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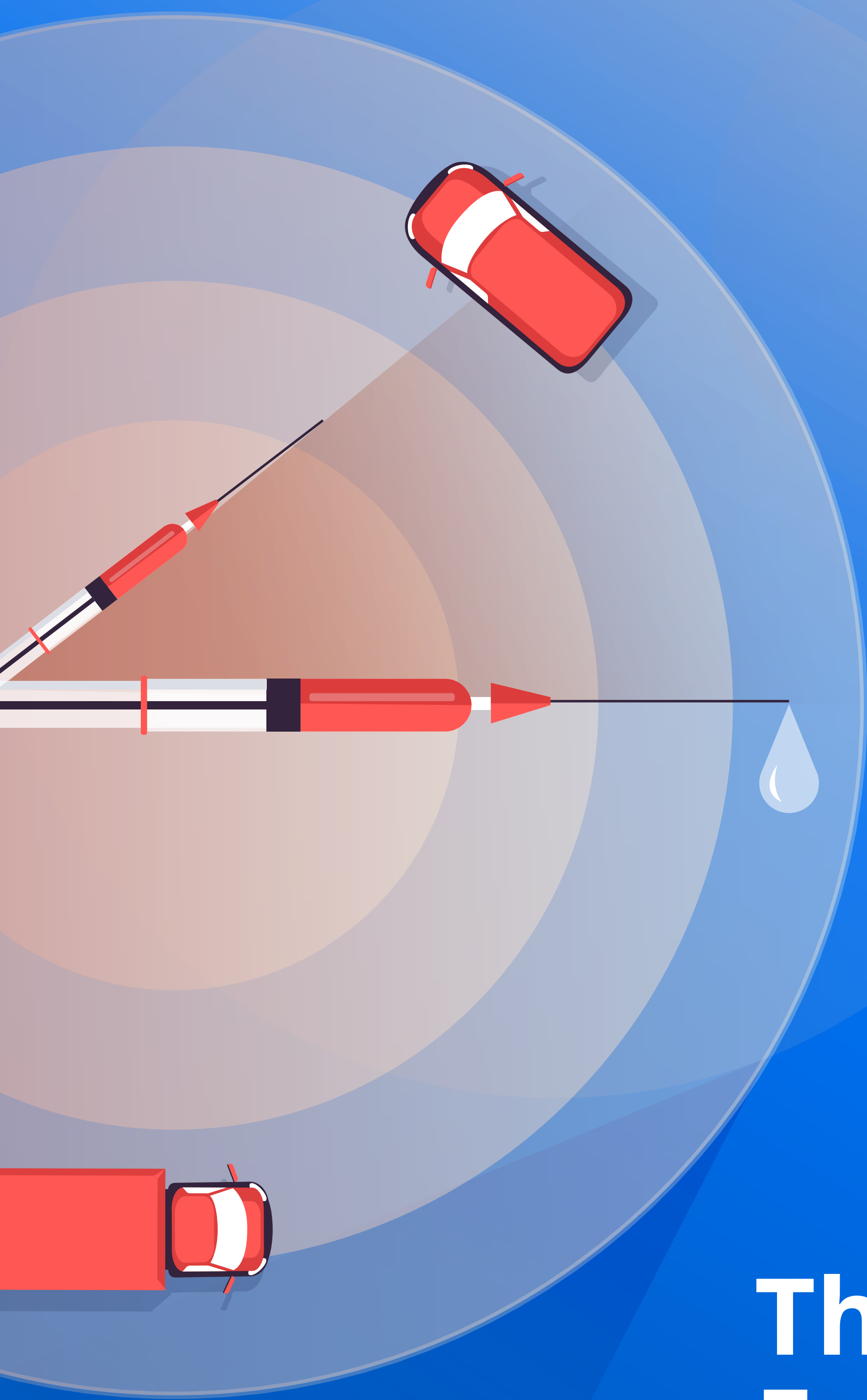

The Final Frontier

Designing an optimal cold chain network to distribute the COVID-19 Vaccine

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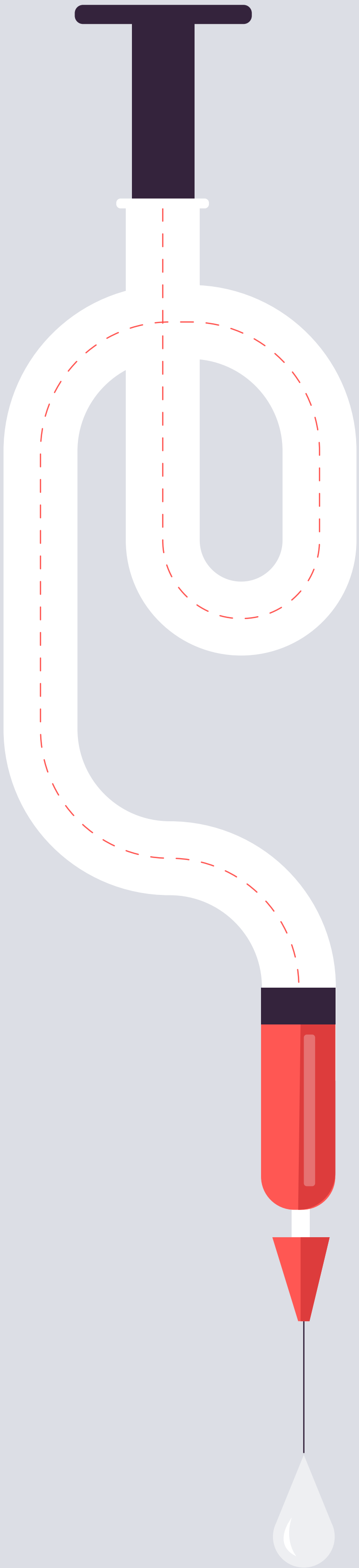


Executive Summary

- The COVID-19 vaccine distribution might very well be the most challenging task undertaken in modern times.

- With over 46 million infections worldwide as of Nov 1, 2020, and more than 1.2 million deaths, it is by far one of the worst epidemics ever witnessed on earth, after the infamous Spanish Flu of 1918.

- Formulating and then distributing the vaccine is a race against time. As recently summarized by the WHO, there are currently at least 125 different vaccination research projects underway for the prevention of COVID-19. Researchers are testing 50 vaccines in clinical trials on humans, and at least 87 preclinical vaccines are under active investigation on animals.

- While this is positive news, how exactly do these vaccines make it to every person on the planet. The distribution might well be the hardest task of it all.

- While multiple governments and vaccine manufacturers have come up with high-level vaccine distribution plans, they do not get into the details of the required cold chain network. We have made an attempt to design the required supply chain (cold chain) network.

- We have taken the US as an example to come up with an on-ground distribution strategy.

In this paper, based on the data points available from the vaccine manufacturers, WHO, and the U.S. Federal Government (as of November 20, 2020),

we propose a two-layer distribution model to deliver the vaccine doses to the masses. We optimally determine five mother warehouse locations and 26 regional warehouse locations to ensure that every US citizen is vaccinated.

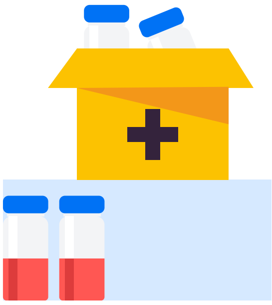
We simulate the proposed distribution model to visualize the flow of vaccine doses within the cold chain network. We also present a high-level estimate of the required transport capacity at each leg of the proposed plan.

Abstract

There is a general consensus now that the exercise of vaccine distribution would be the first most challenging task the logistics industry would be facing since the onset of this century.

Technology has been an integral part of the Transportation and Distribution industry for some time. Though the penetration is still quite low, we have the best technology for supply chain now more than ever in history. Leveraging technology to solve such a humongous challenge would increase the efficiency and effectiveness of the distribution exercise.

Initial plans for vaccine distribution have been published by some of the Governments and also the vaccine manufacturers. However, they do not provide a detailed overview of the supply chain network that might be required for distributing the vaccine to the entire population.



In this paper, we have made an attempt to design the required supply chain (cold chain) network for vaccine transportation and distribution. We have proposed a model based on the available constraints and information from two of the vaccine manufacturers - *Pfizer-BioNTech (hereafter referred to as Pfizer) and Moderna.* The vaccine candidates from these two manufacturers are in the advanced stages of trials and are likely to be authorized for use soon.

The scope of this paper is limited to the geography of the United States.

A two-layer distribution model has been proposed in this paper—it has mother warehouses and regional warehouses between the manufacturer facility and the administration site. To determine the optimal location for the warehouses, Locus' K-Means clustering algorithm was deployed on the US population data so as to cluster U.S. zip codes to various regional warehouses. Later, the same algorithm was deployed on regional warehouse locations and the associated population linked to those warehouses, to determine the mother warehouse locations so as to distribute the vaccine across the United States. Five mother warehouse locations and 26 regional warehouse locations were determined along with a one-to-one mapping of every zip code in the United States with the regional warehouses by using the output of the algorithm.

Post determining the optimal locations for the warehouses, the proposed cold chain network and the flow within the network were visualized. Locus' network optimization algorithm was used to simulate an end-to-end supply chain network— from the manufacturing unit till the end administration point, based on the available data. The optimal number of trips in each lane to distribute the doses across the country was also computed.

The proposed model in this paper presents a high-level overview of the possible distribution plan and the transportation capacity required. This can be used as a base to come up with exhaustive plans and robust models in the coming days, as we move closer to a successful vaccine.

01

The World Eagerly Awaits the COVID-19 Vaccine

The World Eagerly Awaits the COVID-19 Vaccine

The COVID-19 pandemic has been nothing short of a catastrophe in the history of mankind. With over 46 million infections worldwide as of Nov 1, 2020, and more than 1.2 million deaths, it is by far one of the worst epidemics ever witnessed on earth, after the infamous Spanish Flu of 1918[1].

