of production, affordability, allocation, and deployment of vaccines. (Wouters et al., 2021) This paper aims to provide a model for the effective allocation of the different vaccines available to countries, as per their demand and supply. It also proposes a model for inventory control to minimize vaccine wastage, consequently minimizing the cost of the vaccination drive. The allocation model is designed as a transportation problem, which is a special type of linear programming problem. The inventory control model too is a linear programming problem solved using the Simplex method. Linear programming has been used by other authors for solving vaccine allocation and affordability problems. (Rais&Vianaa, 2011) The paper largely uses actual values of the cost, supply, and demand of vaccines.

The model can be used by bodies like Covid-19 Vaccines Global Access Facility (COVAX), which is a collaboration between the Coalition for Epidemic Preparedness Innovations (CEPI), Gavi, World Health Organization, and United Nations Children's Fund (UNICEF) to procure, develop and ensure equitable distribution of vaccine doses to every country in the world (COVAX Facility, 2020). The inventory model is useful for suppliers of vaccines. It gives ideal production values, given the short shelf-life of the vaccines. The paper is written from the perspective of buyer countries and consumers of the vaccine. The models aim to minimize the cost of vaccines for governments and consequently the ultimate consumer of the vaccine.

II.LITERATURE REVIEW

The four major dimensions of the global vaccination challenge that Covid-19 poses are – production and development, affordability, allocation and, deployment. Production and development deal with producing regulatory body-approved vaccines at scale. Affordability relates to the pricing of vaccines in a way that low- and middle-income countries, that house nearly 85% of the world's population, can afford the vaccine. Allocation deals with creating sufficient global availability of the vaccine. Lastly, deployment deals with the infrastructure and awareness required to distribute the vaccines. (Wouters et al., 2021) Our literature review discusses previous research organized as per these four dimensions.

The first stage in the development of a vaccine revolves around deciding its contents. This is crucial for the process of production, especially when the concerned disease is relatively new. The Authors suggested a discrete-time decision model consisting of three probable decisions every time; to choose the present vaccine strain, to be up to date with the most common strain, or wait until the next period to make a decision. The side effects of the composition decision are included in the next step in the supply chain; the production of vaccines. Ozaltın et al. (2011) consider uncertain yields and allow you to choose between many strains for a vaccine and not just a common one. They used a stochastic mixed-integer model to incorporate the composition decision of the vaccine and the timing of that composition decision. (Duijzer et al., 2018) A mixed integer model is one where some of the variables are set to have integer values at the optimal solution. (Optimization Problem Types - Mixed-Integer and Constraint Programming | Solver)

The production process also involves deciding appropriate packages for the vaccine. Lee et al. (2010) proposed a general spreadsheet model to study the effects of different vial sizes on the costs in the supply chain related to storage, distribution, and wastage. The inference from the study was that the optimal container size is directly proportional to the demand of the patients. In a situation of high demand, bigger containers minimize wastage costs.

Dhamodharan and Proano (2012) also worked on the problem of determining the optimal container size.The Monte Carlo Simulation model is used to account for probabilistic demand and solve an integer programming problem to find optimal ordering policies and the best container size. (Duijzer et al., 2018) The Monte Carlo simulation is used to study the possible outcomes of an uncertain event. (What Is Monte Carlo Simulation? - India | IBM, 2020)

Once a vaccine is developed, a reasonable price must be set by the manufacturer so that it can be administered to the masses. Jacobson et al. (1999) developed integer programming models to determine the price of combination vaccines for childhood immunization. Combination vaccines take two or more individual vaccines and put them into one shot. (Weniger, 1999) Their models consider all available vaccines at their market prices and their objective is to find the prescribed vaccine combinations with the lowest overall cost. The models are based on the first five years of the recommended childhood immunization schedule against six diseases. (Zhang & Mason, 2011)

