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Introduction

Supply chains for distributing vaccines consist of three types of locations. The first is the manufacturer’s warehouse, which receives the production of vaccines. The second set of locations we call Distribution Warehouses. These warehouses receive shipments directly from the manufacturer’s warehouse. There may be one manufacturer’s warehouse, but there are likely to be hundreds of Distribution Warehouses located throughout the United States, for example. Each of these Distribution Warehouses is responsible for supplying a collection of locations at which vaccines are administered, which designate as Dispensing Locations. There will many thousands of such locations. The number of both Distribution Warehouses and Dispensing Locations per Distribution Warehouse will vary by country.

The purpose of the following comments is to provide insight into the spreadsheet tools that can be employed to determine daily allocations of available supplies from the manufacturer’s warehouse to Distribution Warehouses, and from Distribution Warehouses to Dispensing Locations. The model is designed to be executed every day as conditions change. These allocations are determined considering:

1. Uncertainty in demand each day at each Dispensing Location.

2. Lead times associated with the transfer of stocks from one location to another.

3. The manufacturer’s vaccine box quantity (doses of vaccine per box).

4. The available stock at the manufacturer’s warehouse and Distribution Warehouses.

5. The on-hand stock at each Dispensing Location.

6. The desired level of service at each location in the distribution system.

By including service level targets, we provide the user with the flexibility to prioritize allocations to the most vulnerable patient communities served by each Dispensing Location. As we will see, the spreadsheet user is asked to provide data pertaining to all these parameters. While it seems to be a substantial task to enter these data, we will also see that it is not a daunting one. Once entered, the best possible allocations are determined by running the model. The mathematics used to determine the allocations can be found in our paper Application of Supply Chain Principles to Pandemic Planning.

In this document, we focus on a spreadsheet tool for making allocations from one manufacturer warehouse to a collection of Distribution Warehouses. We call this spreadsheet the “Vaccine Distribution Warehouse Allocator”. In another document (titled “Vaccine Dispensing Locations Allocator User Guide”), we show how to employ a companion spreadsheet (titled “Vaccine Dispensing Locations Allocator”) for making allocations from a Distribution Warehouse to a collection of Dispensing Locations.
Why Use the Vaccine Distribution Warehouse Allocator?

The Vaccine Distribution Warehouse Allocator is based on fundamental supply chain principles that have a long pedigree in the field of operations research. Together with its companion spreadsheet Vaccine Dispensing Locations Allocator, it applies a supply chain distribution method that maximizes “vaccinated person-days”, a concept that refers to the number of days patients have protection from the virus that the vaccine targets. While it was developed as a response to Covid-19, the method is equally applicable to other pandemic supply chain responses that may arise.

By maximizing vaccinated person-days, we minimize the time from a manufacturer’s production of vaccines to the time patients receive shots in their arms. In other words, it provides the most protection, for the most patients, in the least amount of time. By doing so, it both minimizes each patient’s risk of becoming ill and reduces the chances of virus variants from occurring. It accomplishes the latter result by vaccinating more people, more quickly, than when using other allocation strategies.

In summary, when vaccine supplies can be allocated and distributed as suggested by the Vaccination Distribution Warehouse Allocator and its companion Vaccine Dispensing Locations Allocator, people get vaccinated sooner, supplies are used up faster, fewer people experience COVID symptoms, fewer people are hospitalized, and fewer people will succumb to the disease.

We illustrate the concept of vaccinated person-days using a simple example. Suppose a vaccination dispensing site receives 100 doses of vaccine on a Monday. If the site vaccinates 100 people on Monday, 100 x 5 days = 500 vaccinated person-days occur over a five-day time horizon. If the site is capable of only vaccinating 20 persons per day for 5 days, the corresponding number of vaccinated person-days over that five-day period would be 20 x 5 + 20 x 4 + 20 x 3 + 20 x 2 + 20 x 1 = 300 days. By administering the vaccine as soon as it arrives, 67% more days of coverage are provided for those 100 patients. The model’s imbedded algorithms allocate vaccine supplies so that vaccinated person-days are maximized, with priority given to sites having higher service level targets.