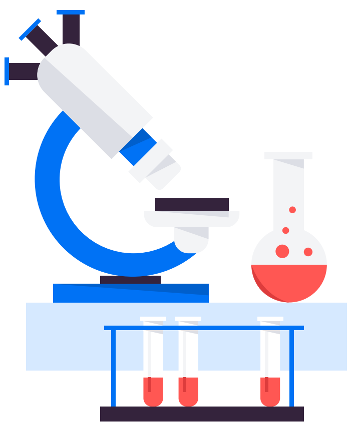
When the first few cases of Coronavirus were registered in China's Wuhan province in the month of December 2019, most populations assumed it would be like the SARS pandemic of 2003, affecting relatively few people and not disrupting daily life[2]. But, COVID-19 turned out to be more virulent and deadly. In just a short period, the outbreak developed exponentially into a pandemic that infected millions of people, with a global death toll of more than 500,000 during its first six months[3].

As the virus spread rapidly across continents, infecting hundreds of thousands of people with each passing day, it also caused widespread global disruptions all around, leading to uncertain periods of lockdowns, bans on international travel, and shutting down of several industries.

It has become evident that COVID-19 is no small beast. Researchers suggest we may be dealing with it for at least two years, as several cases of reinfection are emerging. Almost a year into the pandemic, we have gradually come to terms with what the new normal means — wearing masks, using sanitizers, regular handwashing, social distancing, working from home, online shopping, and what not!

But the world desperately needs and awaits the development of a life-saver vaccine against the virus that can put an end to this global misery, bring back the normal ways of living, and put derailed economies and businesses back on track.

Vaccines usually need years of thorough research and testing before they're finally released for public use. But this is a race against time, and scientists around the world are working hard to develop a successful vaccine by the first quarter of 2021.



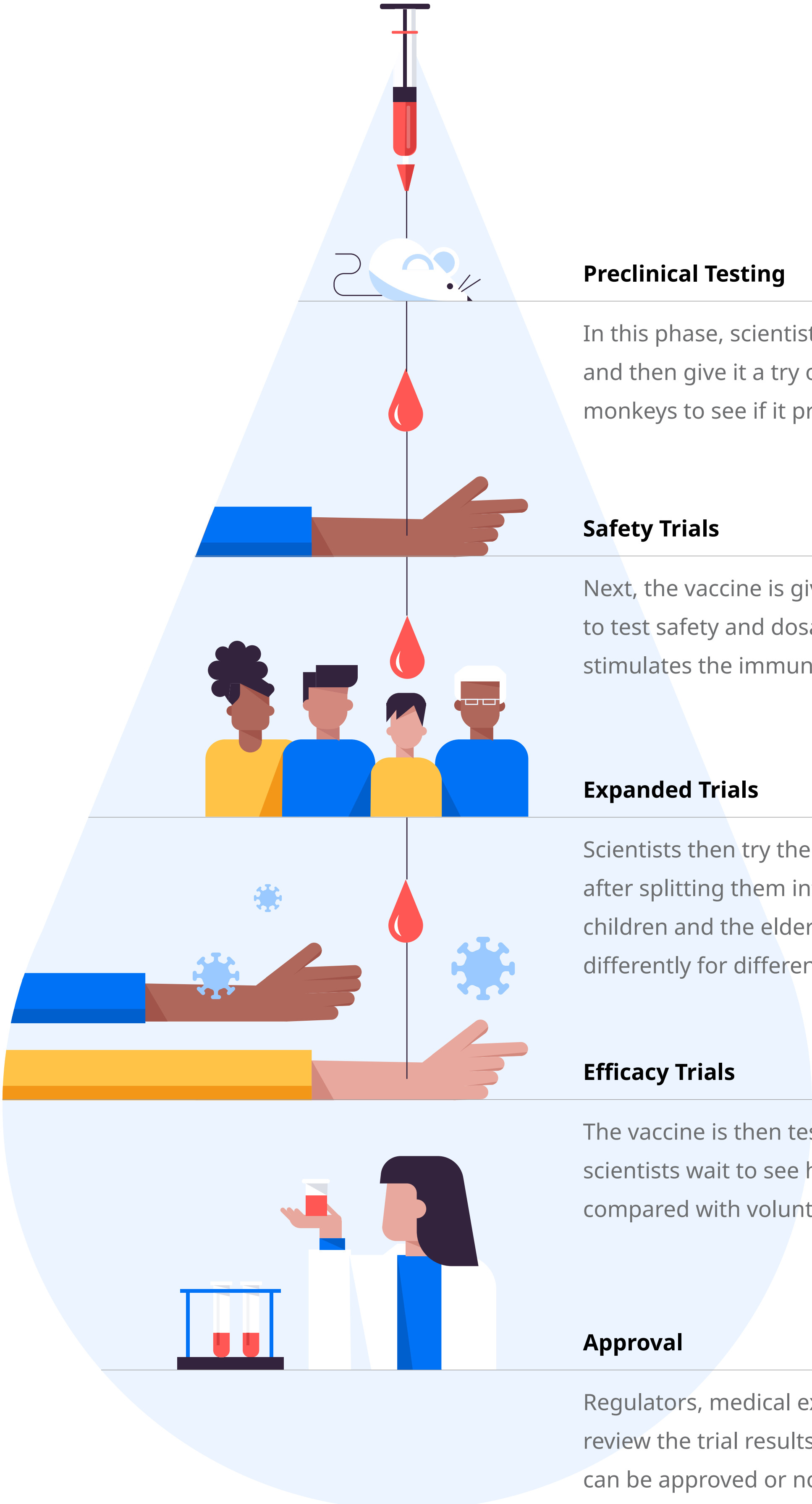
As recently summarized by the WHO

125 **COVID - 19 vaccination research projects[4]**

50 **vaccines in clinical trials on humans**

87 **preclinical vaccine trials on animals[5]**

Vaccine research and development typically takes place in five phases[6].



Preclinical Testing

In this phase, scientists test a vaccine on cells in a lab and then give it a try on animals such as mice or monkeys to see if it produces an immune response.

Safety Trials

Next, the vaccine is given to a small number of people to test safety and dosage as well as to confirm that it stimulates the immune system.

Expanded Trials

Scientists then try the vaccine on hundreds of people after splitting them into groups, such as men, women, children and the elderly, to see if the vaccine acts differently for different recipient groups.

Efficacy Trials

The vaccine is then tested on thousands of people and scientists wait to see how many become infected, compared with volunteers who received a placebo.

Approval

Regulators, medical experts, and healthcare authorities review the trial results and decide whether the vaccine can be approved or not.

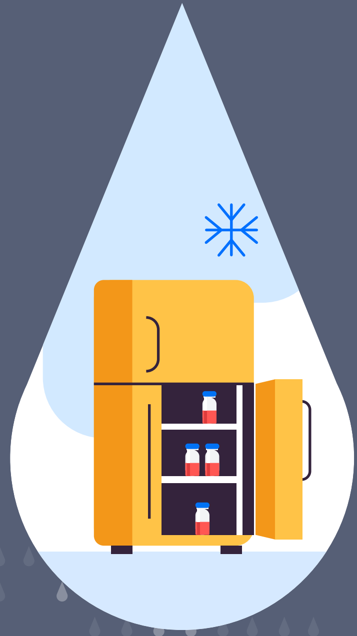
Some of the world's leading healthcare companies are working towards the research, development, and production of the COVID-19 vaccine.

Company	Collaboration	Vaccine
AstraZeneca	*in collaboration with* University of Oxford	ChAdOx1
moderna	*in collaboration with* National Institute of Health	mRNA-1273
sinovac		CoronaVac
BHARAT BIOTECH	*in collaboration with* Indian Council of Medical Research & National Institute of Virology	Covaxin

Source: CNBC TV18

Sooner or later, an effective vaccine will be approved and released for public use. But finding a vaccine alone is not the biggest trouble. Once a vaccine is devised, it needs to be produced in large quantities and distributed worldwide effectively.

Although global health organizations are preparing for rapid mass production and supply of the COVID-19 vaccine, the real challenge lies in the distribution of this vaccine to every nook and corner of the globe and ensuring that it reaches every human alive.



02

Non-Stop Sterile Refrigeration and Storage of the Vaccine- A Far Dream

Non-Stop Sterile Refrigeration and Storage of the Vaccine- A Far Dream

Credited for saving millions of lives, vaccines are one of the most significant public health achievements in the history of life sciences. But vaccine durability and potency depends on proper handling and storage, throughout its journey from the point it is produced till the time it is finally consumed. Even slight fluctuations in storage temperature can render these life-saving vaccines ineffective.

Vaccines must be maintained at the temperatures recommended by manufacturers and protected from light at every link in the cold chain. Most vaccines can tolerate freezing temperatures but deteriorate rapidly if they are removed from storage and exposed to temperature fluctuations such as extreme heat or even slightly varied temperatures. Potency can also be impacted if vaccines are left out too long or exposed to multiple temperature excursions (out-of-range temperatures).

The COVID - 19 vaccine being developed by the below two manufacturers have different temperature specifications.