Jacobson and Sewell (2003) also proposed an integer-programming model to measure the economic premium of combination vaccines in a follow-up study. They used the Monte Carlo simulation and reverse engineering to find the probability distribution of four hypothetical combination vaccines – this would help manufacturers understand the market share they can attain for different price ranges of the vaccine. (Rais&Vianaa, 2011)

After arriving at a reasonable, affordable price for the vaccine, it is necessary to understand how the supply will be effectively allocated. Especially in pressing public health situations like epidemics, limited supply has to be matched with much larger demand. However, low prices serve as a disincentive for manufacturers to supply. A research paper by Chick, Mamani, and Simchi-Levi provides solutions to 2 major challenges in the influenza vaccination supply chain. Their thesis proposes contracts that align with manufacturers' choice of production volume and need for profitability and also balances the governmental choices relating to the costs and public health benefits of vaccination projects. It also proposes contracts which balance the cost and benefits of the vaccination program with different priorities of the government. The thesis is one of the first to link supply contract design with epidemic modeling to yield a system-wide cost-benefit analysis. (Chick et al., 2008)

Since vaccine allocation problems have constraints related to vaccine manufacturing and supply chain logistics, the use of Linear Programming Problem (LPP) was deemed suitable by Becker and Starczakth (1997) for calculating the optimal allocation of vaccines to prevent epidemics. Their LPP model considers variations among individuals and focuses on minimizing the basic reproduction number, which is the number of people an infected person further infects, for given vaccination coverage. Their strategy concluded that individuals in larger households need to be prioritized during an epidemic vaccination drive. (Zhang & Mason, 2011)

Four Coverage Models also apply linear programming including binary, single variable, and multiple variable models, and implement outreach to improve vaccination rates and also maximize the number of people to get vaccinated in low- and middle-income countries. (Lim et al., 2016)E.K. Lee et al. researched on RealOpt, a simulation and decision support system, which is a software used to optimize decisions, courses of action and helps in the allocation of medicines and remedies during disease outbreaks and emergencies. (Lee et al., 2006)

Authors have also contributed to problems related to vaccination strategy for bio-defense. For instance, Kaplan et al. (2003) analyzed bioterror response logistics using smallpox as an example. A model for tracing the vaccination process has been presented by the authors using Ordinary

Differential Equations (ODEs) which includes waiting time and scarcity of vaccines by the public. This helps in estimating the death count due to the mass vaccination and the length of queue lines required which is further used to find thresholds for controlling an outbreak. (Zhang & Mason, 2011)

After supply has been allocated, the last leg of the inoculation process is to physically distribute the vaccine to the ultimate consumer. Kay Aaby et al. used discrete event simulation models, production capacity planning, and queuing system models (for waiting lines) for Montgomery County's Public Health service for the distribution of vaccines. (Aaby et al., 2006) Discrete-event simulation recreates the performance of a real-life process or system. DES treats the system as a series of events and assumes no change in the system between events. (Allen et al., 2015)

Effective distribution of the vaccine has much to do with the layout of vaccination centers and the time required to carry out the entire vaccination process. Simulation has been used to model these processes and understand their shortcomings. Simulation methodology refers to the setting up of a model of a real system or environment - the outcome of which has a random probability and then performing experiments on that model to test it. Optimization technique focuses on maximization or minimization of a problem with respect to certain constraints. In a paper about the optimal design of Covid-19 vaccination centers, the authors used modeling and computer simulation to optimize the 4-step vaccination process. The model was subjected to staff and capacity constraints. However, the authors did identify the need for simulation software that will be able to model unforeseen shocks in the vaccination process. (Wood et al., 2020)

The simulation model by Gupta et al. lets both learned and inexperienced users input multiple variables like the number of vehicles which are assumed to arrive following Poisson distribution, multiplication factor which is like that of the flu drive-through clinic, etc. to help find the optimum length and number of lanes, workers required and average waiting time for vehicles coming to the drive-through to get vaccinated. This is achieved using Arena v13 software where the process from Arrival to Departure of a vehicle is divided into a flow chart. (Gupta et al., 2013)The research paper has a user-friendly model but does not consider the allocation and arrival of vaccines daily to the drive-through location, which could be insufficient and costly as per the requirements of the project. It also does not account for senior citizens visiting the drive-through and provisions for them.