During the Covid-19 pandemic, it has not been uncommon for some states in the US to be allocated more supply than they could quickly use, while other states had more patients seeking vaccinations than they had supply. The Vaccination Distribution Warehouse Allocator can avoid these misallocations by using updated estimates of patient vaccine demand levels and vaccine administration capacities. The model incorporates uncertainty of daily demand at each Distribution Warehouse. To incorporate uncertainty in the spreadsheet, the user provides the mean, standard deviation, and maximum likely doses needed at each Distribution Warehouse. For Distribution Warehouses that are already operational, these estimates should be easy to obtain from historical vaccination data.

As we have stated, when vaccine supplies are allocated efficiently and effectively, people get vaccinated sooner, supplies are used up faster, fewer people experience COVID symptoms, fewer people are hospitalized, and fewer people will succumb to the disease. The easy-to-use Vaccine Distribution Warehouse Allocator and its companion Vaccine Dispensing Locations Allocator ensures
such allocations occur. Furthermore, the tool requires no specialized knowledge or skill to use. It is helpful however to have basic familiarity with Microsoft Excel and rudimentary knowledge of statistics.

Model Assumptions

The Vaccine Distribution Warehouse Allocator is based on the following assumptions:

1. The supply of vaccines to be distributed is a single vaccine type, e.g., Pfizer-BioNTech, or Moderna, or Johnson & Johnson, or another. If Distribution Warehouses provide vaccines from multiple manufacturers, separate “Vaccine Distribution Warehouse Allocator” spreadsheets must be used for each. Demand estimates must then be provided for each manufacturer’s vaccine independently. The model will not “mix” vaccines from multiple suppliers.

2. Distribution Warehouses are served from a single source of a manufacturer’s supply. One manufacturer provides all supply of a particular vaccine type to each Distribution Warehouse.

3. Vaccines are distributed in whole boxes only. The model does not accommodate dividing single boxes of vaccines among multiple Distribution Warehouses.

4. Vaccine supplies cannot be shared between locations. The model does not accommodate re-allocation of excess supply at one Distribution Warehouse to another. In practice, if excess from one location does get shipped to another, enter the Supply on Hand from the sending location to the receiving location in Column D when preparing the inputs for the next planning period’s allocation worksheet.

5. Demand quantities are not known with certainty. For this reason, the model requires estimates of the daily mean, standard deviation and maximum quantities to be needed at each Distribution Warehouse.
Spreadsheet Overview

The above sample spreadsheet contains all required input data needed to make allocations to Distribution Warehouses. The cells shaded in green are those in which input data are required. The cells colored gold and gray have computed values in them. All other cells contain data that result from executing the allocation algorithm. We will next discuss the content of each of the green cells.

**Column B “Distribution Warehouse”** contains the names of the warehouses; enter your Distribution Warehouse names in this column. In this example, there are 52 warehouses: one for each state in the US.

<table>
<thead>
<tr>
<th>Distribution Warehouses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Alabama</td>
</tr>
<tr>
<td>2 Alaska</td>
</tr>
<tr>
<td>3 Arizona</td>
</tr>
<tr>
<td>4 Arkansas</td>
</tr>
<tr>
<td>5 California</td>
</tr>
<tr>
<td>6 Colorado</td>
</tr>
<tr>
<td>7 Connecticut</td>
</tr>
<tr>
<td>8 Delaware</td>
</tr>
<tr>
<td>9 Florida</td>
</tr>
<tr>
<td>10 Georgia</td>
</tr>
<tr>
<td>11 Hawaii</td>
</tr>
</tbody>
</table>

Etc.
Cell C8 “Manufacturer to Distrib Warehouse Lead Time” indicates the number of days to ship, receive and prepare vaccines for allocation at a Distribution Warehouse. The worksheet determines the total supply needed to be in process plus on order in order to meet the demands at each Distribution Warehouse this number of days into the future.