Pfizer — *to be stored at* — **-94° Fahrenheit**

moderna — *to be stored at* — **-4° Fahrenheit**

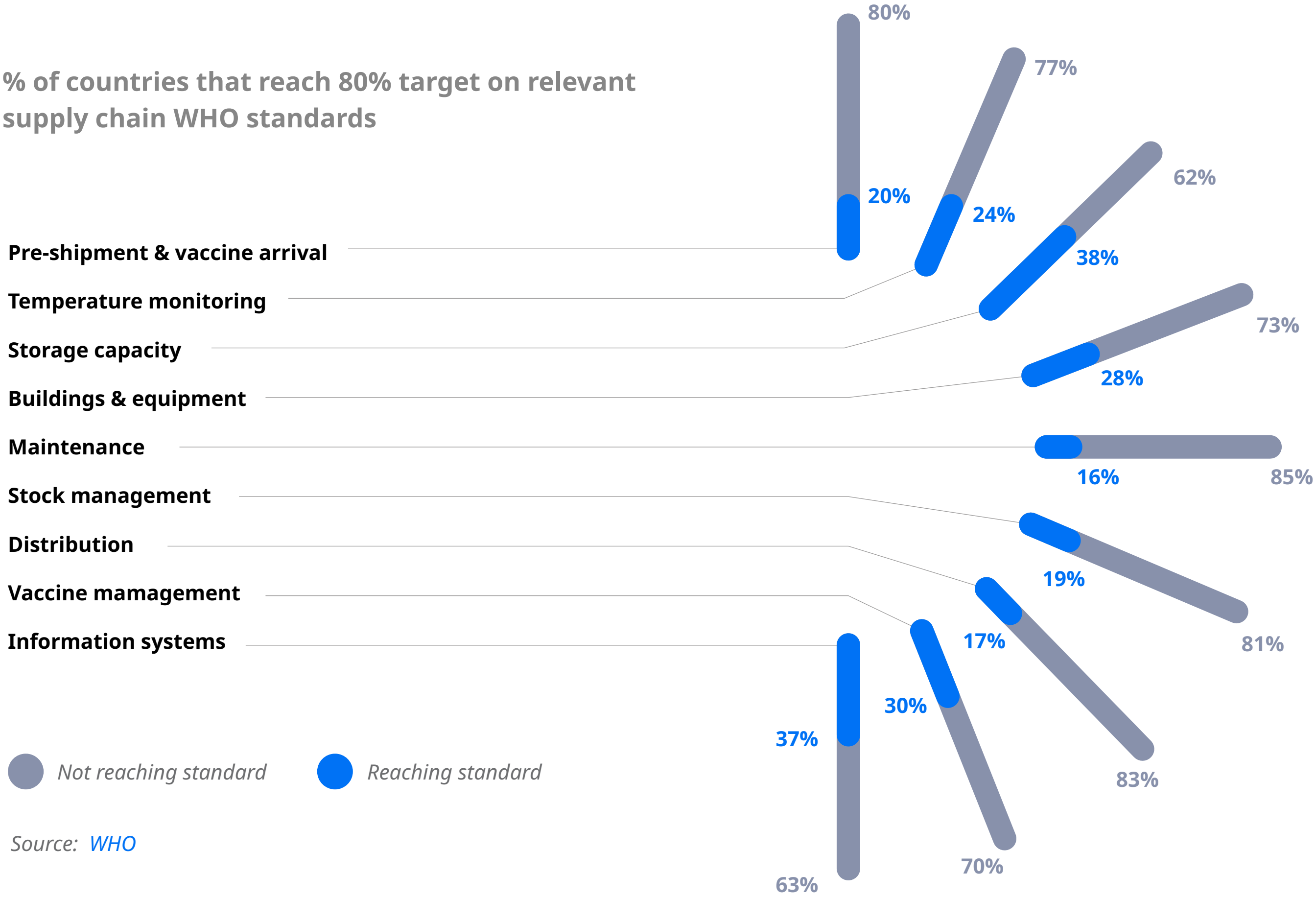
Source: Worldometer

These vaccines will need specially-designed refrigerators for storage and cold chain containers for transportation.

According to the Lancet, around nine billion COVID-19 vaccines would be produced in 2021[7]. However, most countries in Central Asia, much of India and Southeast Asia, Latin America, except for the largest countries, and all but some parts of Africa, lack the refrigeration infrastructure to administer an effective vaccination program.

How many national supply chains meet WHO Immunization standards?

% of countries that reach 80% target on relevant supply chain WHO standards



Source: WHO

A reliable global cold storage infrastructure is an absolute necessity to ensure that the hundreds of millions of vaccine doses reach the people in the most optimal conditions. However, the global supply chain is not yet fully equipped to handle the storage of these vaccines, and this could lead to significant losses due to life-saving drugs becoming impotent and thereby could cause uncertain delays in the distribution of vaccines to all parts of the world.

03

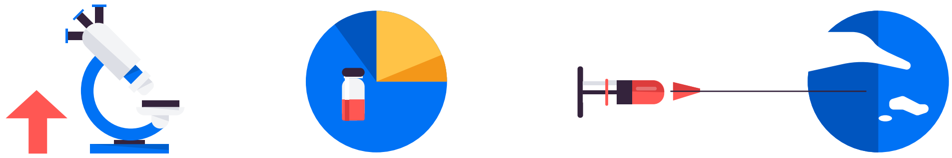
Vaccine Distribution Readiness Strategies- A Global Outlook

Vaccine Distribution Readiness Strategies-
A Global Outlook

COVAX - Access to COVID-19 Tools Accelerator (ACT-A)

COVAX is the vaccines pillar of the Access to COVID-19 Tools (ACT) Accelerator.

Primary motive



- **accelerated development**
- **equitable allocation**
- **scaled-up delivery of vaccines to all parts of the world**

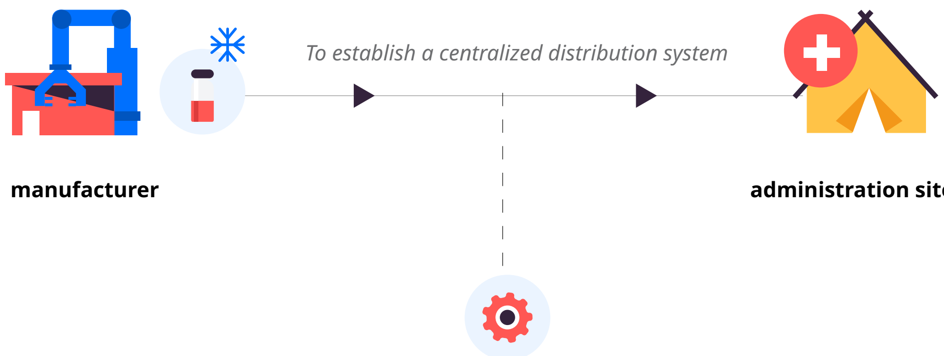
Participants in COVAX

- Bill & Melinda Gates foundation
- CEPI New vaccines for a safer world
- Gavi The Vaccine Alliance
- The Global Fund To Fight AIDS, Tuberculosis and Malaria
- FIND Because diagnosis matters
- World Health Organization
- World Bank Group
- Unitaid Innovation in Global Health
- wellcome

Centers for Disease Control and Prevention (CDC) - USA

Centers for Disease Control and Prevention (CDC), the USA's national public health institute, is working with state, local, and tribal health departments to hone existing plans for vaccine distribution and administration.

Primary motive



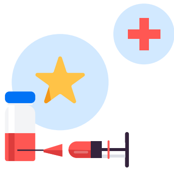
Partnership

McKESSON — **centralized system**

The European Union’s Vaccine Distribution Preparedness

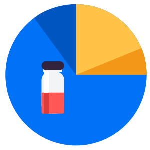
Ensuring the availability of a safe vaccine for all Europeans is a top priority of the European Commission. The Commission is proposing an EU strategy to accelerate the development, manufacturing, and deployment of vaccines against COVID-19.

Distribution Strategy



Ensuring the quality, safety and efficacy

Securing timely access to vaccines



Ensuring equitable access for all in the EU

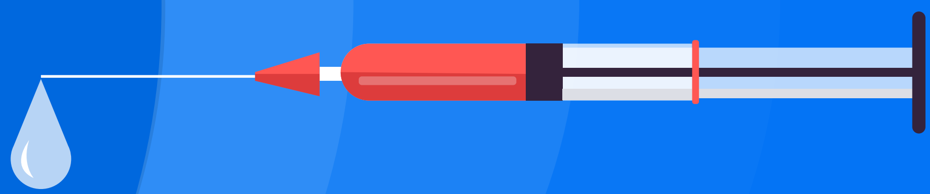
The Commission is also planning a coordinated approach for the distribution of vaccines across the EU Member States.