In the review of past research on the use of operations research in mass vaccination and epidemic prevention, limited literature was available on the equitable allocation of vaccines to low- and middle-income countries at affordable prices. In order to support the low costs required to supply vaccines at affordable prices, vaccine manufacturers will need to minimize costs. A controllable cost that can be achieved through inventory optimization is vaccine wastage cost. Firstly, this paper aims to propose solutions for the equitable supply of vaccines to low- and middle-income countries at the lowest possible prices.Secondly, it aims to provide a solution for wastage minimization so that manufacturers can keep prices low without facing losses.

III. METHODOLOGY AND DATA

The methodology used in our paper consists of an Inventory Model and a Transformation Problem.

TABLE I- Data used in transportation problem

All supply, demand, and revenue figures are in billions.

	India	EU	South Africa	US	Supply
Pfizer	$ 19.46	$ 14.70	$ 6.75	$ 19.50	1.20
Moderna	$ 31.92	$ 18.00	$ 30.00	$ 15.00	1.00
AstraZeneca	$ 2.06	$ 2.15	$ 5.25	$ 4.00	1.10
Demand	2.20	1.84	0.02	1.10	

(COVID-19 Vaccine Contract Size by Region 2021 | Statista, 2021)

(COVID-19 Vaccine Prices Revealed: Pfizer, Moderna and AstraZeneca | Observer, 2020)

(Pfizer and BioNTech to Provide U.S. Government with an Additional 200 Million Doses of COVID-19 Vaccine to Help Meet Continued Need for Vaccine Supply in the U.S. | Pfizer, 2021)

(Scaling Up to Manufacture and Supply a COVID-19 Vaccine, If Approved | Pfizer, 2020)

(The Price Tags on the COVID-19 Vaccines, 2021)

(Vaccine Monopolies Make Cost of Vaccinating the World against COVID at Least 5 Times More Expensive than It Could Be | Oxfam International, 2021)

A. Transportation Problem

The minimization type transportation problem is used to create a model for the effective allocation
of vaccines. The matrix has the prices of different vaccines in different countries. The data has been extracted from several sources and is the tentative real price of the vaccines in these countries. The differential pricing could be due to different supply costs in different countries. Manufacturers also tend to supply vaccines at a higher price to more affluent countries.

Microsoft Excel's Solver Add-In has been used to solve the problem. To improve our analysis, two constraints have also been considered, which are as follows:

1. The Indian government has a contract with AstraZeneca to receive 0.7 billion (700 million) vaccines.
2. The USA government has a contract with Pfizer for 0.5 billion (500 million) vaccines.

These constraints have been considered to replicate a real-world situation wherein countries are entering contracts with vaccine manufacturers for the supply of vaccines.

All supply and demand values in the model are in billions.

The Transportation problem will be solved in MS Excel by firstly putting all the prices into a matrix. Another matrix of allocations will be made below it. The total of every column of the allocations matrix gives the allocated demand for the respective country, and the total of every row in the matrix isthe allocated supply for the respective manufacturer. The Total Revenue cell contains a formula that is the product of the allocation and the corresponding price. The objective has been set to a minimum. Next, the changing cells are all the cells in the allocations matrix. Their value is zero before the problem is solved. In the constraints, allocated demand has been taken as less than or equal to the actual demand, as the total demand is greater than the total supply in the problem. Allocated supply is taken as equal to the actual supply because all the supply must be allocated, and this method will be used to solve the problem is Simplex LP. The data used in the Transportation Problem is given in Table II below.