![Manufacturer to Distrib Warehouse Lead Time](image1)

Cell C9 “Manufacturer’s Supply” indicates that a supply of 3,000,000 doses of vaccine is available to allocate from the manufacturer, and the “Box Size” in Cell C10 is 100 doses.

![Manufacturer’s Supply](image2)

The data in rows 15 through 64 in column C “Target probability of not running out of stock” indicate the target probability of not running out of stock at the end of the lead time at the corresponding Distribution Warehouse. This number must be a number between 0 and 1, but less than 1. By setting this value, you set priorities for allocating the available supply. In our example, we set this value to .91 for each Distribution Warehouse.

![Target probability of not running out of stock](image3)

Etc.

Caution: when supplies are constrained, care should be taken in setting the target probability of running out of stock too close to 1. That can result in high levels of expected excess being “trapped” at some locations and unavailable for use at other locations where there might be shortages. Users are advised to run the model with various combinations of targets until a desired balance between expected shortages and expected excess quantities are achieved at all Distribution Warehouses.
The total number of doses in transit to and on hand at Distribution Warehouses plus total supplies at dispensing sites prior to allocation of additional vaccine to them is displayed in column D “Distribution Location Net Inventory”.

In the same rows in columns E through G, enter the daily mean, standard deviation and maximum patient demands you expect to have on the day at the end of the lead time at the corresponding Distribution Warehouse.

Etc.

Etc.
Columns H-J present the expected demands during one lead time. These are simply the values in columns E-G multiplied by the lead time entered in cell C8.

The spreadsheet can accommodate up to 200 Distribution Warehouses served by one Manufacturer. There are no restrictions on naming conventions. However, you are not permitted to enter Distribution Warehouse with zero or blank demand estimates between locations with positive demand estimates.

After you have entered these data, click the large “Allocate Vaccine to Distribution Warehouse” button:

For most scenarios, the model runs very quickly, and results are displayed almost immediately. In some scenarios, for example when box sizes are large and supplies are constrained, there may be some delay in displaying results while the calculations are performed. When the model completes calculating and posting its results, a done message will appear:

Upon completion, click the “OK” button to view results.
The results of the allocation decision will be displayed in columns K through R:

<table>
<thead>
<tr>
<th>Allocation in doses</th>
<th>Allocation in boxes</th>
<th>Doses Available for Dispensing</th>
<th>Expected Shortages in doses</th>
<th>Expected Excess Supply in doses</th>
<th>Expected Vaccination (Fill Rate)</th>
<th>Optimal Stock Level $S_j$</th>
<th>Safety Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>44,100</td>
<td>441</td>
<td>136,650</td>
<td>16</td>
<td>600</td>
<td>0.9999</td>
<td>136,631</td>
<td>581</td>
</tr>
<tr>
<td>6,700</td>
<td>67</td>
<td>20,743</td>
<td>0</td>
<td>130</td>
<td>0.9999</td>
<td>26,977</td>
<td>84</td>
</tr>
<tr>
<td>68,200</td>
<td>682</td>
<td>202,878</td>
<td>23</td>
<td>861</td>
<td>0.9999</td>
<td>202,847</td>
<td>830</td>
</tr>
<tr>
<td>26,900</td>
<td>269</td>
<td>82,871</td>
<td>5</td>
<td>416</td>
<td>0.9999</td>
<td>82,788</td>
<td>333</td>
</tr>
<tr>
<td>352,700</td>
<td>3,527</td>
<td>1,086,715</td>
<td>133</td>
<td>4,428</td>
<td>0.9999</td>
<td>1,086,679</td>
<td>4,392</td>
</tr>
<tr>
<td>51,000</td>
<td>510</td>
<td>517,390</td>
<td>16</td>
<td>724</td>
<td>0.9999</td>
<td>517,326</td>
<td>662</td>
</tr>
<tr>
<td>12,000</td>
<td>122</td>
<td>99,388</td>
<td>10</td>
<td>442</td>
<td>0.9999</td>
<td>99,360</td>
<td>414</td>
</tr>
<tr>
<td>8,100</td>
<td>81</td>
<td>24,868</td>
<td>0</td>
<td>130</td>
<td>0.9999</td>
<td>24,822</td>
<td>84</td>
</tr>
<tr>
<td>191,000</td>
<td>1,917</td>
<td>591,967</td>
<td>72</td>
<td>2,430</td>
<td>0.9999</td>
<td>591,959</td>
<td>2,402</td>
</tr>
<tr>
<td>95,300</td>
<td>953</td>
<td>293,924</td>
<td>12</td>
<td>1,208</td>
<td>0.9999</td>
<td>293,875</td>
<td>1,159</td>
</tr>
<tr>
<td>12,100</td>
<td>121</td>
<td>37,360</td>
<td>1</td>
<td>256</td>
<td>1.0000</td>
<td>37,269</td>
<td>165</td>
</tr>
</tbody>
</table>