COVAX Source: WHO

CDC Source: United States Department of Health and Human Services

EU Source: European Union

04

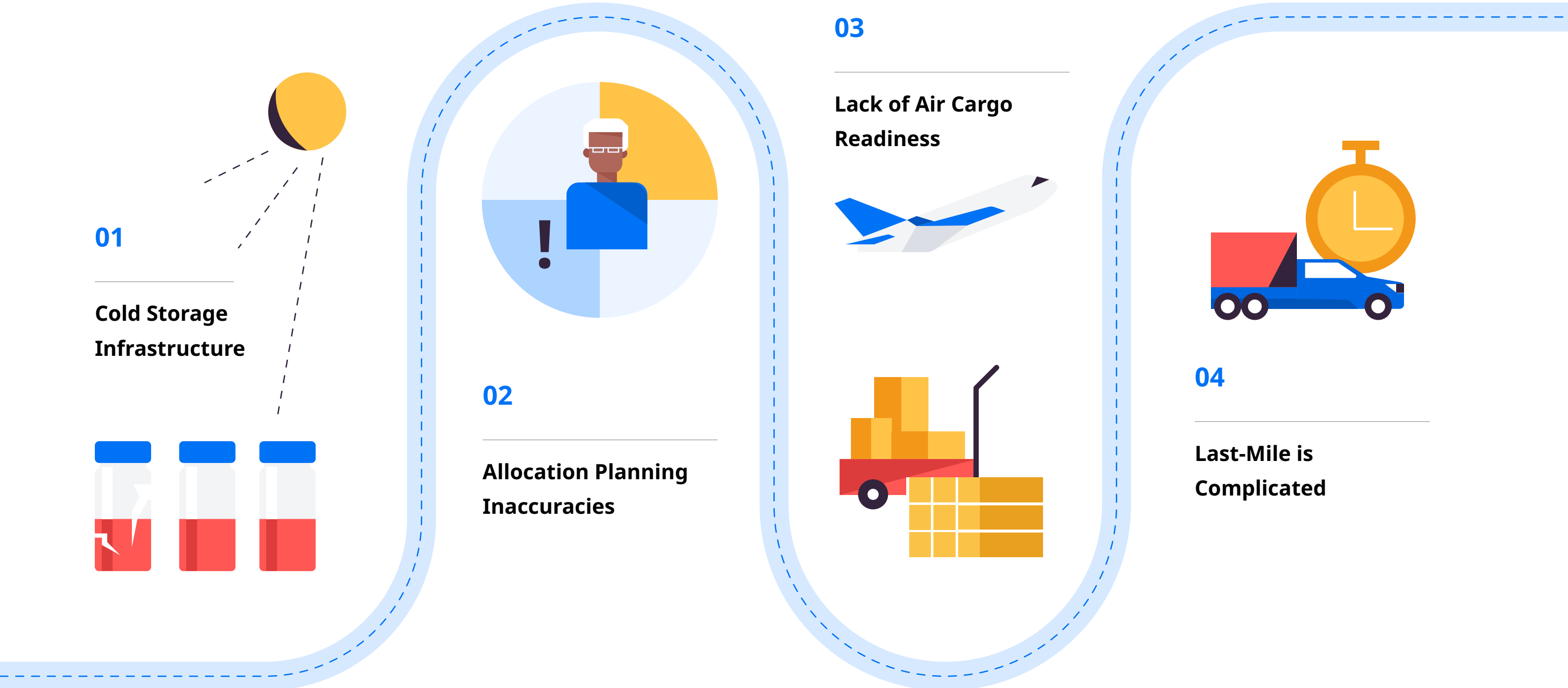


“It’s going to take four to five years until everyone gets the vaccine on this planet.”

Aadar Poonawalla, CEO, Serum Institute[8]

The Logistical Challenges in COVID-19 Vaccine Distribution

Once a vaccine is announced by the FDA, there will be huge pressure to begin distribution operations almost immediately. Currently, the global vaccine supply chain has a number of broken links and is not fully capable of handling the storage, shipment, and last-mile distribution of the vaccine.



01 Cold Storage Infrastructure

The “cold chain” is the sum total of safe handling practices, including materials, equipment, and procedures, that maintain vaccines within this temperature range from the time they are manufactured to the time they are administered to patients. Vaccines should be stored in refrigerators dedicated for this purpose.

Challenge

Cold storage is a major challenge for almost all countries in the world, including some of the most developed economies such as the USA and many European nations. Many under-developed countries of the world are deprived of regular electricity supplies, which means that COVID-19 vaccine storage is going to be a huge issue for such geographies.

Facts

The WHO estimates

that half the vaccines made globally are lost to wastage, either from heat exposure or broken vials in transit.

Nearly 3 billion of the world's 7.8 billion people live where temperature-controlled storage is insufficient for an immunization campaign to bring COVID-19 under control.

02 Allocation Planning Inaccuracies

Another major struggle with regards to vaccine distribution that most governments are facing is the categorization of the general public into priority groups for immunization. All the current vaccine allocation plans during the first wave of vaccine availability in the United States revolve around vaccinating people over 65 years old first, while others prioritize police and firefighters. Some other plans are prioritizing populations with risk factors for high COVID-19 mortality rates, such as hypertension, cancer and obesity, or those living in crowded or multigenerational housing. While these are on-paper plans for the upcoming vaccine allocation, reality is quite different. Early vaccine access is often given to places where it is politically and logistically expedient, instead of making distribution to the vulnerable and disadvantaged groups. This has happened in the past, and if a systematic, well-planned and equitable allocation distribution plan is not chalked out before the vaccine is released, the poor and under-privileged will be the last ones to be immunized.

03 Lack of Air Cargo Readiness

Challenge

Vaccines must be handled and transported in line with international regulatory requirements, at controlled temperatures and without impacting the quality, potency, and security of the drugs.

Facts

According to the International Air Transport Association (IATA),

the potential size of the delivery is enormous. Just providing a single dose to 7.8 billion people would fill 8,000 747 cargo aircraft[9].

The International Air Cargo Association (TIACA), along with Pharma.Aero, has expressed a strong concern over the current state of the global air cargo readiness for the upcoming COVID-19 vaccine transportation, stating that only 28 percent of the industry is well prepared for it[10].

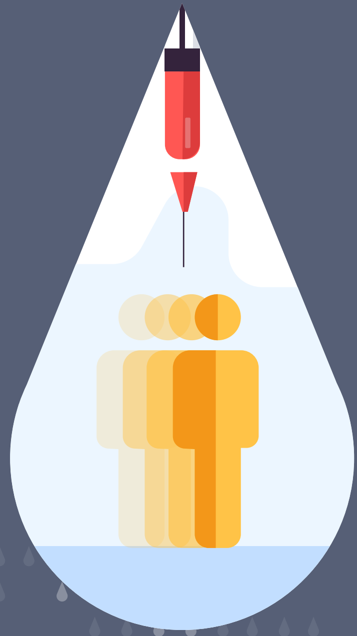
04 Last-Mile is Complicated

Challenge

Varying last-mile readiness of different geographies, could impact the quality of the vaccine.

Once opened for public use, each batch of vaccine must be consumed quickly, say, within a timeline of a few hours to a few days.

Lack of transparency and visibility in the distribution chain is a major challenge for authorities to keep track of how the vaccine is transported within states, cities and towns, and to whom it is being distributed.



05

Cold Chain Network for an Optimized and Safe Vaccine Distribution-Based on Locus' Network Optimization Algorithm

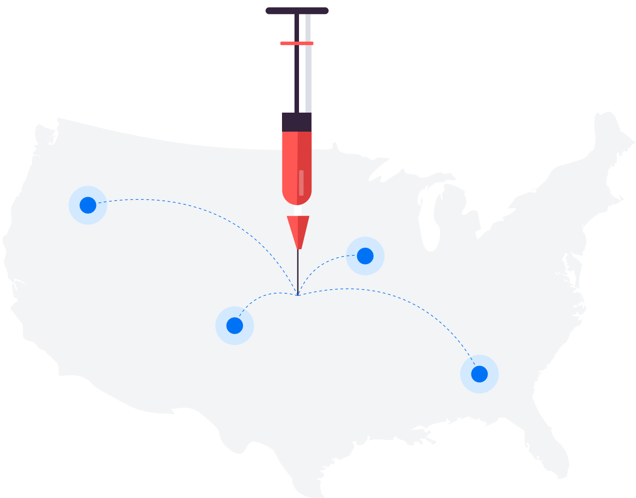
Cold Chain Network for an Optimized and Safe Vaccine Distribution- Based on Locus' Network Optimization Algorithm

As discussed in the previous sections, while the race to come up with a suitable vaccine for COVID-19 is still on, discussions have started in the logistics community on the humongous task of distributing the vaccine to 7.8 billion people worldwide. Estimates are getting clearer day by day with more data and specifications from the manufacturers. However, the world still does not have a clear distribution plan for when the vaccine is ready.

The U.S. Department of Health and Human Services released a high-level overview of the intended distribution plan which had two levels between the manufacturer and the final administration sites[11]. However, there has been no detailed outline of the distribution strategy. Pfizer recently spoke about its 'just-in-time' distribution plan. "The packages will be shipped via air to major distribution hubs and then delivered by ground transport to dosing locations, which may include hospitals, outpatient clinics, community vaccination locations and pharmacies," Pfizer spokesperson Kim Bencker told NBC News[12].

However, this announcement was met with skepticism from the logistics space. Just-in-time distribution of the vaccine calls for mass vaccination events to be organized across the United States. The feasibility of these is still a question. Other points were also raised- the U.S. had never undertaken such mass distribution through dry ice, availability of dry ice, etc. Considering these points, it is evident that distribution of the vaccine at a large scale does not require a centralized approach, but would instead need a tiered/decentralized approach. We propose a decentralized model for an efficient vaccine distribution in this paper.

In this section, we propose a detailed distribution model for any COVID-19 vaccine candidate. We base our study on an understanding that any vaccine distribution strategy should be a function of the population of a given area (country, district, county) i.e, densely populated areas would need more dosages compared to the sparsely populated ones.



The objective of this exercise is to determine an ideal cold chain network for optimized and safe vaccine distribution and administration.

We limit the scope of this exercise to the geography of the United States (due to data availability).

Population Distribution

The heat map in the below figure depicts the population distribution of the United States. It can be observed that there is a heavy population skew towards the eastern side of the country, due to various factors like European population migration to the east in the 1800s, the presence of lakes and rivers in the east for boats and ships to transport goods, and mountainous terrain in the western part of the country. We use this as a base to determine the optimal distribution plan.