TABLE II: Data for Inventory Control Model

Category	$ Per Dose
Marketing	0.8891
Overheads	0.2842
R&D	0.0961
Storage	0.1224
Transport	0.0191
Production	1.20
Total	2.6107

(Griffiths et al., 2021)

B. Inventory Model

Prerequisites

1. Excel 2013 and above for enabling the Solver Add-in,
2. Projected demand of vaccines and opening/closing balance requirements,
3. Maximum production capacity of the plant(s),
4. Details related to costs of manufacturing, transportation, and delivery of vaccines.

Once these requirements are set, Microsoft Excel's Solver Add-In can be used to calculate the optimum production and cost.

The following procedure has been followed to use the model:

The solver add-in needs to be installed separately, which can be done from Excel's Add-In manager under options. One of the constraints in the Inventory Model is that supply should always be more than the demand the constraints have been set, launch Solver from the Data Tab.

Since the objective is to minimize cost, select the cell and select "Min" (minimum). Under the "by changing variable cells," select the row where the production values are to be displayed. This is because the cost will be minimized by optimizing the production amounts. Next to add the constraints, click on "Add" and add the constraints for minimum production, maximum production, minimum opening balance, and maximum closing balance. Make sure the option "Make Unconstrained Variables Non-Negative" is checked, and the solving method is set to Simplex LP. The last step is to click solve and the optimum production values along with the cost break-up will be calculated. The data used in the Inventory Control Model is given in Table II.

IV. ANALYSIS

A. Transportation Problem

The data used in the Transportation Problem is taken from Table I. Table III below is the problem statement and Table IV below is the solution to the same.

A minimization problem is ideal for this case since it is important to look at allocation from the perspective of the buyer, i.e., the countries. The buyers aim to maximize the quantity bought at the lowest possible cost. Thus, the optimum process would be to minimize the revenue of the three manufacturers in the problem, namely Pfizer, Moderna, and AstraZeneca.

TABLE III: Transportation Problem Table

All supply, demand, and revenue figures are in billions.

	INDIA	EU	SOUTH AFRICA	US	SUPPLY
PFIZER	$19.46	$14.70	$6.75	$19.50	1.20
MODERNA	$31.92	$18.00	$30.00	$15.00	1.00
ASTRAZENECA	$2.06	$2.15	$5.25	$4.00	1.10
DEMAND	2.20	1.84	0.02	1.10	

TABLE IV: Transportation Problem (Solution) Table

	INDIA	EU	SOUTH AFRICA	US	ALLOCATED SUPPLY
PFIZER		0.68	0.02	0.50	1.20
MODERNA		0.40		0.60	1.00
ASTRAZENECA	1.10				1.10
ALLOCATED DEMAND	1.10	1.08	0.017	1.10	

Total Revenue	$38.37	Billion

The transportation problem meets the objective of minimizing costs to countries even though, the allocated demand is not equal to actual demand for all countries because total demand exceeds total supply. The model succeeds in fairly distributing limited supply, which is a real-world situation thatwould have been biased towards countries that can pay more for the vaccines.

Only 50% of India's demands were met and 58.7% for E.U. Since this is a minimization problem, countries that are willing to pay higher prices for the vaccines are given the lowest priority.

In the cost matrix, one can see that India pays a higher price for both Pfizer and Moderna as opposed to the EU.

B. Inventory Control Model

The data used in this model is taken from Table II above. Table V gives the final production and inventory schedule; Table VI shows the constraints that have been used in the model and Table VII outlines the different costs used in the problem.

Table V: Production and Inventory Table

VARIABLES OF VACCINE DOSES	DAYS									
	1	2	3	4	5	6	7	8	9	10
OPENING BALANCE		50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
PRODUCTION	**6,34,653**	**4,00,770**	**4,05,302**	**5,67,872**	**4,50,218**	**5,52,897**	**4,70,865**	**5,47,363**	**4,65,456**	**5,54,720**
DEMAND	5,84,653	4,00,770	4,05,302	5,67,872	4,50,218	5,52,897	4,70,865	5,47,363	4,65,456	5,54,720
CLOSING BALANCE	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000