Based on the available stock to allocate from the Manufacturer, the target probabilities of not running out of stock and the mean, standard deviation and maximum demand parameter values for each Distribution Warehouse (rows 15-64 in the sample spreadsheet), there corresponds an expected number of potential patients that would not be accommodated (column N), the expected number of doses remaining unused at the end of the following day (column O), the expected vaccination or fill rate (column P), the target stock level (column Q) and target safety stock level (column R).

The vaccination rate is defined to be $1 - \text{expected number of potential patients that would not be accommodated} / \text{total expected demand for all Distribution Warehouses}$. Note that while 3,000,000 doses were available for allocation, only 2,927,500 were shipped to Distribution Warehouses. This occurred because the target probability of not running out of stock, .91, at each Distribution Warehouse was achieved without allocating all the stock. Note also that although the target probability of not running out of stock was .91 at all Distribution Warehouses, the expectation was that nearly all persons desiring vaccinations would receive them (vaccination rate = .9999 or close to 1).
A Few Notes About Using the Worksheet

Most of the instructions contained in this user guide are also contained in the worksheet itself, as summarized by the statement in row 5:

*Enter data in green cells. Other cells contain model outputs. See explanations in notes fields. Click "Allocate Vaccine to Distribution Warehouse" button to run the model.*

The worksheet is protected. All but the green cells are locked, preventing any accidental input into cells intended for model outputs. To further aid the user, if an invalid number is entered in any of the green cells, error messages pop up. Informative messages guide the user to what values are valid. For example, if anything but a whole number greater than zero is entered in the “Manufacturer’s Supply” field in cell C9, the following error message will appear:

The spreadsheet contains information about both data input and data output fields at the top of the columns of data. The notes appear by hovering over any cell with a red triangle in the upper right portion. For example, when hovering over the “Manufacturer’s Supply” field in cell C9, the following explanatory note appears:

Each note follows a similar convention: a short description of the field is provided at the top of the note, a more detailed discussion follows. In the example above, we provide a short description of
“Enter the expected supply for the planning period”. In the discussion section, we explain how to run the model and how the model allocates the supply.

As stated previously, one worksheet represents the distribution of a single manufacturer’s vaccine type from a single source of supply, for a single planning period, typically one day. To prepare multiple planning periods or multiple sources of supply, the worksheets can be copied and renamed within a single workbook and/or multiple workbooks can be copied and saved:

In the example above, we have modelled a 50-state allocation of nearly 3 million vaccinations per day. The demand rates have been scaled to the populations of each state. The Distribution Location net inventories for each state are roughly equal to two days of supply, plus sufficient safety stock to achieve the target probabilities of not running out of stock during the 3-day lead time assumed in cell C8. Notice that the Doses Available for Dispensing in column M are all slightly higher than the Optimal Stock Levels listed in column Q. This is due to the allocations of whole boxes containing 100 doses per box.

How to Report Problems or Suggestions

Comments and questions may be sent to ciddp@med.cornell.edu. We will strive to answer your questions in a timely manner, but our resources are limited and responses are not guaranteed.