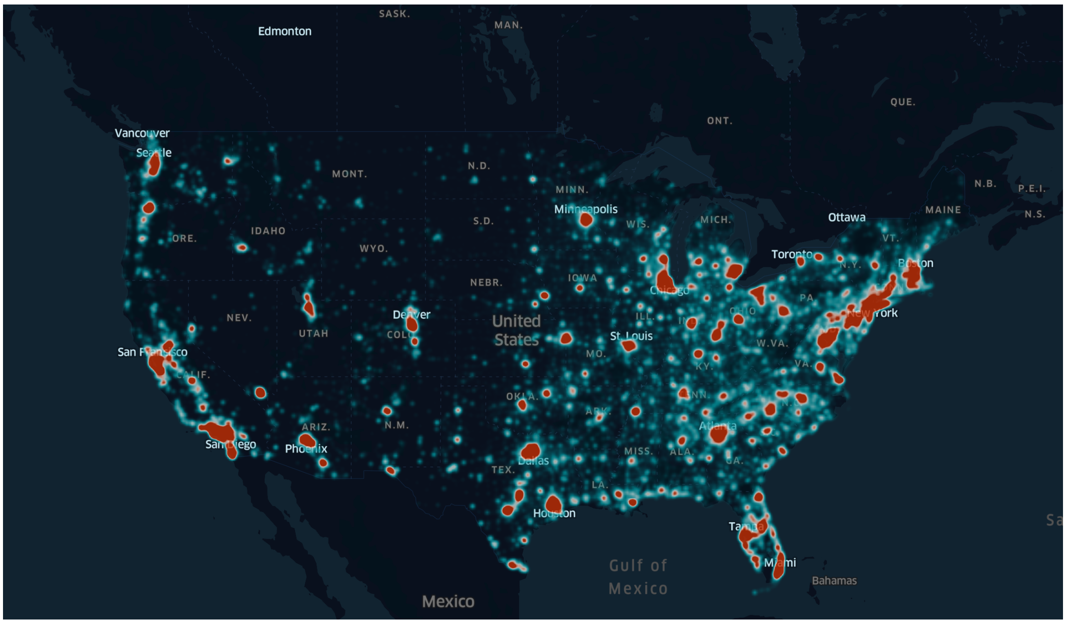


Figure 1: Population Distribution Heatmap for the United States

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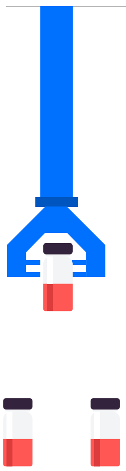
Current COVID-19 Vaccine Manufacturing Locations of Pfizer and Moderna



Pfizer

Kalamazoo,
Michigan[14]

Moderna

Norwood,
Massachusetts

Lonza Biologics,
New Hampshire

Catalent Pharma Solutions
Indiana[15]

Out of the multiple vaccine candidates currently in various stages of trials and experiments, Moderna's and Pfizer's have come out to be the leading contenders with a 90%+ success rate[13]. In this white paper, we have considered these two manufacturers and their specifications as constraints for further computations and simulations on storage and distribution. At points where there were two different specifications, we have considered Pfizer because Pfizer's vaccine candidate has been the most extreme case in terms of specifications so far.

We have visualized these locations on a map and the below figure clearly indicates that

the facilities, like the population, are also skewed towards the eastern half of the country. This implies that there would be a bulk transport movement happening from the east coast across the country.

Figure 2: Vaccine Manufacturing Locations

Distribution Model - Cold Chain Network

Every vaccine that humankind has discovered so far requires to be stored at the specified temperature to maintain its potency against the virus. Certain vaccines like Oral Polio Vaccine (OPVs), Influenza, etc. are extremely sensitive to heat and must be stored at a sub-zero temperature. This makes the vaccine distribution difficult and a cold chain network comes into the picture.

Most of the heat-sensitive vaccines are expected to be stored in normal refrigeration units. For example, all oral polio vaccines, which are the most heat-sensitive vaccines to date, can be stored up to six months if kept at around -20 degrees celsius but can be stored for up to one month if kept up to +2 - +8 degree celsius[16]. However, what makes COVID-19 vaccine distribution challenging is its extreme temperature requirements for storage. Unlike the usual vaccines where the potency can be maintained for a significant period of time in the normal refrigerator units, the temperature requirements for both Pfizer and Moderna are upward of -20 degrees celsius. Pfizer's vaccine candidate would be stable in a refrigeration unit for hardly 5 days (vs 1 month for OPVs). Storage, handling, and transportation of such vaccines need deep freeze units and temperature monitoring/controlling equipment to ensure that the vaccines are fully potent when the dose is being administered.

Pfizer has announced that its vaccine candidate can be stored for around six months in the specified temperature (around -70-degree celsius), up to 15 days in specially designed containers with re-filling of dry ice, and up to five days in a refrigeration unit[17]. We use these specifications as a benchmark and consider them as constraints in our model, as they are the most extreme constraints announced so far by any vaccine manufacturer.

The vaccine can be stored for five days in a normal refrigeration unit, which is the capacity available in most of the current cold chains. This constraint leaves us with only a few options for storage and transportation.

Hence, from a feasibility and safety perspective, we recommend the following model for the distribution process (along with the relevant modeling assumptions)

We propose the following legs of movement from the manufacturing facilities to the administration sites:

Leg 1:
Primary movement from manufacturing facilities to mother warehouses

Storage at Manufacturing Facilities: Deep Freezer
(at manufacturer-specified temperature)

Storage at Mother Warehouse: Deep Freezer
(at manufacturer-specified temperature)

Mode: Air

Storage during Transport: Dry ice/ Deep freezer refrigeration units

Transport constraints: 1 day

Leg 2:
Secondary Movement - from mother warehouses to regional warehouses/distribution centers/depots

Storage at regional warehouse: Dry ice

Mode: Truck Trailers

Storage during Transport: Dry ice

Transport and storage constraints: 10 days in the best-case scenario, up to 15 days in the worst-case scenario (with refilling of dry ice). This implies that once the vaccine leaves the mother warehouse, it should reach and move out from the daughter warehouse within 5 - 10 days.

Leg 3:
Last-mile Movement - Regional Warehouses to Administration Sites

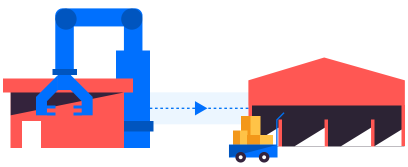
Storage at Administration sites: Refrigeration units

Mode: Trucks with cold boxes

Storage during Transport: Dry Ice / Refrigeration units

Transport and Storage Constraints: 5 days

All the constraints above are manufacturer-specified. We dive deep into the above legs of movements in the following sections.



Leg 1: Primary Movement (Manufacturing facilities to Mother warehouses)

Mother Warehouses are large hubs with the relevant facilities to store and handle vaccines in the manufacturer-specified conditions. Given the vaccines would have a few months of shelf life, these hubs would be the primary storage points where the government and authorities can store, plan, and distribute the vaccines based on time-dependent requirements, ground visibility, and local/state requirements.

While manufacturer facilities can act like mother warehouses, the below points necessitate the need for dedicated mother warehouses:

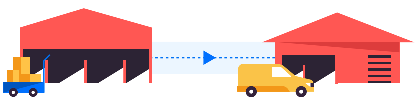
• All the manufacturing units are concentrated in the East - handling and distributing the vaccine to all regions across the country (mainly in the west and central regions) would be easier with a regional site, where the government can store and distribute the vaccines based on the ground requirements

• Manufacturing units would also need to store and transport the global vaccine requirements

• There are multiple vaccine candidates that might be approved for usage in the near future apart from Pfizer and Moderna. Mother Warehouses would act as a consolidation point and as a storage unit for all these different vaccine candidates

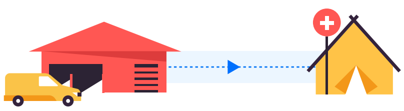
The preferred mode of transport would be air freight, considering that transporting the vaccines from the east coast to the west coast via ground would put the potency of the vaccine at jeopardy. This implies that these hubs should be located close to major airports that can handle large scale air cargo movement.

In addition to the existing four units that would manufacture the vaccines in the USA, these hubs would also handle and store vaccines from other manufacturers globally within the respective manufacturer's temperature specifications.



Leg 2:
Secondary Movement
(Mother warehouses to Regional Warehouses)

Regional warehouses are the smaller warehouses spread across the USA, which will act as distribution centers in our model. These warehouses might not have the required deep freeze facilities to store the vaccines at the extreme temperature range specified by the manufacturer but would have the infrastructure to store the vaccine using dry ice and/or in refrigeration units. This implies that once the vaccine leaves the mother warehouse, it has a maximum time of 15 days to be administered to an American citizen via a regional warehouse. The proposed mode of transport is land (truck), as the regional warehouses would be close to both the mother warehouse and the administration sites.



Leg 3:
Last-Mile Movement
(Regional Warehouses to Administration Sites)

The last-mile movement is the most complex of all, considering the possible number of administration sites across the country. Due to the limited cold chain network, we recommend that this movement happens through land. Once vaccines leave the regional warehouse, they can be stored either in refrigeration units or in a special container with dry ice. The same infrastructure (cold boxes/dry ice) can be used for the storage of the vaccine at the administration site. Refrigerated trucks or trucks with cold boxes can be used for transport. This is recommended due to their wide availability across the country (as last-mile requirements would be large in number).

In general, CDC recommends that vaccines should be administered within eight hours of it leaving the cold storage through refrigerated trucks/cold boxes[18] at locations that do not have the specified cold storage infrastructure. For Pfizer's vaccine candidate, we have a five-day window when stored/transported using refrigeration units.

We constrain the last-mile transportation to eight hours, leaving a window of 112 hours for vaccine administration. In this eight-hour window, we are limiting the time on the road to five hours and the remaining three hours are left for handling of the vaccine at the regional warehouses and at the administration sites (loading/unloading, etc).

In the US, a truck travels an average of 60 miles in an hour[19], which translates to a maximum distance of 300 miles between the final administration point and the regional warehouse.

In the next section, we simulate the above model using the population data of the United States with the specified constraints.