TABLE VI: Constraints Table

Constraints										
Minimum Production	2,00,000	2,00,000	2,00,000	2,00,000	2,00,000	2,00,000	2,00,000	2,00,000	2,00,000	2,00,000
Maximum Production	7,50,000	7,50,000	7,50,000	7,50,000	7,50,000	7,50,000	7,50,000	7,50,000	7,50,000	7,50,000
Minimum Closing Balance	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Maximum Closing Balance	3,00,000	3,00,000	3,00,000	3,00,000	3,00,000	3,00,000	3,00,000	3,00,000	3,00,000	3,00,000

TABLE VII: Production and Inventory Costs

Avg Carried Inventory	25,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Unit Production Cost	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Unit Delivery Costs	1.2884	1.2884	1.2884	1.2884	1.2884	1.2884	1.2884	1.2884	1.2884	1.2884
Daily Storage Cost	3,059.50	6,119.00	6,119.00	6,119.00	6,119.00	6,119.00	6,119.00	6,119.00	6,119.00	6,119.00
Daily Delivery Costs	7,53,246	5,16,338	5,22,176	7,31,626	5,80,045	7,12,333	6,06,646	7,05,203	5,99,677	7,14,681
Daily Production Cost	7,61,583	4,80,924	4,86,362	6,81,446	5,40,261	6,63,476	5,65,038	6,56,835	5,58,547	6,65,664

Total Cost	1,25,60,244.47

(Griffiths et al., 2021)

Inventory control is one of the most essential tasks, especially during a global pandemic where there is a huge spike in demand for vaccines. Additionally, since COVID-19 is a new disease, a lot of money has been spent on the Research and Development of these vaccines. Hence, wastage cannot be afforded.

The Inventory Control model, built on excel, suggests the optimum production levels based on pre-set constraints which include opening stock, closing stock, and demand of the vaccines daily. It is highly recommended to plan for a surplus stock at the end of each day since the actual demand may always deviate from the projections.

Minimizing the cost is another objective of the Inventory Control model. Overhead costs like sanitization, PPE kits and salaries, Storage cost, and production cost are considered for the total cost of the vaccination process from Production to Deployment.

The results concluded that the closing balance on every date was at its minimum prescribed level. This proves that it is cheaper to produce more than to store the supply of vaccines.

On every day, except the first day, the production values exactly match the demand values. This is also due to the constant closing stock which is carried over as the next day's opening stock. Since opening and closing stock are both equal on all days except the first day, one can say there is essentially no surplus inventory being used and the entire daily demand is being produced on the same day. This would have not been the case had the opening and closing stock values been different from each other. On the last day (10^{th} day) had the closing stock been set to zero, the inventory of 50000 would have been used up and yielded a production value 50000 units less than the demand.

IV.FINDINGS AND CONCLUSIONS

A. Transportation Problem

The model gives a total revenue of $38.37 billion with the following allocations:
Pfizer – European Union (EU) – 683 million vaccines @ $14.70 per vaccine
Pfizer – South Africa – 17 million vaccines @ $6.75 per vaccine
Pfizer – USA – 500 million vaccines @ $19.50 per vaccine
Moderna – European Union – 400 million vaccines @ $18.00
Moderna – US – 600 million vaccines @ $15.00

AstraZeneca – India – 1.1 billion vaccines @ $2.06

B. Inventory Control

In the literature review, the focus was applications of operations research in mass vaccination, and the themes of production, affordability, allocation, and deployment were identified. The previous work in this area revolves around regular immunization generally, and not around epidemiology. Although inspiration can be drawn from previous work, the novelty of the situation created by the Covid-19 pandemic requires innovative, multifaceted solutions.

Based on the provided constraints, the inventory control model calculates the optimum production levels with two main objectives – minimizing wastage of vaccines and minimizing the costs in the supply chain, from production to deployment. The results obtained include maximum production of 6.35 lacs units on the first day, while the minimum production was 4 lacs on the second day using sample values. The average production was 5.05 lacs for the period of 10 days.

It is critical to carefully project the demand for vaccines since many vaccines are expiring due to their short life span. However, due to the sudden surge in demand for vaccines, countries must maintain an emergency stock of vaccines. As seen in the inventory production table, an opening and closing inventory should be maintained to meet the minimum level of demand for a particular day.

The transportation problem calculated the optimum solution using the constraints of minimum allocation to specific counties. It ensures that each constraint is fulfilled as per the countries' requirements. However, due to limitations in supply, the demand for vaccines in India and European Union was not completely fulfilled. The total revenue to the vaccine manufacturers and the cost for the countries amounted to $38.37B.

To avoid the problem of unfulfilled demand, instead of a dummy row, another vaccine manufacturer like Sputnik can be included to avoid degeneracy. However, the allocation to the countries mentioned must be possible. Another issue, which needs more attention is the maximization of manufacturers' profits since the transportation problem currently focuses on the complete opposite – reducing costs to countries.

V. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

A. For Transportation Problem:

Concerning the analysis and findings, not all vaccinations mentioned in the table are available in each country specified in the problem. The constraints mentioned in the analysis include the Indian government's contract with AstraZeneca to receive 700 million vaccines and the U.S. government's contract with Pfizer to provide for 500 million vaccines. Therefore, due to these constraints, the minimum possible cost cannot be achieved.

By solving the transportation problem there is a reduction in the cost of vaccinations borne by the 4 countries together, and not of any individual country from those specified.

The main motive for the transportation problem was to minimize costs for countries that are buying Covid-19 vaccinations. One disadvantage to this is that the company's manufacturing and supplying the vaccinations wouldn't be able to maximize their revenue, by selling to countries where they benefit the most, and hence they might also face losses. Realistically, their supply allocation would be profit-oriented.

This model oversimplifies the problem of vaccine allocation. In reality, several complex factors relating to the socio-political environment of countries influence allocation decisions.

In the real world, vaccine manufacturers are not working in coordination as they ideally should. Instead, their focus is on maximizing their own profits. However, the model does not take this into consideration.

B. For Inventory Production Model:

Business risks cannot be eliminated but can only be reduced by employing efficient inventory control methods.(Inventory Control: Its Objectives, Advantages, and Limitations) The

United Kingdom, along with other wealthy countries has obtained hundreds of millions of Covid-19 vaccines that are expired and therefore, no longer of any use to these countries. (Feinmann,2021)
The demand on average may rapidly increase due to a possible spike in the cases relating to Covid-19 or due to a new variant discovered of this virus. The inventory maintained to meet the forecasted demand may fail to meet the actual demand during those times.
The demand projection needs to be highly accurate since the entire calculation revolves around the same. Any major inaccuracy in the projections will significantly affect the model's applicability.

VI. RECOMMENDATIONS:

A. For Transportation Problems:

A country can reach out to several suppliers as required, to fulfill their essential demands, if they are not met by existing suppliers. For example, since the quantity demanded by India was not fulfilled by AstraZeneca, it could reach out to different suppliers, other than those mentioned in the table, willing to supply to India. When allocating, instead of a dummy row, one more vaccine manufacturer, like Sputnik, can be included in the table to avoid degeneracy. This will also avail vaccinations to countries like India and European Union, which are short in supply for vaccination doses. However, their allocation to the countries mentioned must be possible.
The models proposed in this paper are elementary and can possibly be refined using advanced software that can consider complex factors like tariffs, transportation risks, the probability that contracts will be honored, and others. Softwares could also solve the problem for a dual objective of ensuring a minimum level of profit to manufacturers while keeping costs minimized. To solve the vaccination affordability problem for the vaccines borne by each country, a different aspect could be adopted in which the solution would contain a transportation problem for each country. This would separately minimize the cost for each country instead of minimizing it for all of the countries together.