06

Determining the Location of the Warehouses

Determining the Location of the Warehouses

We used the population data of the United States by ZCTA's (Zip code Tabulation Area) as an input[20]. Each ZCTA was mapped to its corresponding zip code[21]. ZCTA/Zip codes were considered as they are one of the smallest units by which population data is collected by the census bureau. As a micro-unit, they are ideal clusters to host the vaccine administration units.

Regional warehouse locations

Based on the above-mentioned constraints, the regional warehouses should be located in such a way that they can collectively serve/cover most part of the population/geography in and around five hours or 300 miles. To meet this objective, Locus' K-Means clustering algorithm was deployed on the US population data to cluster zip codes to various regional warehouses. The output of the algorithm solves for three questions:

How many regional warehouses are required?

Where should these warehouses be located?

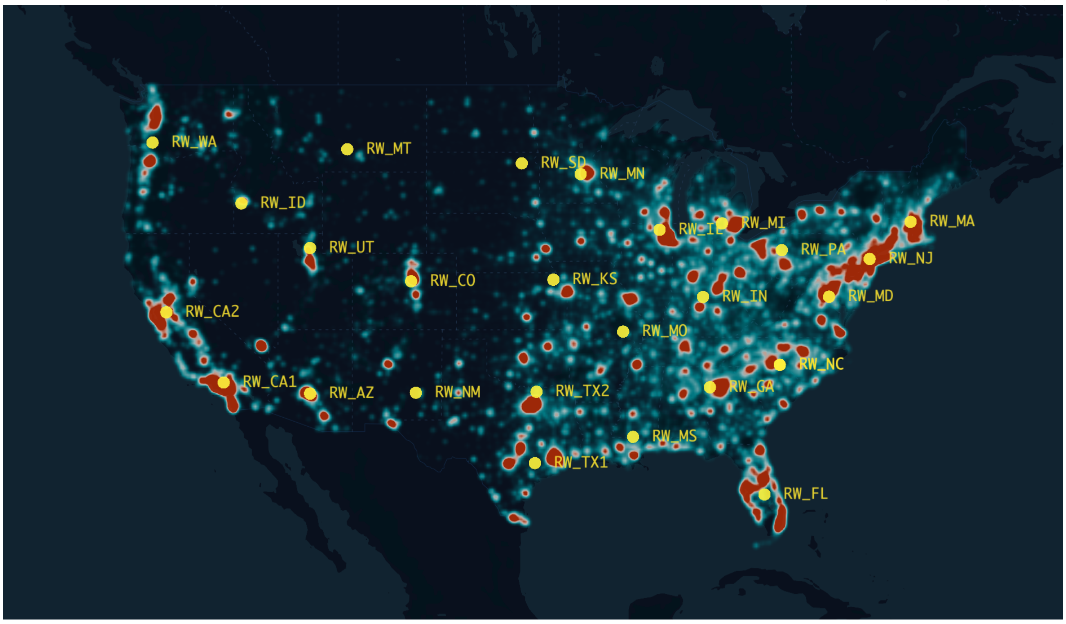
Which zip code is to be mapped to which warehouse based on proximity?

26

regional warehouse locations

Based on the output from the algorithm, we recommend 26 regional warehouse locations, which would optimally serve all the zip codes within five hours/are in the proximity of 300 miles from every point in the United States.

Figure 3: Locations of the proposed regional warehouses



The table 'Regional Warehouse Locations' in the datasheet translates the map locations to physical locations.

Mother warehouse locations

The mother warehouses need to be lesser in number (due to the requirement of deep freeze infrastructure), bigger in size, and located in such a way that they are not too far away from the regional warehouses. To meet this objective, Locus' K-Means clustering algorithm was deployed on regional warehouse locations and the associated population linked to those warehouses. The output of the algorithm solves for three questions:

How many mother warehouses are required?

Where should these warehouses be located?

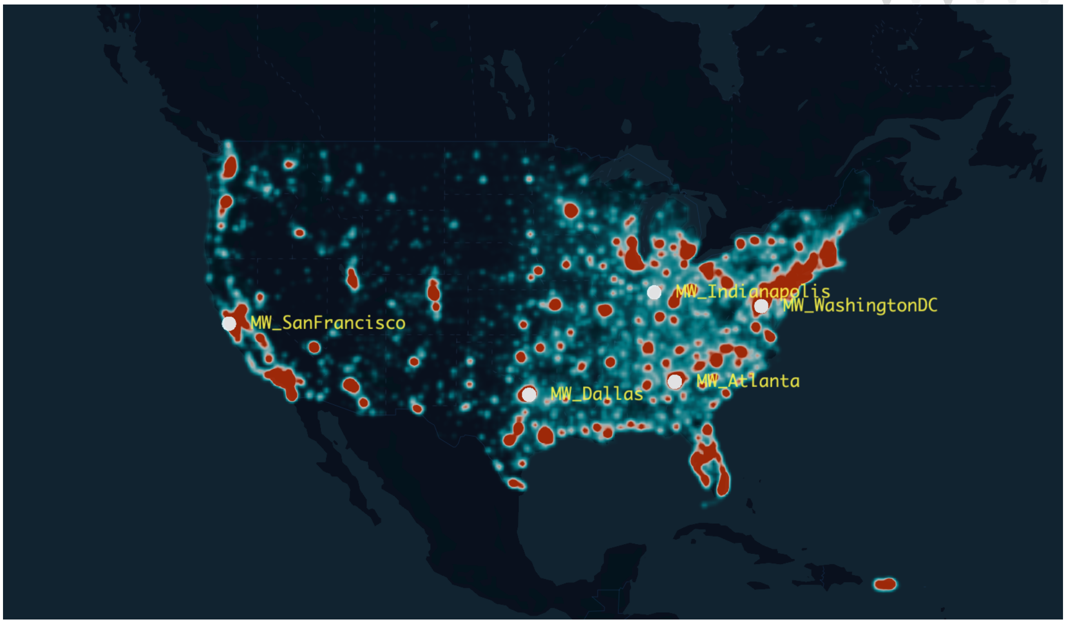
Which regional warehouse is to be mapped to which mother warehouse based on proximity?

05

mother warehouse locations

Based on the output from the algorithm, we recommend five mother warehouse locations, which would optimally serve all the regional warehouses.

Figure 4: Locations of the proposed mother warehouses

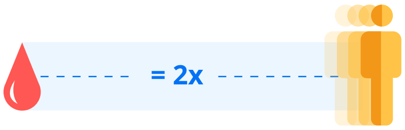


The table 'Mother Warehouse Locations' in the datasheet translates the map locations to physical locations

Mapping warehouses, vaccines, and population

From the above sections, we understand where the vaccines are manufactured, where they should be stored at primary and secondary locations, how they should be transported, and how the populations are mapped to the locations, the next step is to understand the quantities passing through every lane and location.

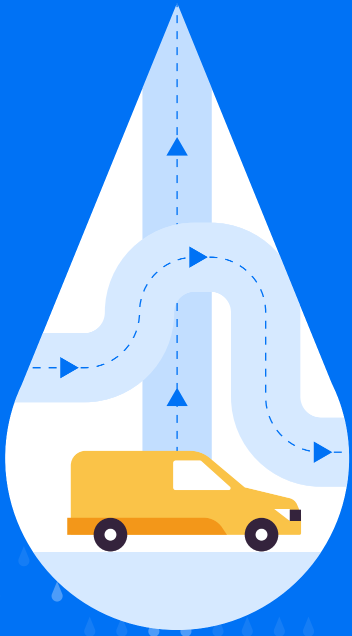
Though around 70% of the population needs to be inoculated to build herd immunity[22], the US government and other governments across the world are planning to vaccinate the entire population. Also, based on the existing information available about the dosage from the manufacturers, we know that every receiver gets two doses in an interval of three weeks[23].



This implies that the doses of vaccine moving in a lane would be equal to twice the sum of the population of the area served by all the end administration points.

For example: the zip code 01430 has a population of 6253, implying that the regional warehouse would need to hold and distribute 12,506 doses to serve the zip code 01430 alone. In the same manner, if the population of all the zip codes that are served by a regional warehouse add up to X, the corresponding regional warehouse would have to store and distribute 2X doses (we have ignored the safety stock requirement due to its variation based on the regions and other factors). Extrapolating further, if a mother warehouse serves five regional warehouses, whose served population adds up to Y (population number), the mother warehouse would have to store and distribute 2Y doses. This calculation of associated population with each mother warehouse and regional warehouses can be found in the datasheet (Tables 'RW to MW Mapping' and 'MW Population Mapping').

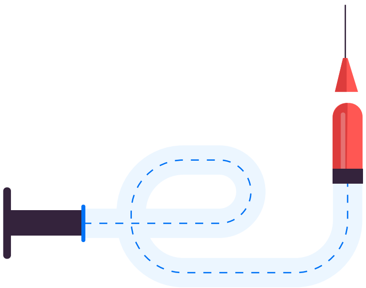
We currently do not have visibility on the manufacturing capacity of the individual manufacturing units of Pfizer and Moderna, and thus we will not be able to map the manufacturing units to the mother warehouses. We assume that vaccines are consolidated in the mother warehouse from all the manufacturing units. The table 'Population Mapped to Warehouses' in the datasheet depicts the population (by ZCTAs) mapping to regional warehouses, and mapping of regional warehouses to mother warehouses based on Locus K-means clustering algorithm output.