B. For Inventory Production Model:

For reducing wastage, countries must make sure not to stack up a large number of vaccination doses together. As seen in the inventory production table, an opening and closing inventory should be maintained to meet the minimum level of demand for a particular day. This could prevent wastage and also provide a sense of how many vaccinations are required daily.
Lastly, to fulfill the sudden surge of demand for vaccinations on a particular day, countries must maintain an emergency stock of vaccinations, which does not lead to wastage.
Moreover, queuing theory can also be used to tackle this problem. The government could construct a queuing model, so that queue lengths and waiting time can be predicted to increase efficiency for allocation of the limited supply of vaccinations.
The models proposed in this paper are elementary and can possibly be refined using advanced software that can consider complex factors like tariffs, transportation risks, the probability that contracts will be honored, and others. Softwares could also solve the problem for a dual objective of ensuring a minimum level of profit to manufacturers while keeping costs minimized.

REFERENCES

[1] *COVID-19 vaccine contract size by region 2021 | Statista*. (n.d.). Retrieved September 8, 2021, from https://www.statista.com/statistics/1197696/covid-19-vaccines-contract-size-countries-and-regions/
[2] Aaby, K., Herrmann, J. W., Jordan, C. S., Treadwell, M., & Wood, K. (2006). Montgomery county's public health service uses operations research to plan emergency mass dispensing and vaccination clinics. *Interfaces*, *36*(6), 569–579. https://doi.org/10.1287/inte.1060.0229
[3] Allen, M., Spencer, A., Gibson, A., Matthews, J., Allwood, A., Prosser, S., & Pitt, M. (2015). *What is discrete event simulation, and why use it?* https://www.ncbi.nlm.nih.gov/books/NBK293948/
[4] Chick, S. E., Mamani, H., &Simchi-Levi, D. (2008). Supply chain coordination and influenza vaccination. *Operations Research*, *56*(6), 1493–1506. https://doi.org/10.1287/opre.1080.0527

[5] *COVAX Facility*. (n.d.). Retrieved September 21, 2021, from https://www.gavi.org/covax-facility#what

[6] *COVID-19 Vaccine Prices Revealed: Pfizer, Moderna and AstraZeneca | Observer*. (n.d.). Retrieved September 8, 2021, from https://observer.com/2020/11/covid19-vaccine-price-pfizer-moderna-astrazeneca-oxford/

[7] Duijzer, L. E., van Jaarsveld, W., & Dekker, R. (2018). Literature review: The vaccine supply chain. *European Journal of Operational Research*, *268*(1), 174–192. https://doi.org/10.1016/j.ejor.2018.01.015

[8] Feinmann, J. (2021). How the world is (not) handling surplus doses and expiring vaccines. *BMJ*, *374*, n2062. https://doi.org/10.1136/BMJ.N2062

[9] Griffiths, U., Adjagba, A., Attaran, M., Hutubessy, R., van de Maele, N., Yeung, K., Aun, W., Cronin, A., Gavi, S. A., Brenzel, L., Resch, S., Portnoy, A., Boonstoppel, L., Thinkwell, C. B., Alkenbrack, S., & Bank, W. (n.d.). *Costs of delivering COVID-19 vaccine in 92 AMC countries Updated estimates from COVAX Working Group on delivery costs 8 th February 2021*. Retrieved September 8, 2021, from https://www.who.int/publications/i/item/10665337553

[10] Gupta, A., Evans, G. W., &Heragu, S. S. (2013). Simulation and optimization modeling for drive-through mass vaccination - A generalized approach. *Simulation Modelling Practice and Theory*, *37*(September), 99–106. https://doi.org/10.1016/j.simpat.2013.06.004

[11] *Inventory Control: its Objectives, Advantages, and Limitations*. (n.d.). Retrieved September 15, 2021, from https://www.yourarticlelibrary.com/inventory-control/inventory-control-its-objectives-advantages-and-limitations/27944

[12] Lee, E. K., Maheshwary, S., Mason, J., & Glisson, W. (2006). Decision support system for mass dispensing of medications for infectious disease outbreaks and bioterrorist attacks. *Annals of Operations Research*, *148*(1), 25–53. https://doi.org/10.1007/s10479-006-0087-7

[13] Lim, J., Claypool, E., Norman, B. A., &Rajgopal, J. (2016). Coverage models to determine outreach vaccination center locations in low and middle-income countries. *Operations Research for Health Care*, *9*, 40–48. https://doi.org/10.1016/j.orhc.2016.02.003

[14] *Optimization Problem Types - Mixed-Integer and Constraint Programming | solver*. (n.d.). Retrieved August 20, 2021, from https://www.solver.com/integer-constraint-programming

[15] *Pfizer and BioNTech to Provide U.S. Government with an Additional 200 Million Doses of COVID-19 Vaccine to Help Meet Continued Need for Vaccine Supply in the U.S. | Pfizer*. (n.d.). Retrieved September 8, 2021, from https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-provide-us-government-additional-200

[16] Rais, A., &Vianaa, A. (2011). Operations research in healthcare: A survey. *International Transactions in Operational Research*, *18*(1), 1–31. https://doi.org/10.1111/j.1475-3995.2010.00767.x

[17] *Scaling Up to Manufacture and Supply a COVID-19 Vaccine, If Approved | Pfizer*. (n.d.). Retrieved September 8, 2021, from https://www.pfizer.com/news/hot-topics/scaling_up_to_manufacture_and_supply_a_covid_19_vaccine_if_approved

[18] *The Price Tags on the COVID-19 Vaccines*. (n.d.). Retrieved September 8, 2021, from https://www.managedhealthcareexecutive.com/view/the-price-tags-on-the-covid-19-vaccines

[19] *Vaccine inequality could cost the global economy trillions: Report*. (n.d.). Retrieved September 15, 2021, from https://www.cnbc.com/2021/08/27/vaccine-inequality-could-cost-the-global-economy-trillions-report.html

[20] *Vaccine monopolies make cost of vaccinating the world against COVID at least 5 times more expensive than it could be | Oxfam International*. (n.d.). Retrieved September 8, 2021, from https://www.oxfam.org/en/press-releases/vaccine-monopolies-make-cost-vaccinating-world-against-covid-least-5-times-more

[21] Weniger, B. G. (1999). Combination vaccines for childhood immunization: Recommendations of the Advisory Committee on Immunization Practices (ACIP), the American Academy of Pediatrics (AAP), and the American Academy of Family Physicians (AAFP). *Pediatrics*, *103*(5 I), 1064–1072. https://doi.org/10.1542/PEDS.103.5.1064

[22] *What is Monte Carlo Simulation? - India | IBM*. (n.d.). Retrieved August 19, 2021, from https://www.ibm.com/in-en/cloud/learn/monte-carlo-simulation

[23] *WHO Coronavirus (COVID-19) Dashboard | WHO Coronavirus (COVID-19) Dashboard With Vaccination Data*. (n.d.). Retrieved September 15, 2021, from https://covid19.who.int/

[24] Wood, R. M., Murch, B. J., Moss, S. J., Tyler, J. M. B., Thompson, A. L., &Vasilakis, C. (2020). *Operational research for the safe and effective design of COVID-19 mass vaccination centres*. *January*.

[25] Wouters, O. J., Shadlen, K. C., Salcher-Konrad, M., Pollard, A. J., Larson, H. J., Teerawattananon, Y., & Jit, M. (2021). Challenges in ensuring global access to COVID-19 vaccines: production, affordability, allocation, and deployment. *The Lancet*, *397*(10278), 1023–1034. https://doi.org/10.1016/S0140-6736(21)00306-8

[26] Zhang, J., & Mason, J. (2011). Applications of operations research to the prevention, detection, and treatment of disease. *… of Operations Research …*, 1–20. http://www.researchgate.net/publication/228840305_Applications_of_Operations_Research_to_the_Prevention_Detection_and_Treatment_of_Disease/file/60b7d52239f8a5b277.pdf