07

Cold Chain Network Visualization

Cold Chain Network Visualization

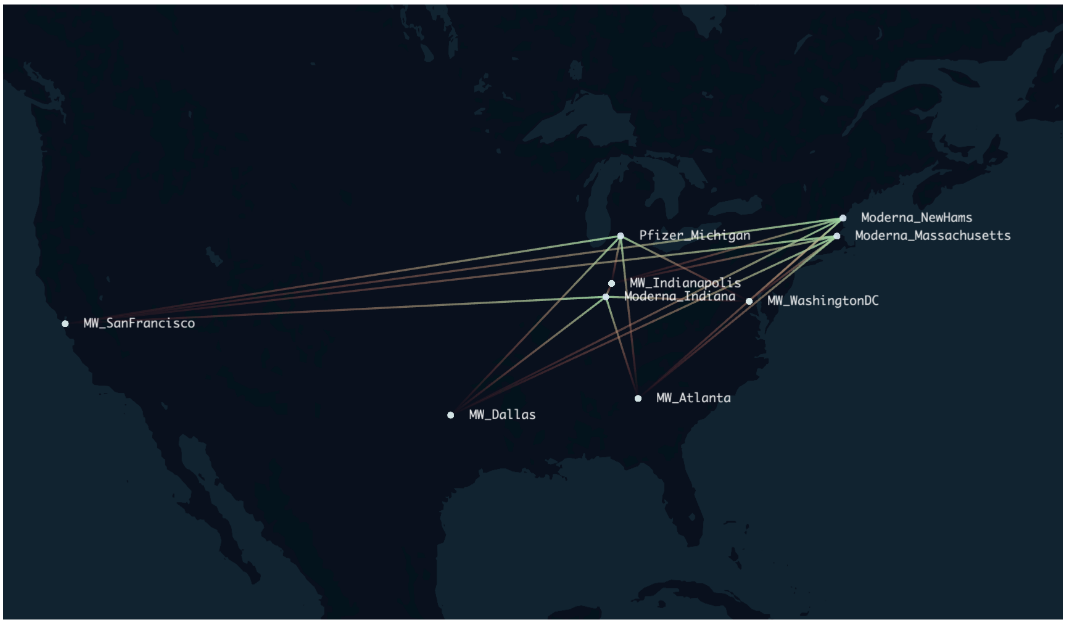


Locus' Network Optimization algorithm was used to simulate an end-to-end supply chain network— from the manufacturing unit till the end administration point, based on the available data. In the next section, we compute the optimal number of trips in each lane to distribute the doses across the country. The visual output from the modeling is presented in this section.

Manufacturing unit to mother warehouse movement

As stated earlier, we assume that all the factories would supply to all the five mother warehouses, implying there would be a 4X5 matrix of 20 flows coming out of the factories into the various mother warehouses. This flow is depicted in *figure 5.*

Figure 5: Flow from manufacturing units to the mother warehouses



Inter-warehouse movement

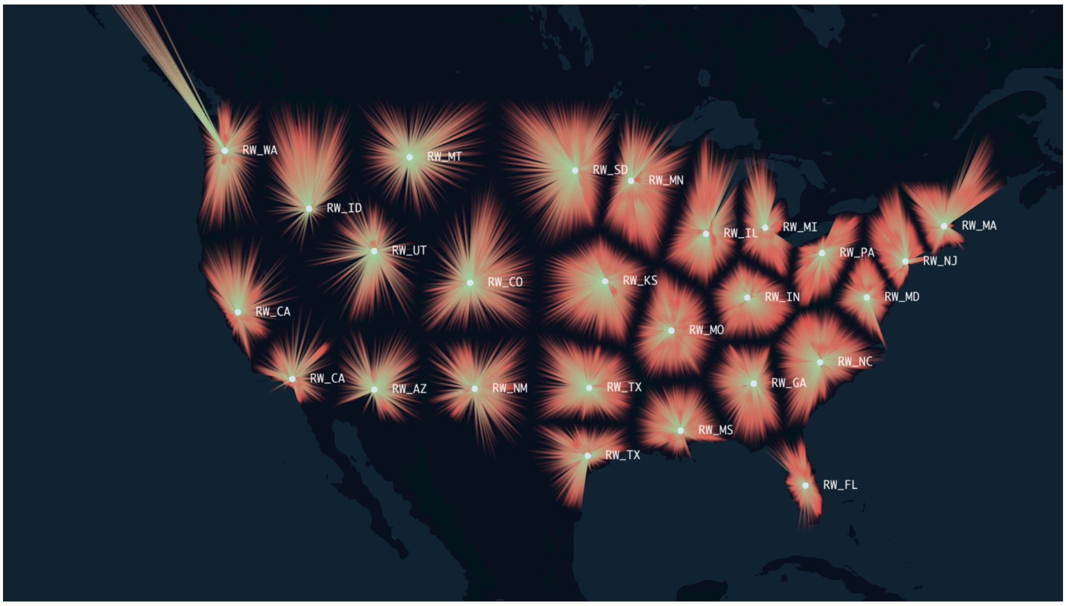
We used distance-based mapping to generate the most efficient transport lanes connecting mother and regional warehouses. As evident from the below figure, there are 26 transport lanes, each representing a one-to-one mapping from the mother warehouses to the regional warehouses. The demand of regional warehouses gets aggregated at a mother warehouse level as seen in the datasheet.

Figure 6: Movement between mother warehouses to the regional warehouses

Last-mile movement

Similar to secondary movement, we used distance-based mapping to generate the most efficient transport lanes connecting regional warehouses and administration sites. It can be seen from the below figure that there are mini clusters created around every regional warehouse, governed by the constraint that they should serve within 300 miles of transport distance. Though the visuals depict air distances, road distances have been used for all modeling-related activities.

Figure 7: Visualization of the last-mile movement from the regional warehouses to the administration sites



08

Transport Mode, Capacity Calculations, and Constraints

Transport Mode, Capacity Calculations, and Constraints

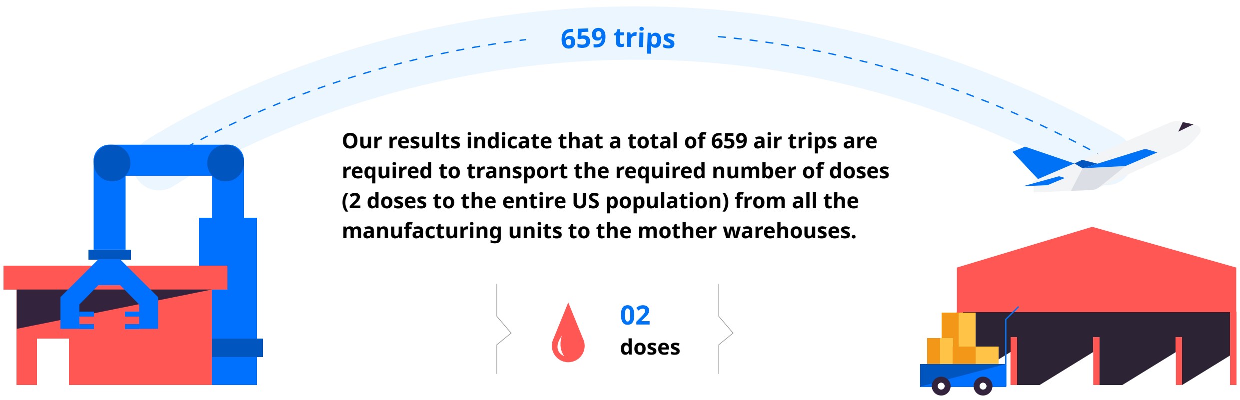
Now that we understand how the different nodes are interlinked and how many units they handle, the next step would be to understand the transport requirements to move the units between the nodes.

Primary movement

IATA estimates

7.8 Billion people | **01 dose** | **8000 747 cargo aircrafts[24]**

We use this data to estimate the capacity and calculate the necessary trips required across all the lanes from various manufacturing units to the mother warehouses for meeting full vaccine requirements of two doses per receiver.



As indicated in the previous sections, the storage mode during air transport would be dry ice. The vaccine's potency can be maintained for up to 15 days using dry ice.

For the breakdown of results on trip requirements, please refer to the sheet 'Primary and Secondary Movement' in the datasheet.

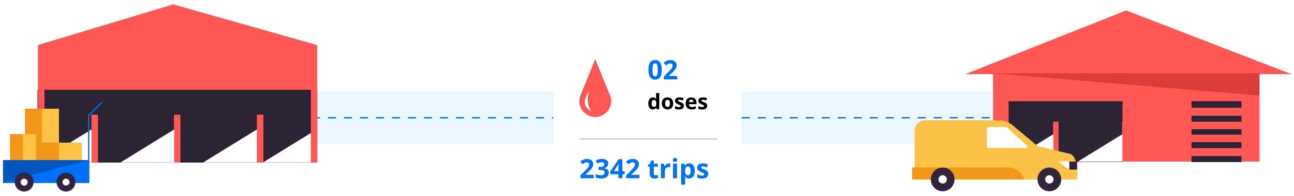
Secondary movement

Secondary-mile movement would include the transportation of vaccines from the mother warehouse to the regional distribution centers. We have assumed that the mother warehouses would have deep freezer units to store the vaccine at the manufacturer-recommended temperature. Thus, in mother warehouses, the vaccines can be stored till the manufacturer-specified shelf life (up to six months, for the Pfizer vaccine candidate).

Pfizer has designed a custom container that can store the vaccine within its recommended temperature range for up to 10 days using dry ice. The box can also be refilled with new dry ice for up to 15 days of storage[25]. Since the potency of vaccines is only for five days in a refrigeration unit, we propose in our model that transportation (secondary-mile movement) and storage of the vaccine in the regional warehouses should happen in specially-designed containers which can store the vaccine in its recommended temperature up to 10 days/15 days using dry ice. Thus, a 10-15 days' time period would be a constraint in our model for secondary-mile movement and storage in daughter warehouses.

As specified by Pfizer, the thermal shipping containers will each be filled with dry ice and 975 vials of the vaccine[26]. Every day six trucks will take the doses to air carriers. The company expects an average of 20 daily cargo flights worldwide. Using these data points, we know that each truck would have multiple trailers which would carry the thermal shipping containers, and we roughly estimate each truck would have the capacity to carry approx. 270,000 vials, which would serve a population of 135,000, with double dose per receiver.

We use the above constraints in our model and our results indicate that a total of 2342 trips are required to transport the required number of doses from all the mother warehouses to the regional warehouses.



As indicated in the previous sections, the storage mode during secondary movement would be dry ice/refrigeration unit.

For the breakdown of results on trip requirements, please refer to the sheet 'Primary and Secondary Movement' in the datasheet.

Last-mile movement

Vaccines are usually transported using vials, ampoules, prefilled devices, plastic dispensers, or tubes. We consider vials for primary packaging in this case considering that they are the most commonly used.

Vials can be single-dose/multi-dose based on the number of doses they hold. A single dose vial can be administered to one patient. Pfizer has disclosed that the current vaccine in development is non-lyophilized and a multi-dose vial would be used for packaging[27].

While transportation using dry ice is possible in the last mile as well (like the secondary mile), there are additional constraints that come with this. The regional warehouses must procure dry ice to replace and that would create an unprecedented demand for dry ice. Thus, for the purpose of this paper, we have considered it as a special case and have excluded it in our model.

Based on the above points, we propose in our model that the last-mile movement and storage at administration sites would happen using refrigeration units. Thus, the constraint in our model would be that the last-mile distribution and administration should happen within five days. As a best practice, we have incorporated an eight-hour transportation constraint for the last-mile movement (constraint for transporting vaccines to administration sites with no storage facility, based on CDC recommendations[28]). This constraint is also included in our earlier model to ensure that regional warehouses can reach all the administration sites within five hours by truck (or are in 300 miles radius).

There are two possible shipping systems for a temperature-sensitive/controlled vaccine[29]:

Refrigerated vehicles – temperature-controlled and temperature-modified

Passive shipping systems

In passive shipping systems, the vaccine vials are kept in a cold box which acts as an independent refrigeration unit. These cold boxes are then transported in the normal trucks. Each cold box consists “of a combination of insulated material and temperature-stabilizing media. When correctly configured, such a combination can keep the internal contents of the package within a specified temperature range for a pre-defined period of transport, without reliance on mechanical assistance”.

While both shipping systems are available in the United States, we consider passive shipping systems in our model. We exclude refrigerated vehicles due to the non-availability of data for our computations. WHO PQS specifications and prequalification procedures are not currently available for refrigerated vehicles, and thus we do not have an authoritative source to qualify refrigerated trucks[30].

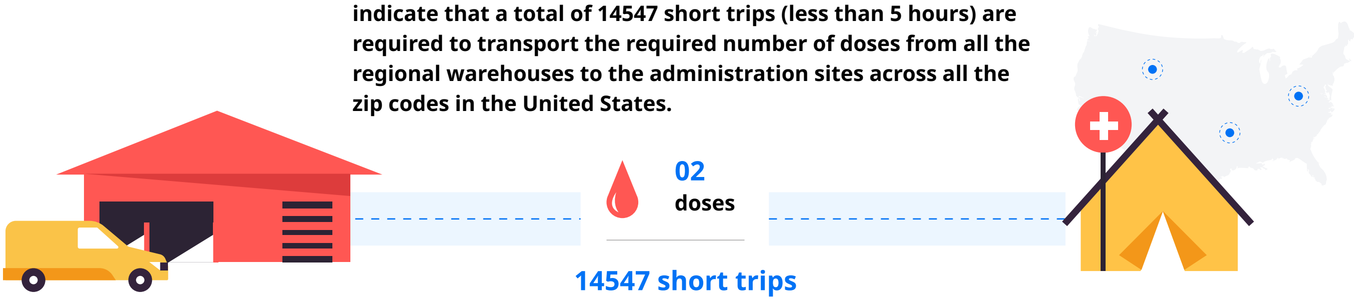
To compute the number of vaccine vials that can fit in a non-refrigerated truck, we need to choose the suitable cold boxes and standard truck dimensions.

We follow WHO Product Information Sheets to choose the cold boxes[31]. The cold life of the Pfizer vaccine is specified to be five days. Based on the given data, we would need a small cold box, long-range with a capacity between 4.0 – 15.0 liters. From the given sample vendors, we choose the vendor with PQS code E004/004, based on our requirement[32]. The external dimension of the cold box is specified to be 55 x 47.5 x 49.9 (in cm). The capacity of the chosen cold box (vaccine storage volume) is 7 Liters.

Also, cold boxes should be kept upright, and at least 1 cm must be maintained between cold boxes.

Using these specifications and constraints, we estimate that a single truck can hold 44,100 vials. Assuming that it would be a single dose vial, this can be used to administer the vaccine for a population of 22,050 with double doses. Detailed calculations can be found in the Appendix.

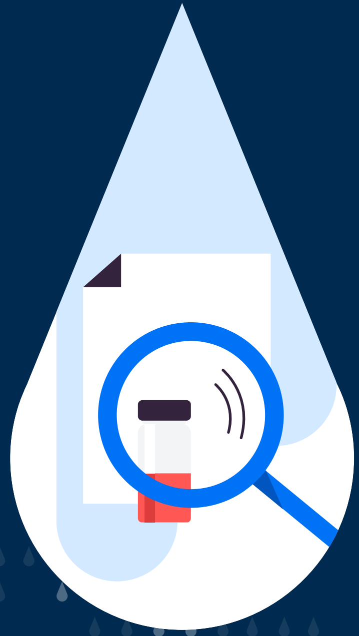
We use the above constraints in our model and our results indicate that a total of 14547 short trips (less than 5 hours) are required to transport the required number of doses from all the regional warehouses to the administration sites across all the zip codes in the United States.



A single trip is mapped to one zip code from the regional warehouse. While there can be multiple administration sites in a zip code, all of them can be served by a single truck in a small time frame, considering that zip code is a microgeographic unit. As indicated in the previous sections, the storage mode during the last-mile movement would be refrigeration units (cold boxes).

For the breakdown of results on trip requirements, please refer to the sheet ‘Last mile Movement’ in the datasheet.

All the above movements - primary, secondary and last - mile are considered to be of full load.



09

Limitations of the Study and Conclusion

Limitations of the Study and Conclusion

This study has been undertaken at a time when there is a lack of exhaustive data points/constraints from the vaccine manufacturers and the government. Below listed are some of the limitations of the study:

• We have considered two vaccine candidates for constraints in our model - due to the lack of data from other manufacturers.

• For our capacity calculations, we have limited ourselves to the number of required trips. Locus' proprietary route planning and optimization algorithm "Dispatcher" can be used to generate a more robust transportation and fleet plan. However, due to non-availability of the locations of the possible vaccine administration sites and fleet data, we could not generate an optimal and comprehensive last-mile administration plan.

• Warehouse operations have been excluded from the model. We have not proposed any plans for inventory management and the volumes to be handled per day at each warehouse.

• Safety stock requirements have not been considered in any of the calculations as they would vary by region (by warehouses) and government specifications.

• For the purpose of calculations, we assumed that all required vaccine doses will be available at one go, which will not be the case in a real-world scenario. Vaccines doses are expected to be delivered in phases. However due to lack of data points, we cannot factor this in the calculations.

These are uncertain times. From vaccine manufacturers to the government, each stakeholder in the supply chain is operating in uncertainty and is planning with assumptions. The proposed model provides a high-level overview and plan for vaccine distribution across the United States. This can be used as a base to come up with exhaustive plans and more robust models in the coming days, as we will have more data points from the stakeholders.

Appendix: Maximum Net Storage Capacity of a Truck

Calculation Step	Desired Result	Value
Internal Dimension of Truck Bed (Obtained from WHO calculations[33] and comparison with average truck dimensions[34])	Truck bed length (cm)	410
	Truck bed width (cm)	171
	Truck body height (cm)	173
External dimensions of passive container (Obtained from WHO PQS Catalog[35] and chosen using WHO Vaccine Management Handbook[36])	Container length (cm) + 1 cm	55 + 1
	Container width (cm) + 1 cm	47.5 + 1
	Container height (cm) + 1 cm	49.9 + 1
Determine maximum layers, considering external height of cold boxes and internal height of truck bed	Maximum number of layers	173 / 50.9 = 3
Determine maximum number of containers per layer, considering external length and width of cold boxes and internal length and width of truck bed	Calculated containers per layer	7 x 3 = 21
Calculate maximum number of containers	Maximum number of containers per load	21 x 3 = 63
Calculate maximum net storage capacity by multiplying maximum number of containers by net storage capacity of each container[37]	Maximum net storage capacity	63 x 7 = 441 Litres

General volume in a vial ranges from 3 - 10 ml. Using these data points, we compute the number of vials in the truck to be 44,100. This can be used to administer the vaccine for a population of 22,050 with double doses.

About Locus

Locus is a deep-tech platform that automates human decisions in the supply chain to provide efficiency, transparency, and consistency in logistics operations.

The platform uses deep machine learning and proprietary algorithms to offer smart logistics solutions like route optimization, real-time fleet tracking, insights and analytics, beat optimization, efficient warehouse management, vehicle allocation and utilization. Locus also helps companies optimize their end-to-end supply chain network with its strategic consulting offering.

Locus has raised $29 million, across multiple funding rounds, from tier-1 investors like Tiger Global, Falcon Edge, Blume Ventures, Exfinity Venture Partners, & growX ventures, among others.

The company powers deliveries across North America, Europe, Southeast Asia, and the Indian Subcontinent.

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