Applying Supply Chain Simulation Models For Planning Vaccination Campaigns

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Abstract

Humanity is facing an unprecedent sanitary crisis. Vaccination campaigns at large scale are being carried out all over the world. This research analyzes and compare two supply chain virtual models that simulate a stratified vaccination campaign in central southern Chile. In the first model the gravity model is applied to locate distribution centers. In the second model, the criterion of service distance is applied to locate distribution centers. Both models have identical three-echelon configuration with 1 supplier, 5 distribution centers and 20 vaccination points. Simulation results revealed that in first model, distribution vehicles travel 14,300 km to deliver 2.48 million vaccines, having a 0.33-day lead time with a fleet of 8 vehicles. In the second model, vehicles travel 21,050 km to deliver 2.48 million vaccines, having a 0.83-day lead time was 0.83 days with a fleet of 13. In both cases, 5 distribution centers are and 100% of the vaccines are delivered on time. In conclusion, simulation results suggest that virtual models for simulating supply chain models can be useful when planning vaccination campaigns and making decision about resources' allocation.

Keywords
Supply Chain Management, Simulation Model, Vaccination Campaign, Transportation Cost, Fleet Sizing

1. Introduction

The world is facing a pandemic at a scale never seen before. Scientists, pharmaceutical companies, and governments are working tirelessly to save lives. Meanwhile, vaccination campaigns are being planned and quickly implemented to immunize population and to maintain the crisis under. However, sanitary infrastructure and medical resources to satisfice a growing number of infected patients are limited. To make things even more complicated, vaccine development and testing take a long time. And when a vaccine is finally approved for use on patients, mass production and distribution pose new challenges.

During the past year governments from all over the world have been working on contracts with pharmaceutical companies to provide enough vaccines for their countries. But with a limited production capacity and an enormous demand, vaccines are expected to be supplied in rather small lots over time. Since it is understandable that a complete population immunization will take a while, governments have developed stratified vaccination plans to saisfied the demand gradually.

Vaccination plans face innumerous difficulties to be implemented successfully. In the first place most of the countries have scheduled restrictions such as total or partial quarantines to restrict people's mobility and so, vaccines will have to be sent wherever people are. On the other hand, high risk groups must be prioritized and provided with doses quickly to overcome their exposure to the virus. However, transporting vaccines from factories to temporary storage locations and from there to vaccination points sets another challenge as, in most cases, the product must be kept under strict climate conditions and tracking protocols.

During the last decades, the application of supply chain management methods has gained attention and interest in different fields outside the classic industrial engineering field and health care systems are a good example of that. Therefore, it is interesting to develop supply chain simulation models to study the effectiveness of a vaccination plan when different approaches are adopted.

In this investigation, a stratified vaccination plan for central southern Chile is analyzed by means of implementing and comparing two supply chain virtual models. In the first model the gravity model is applied to locate the distribution centers where the vaccines are temporarily store before being delivered to the vaccination points. In the second model, instead, the criterion of the service distance, in other words the response time to deliver the vaccines, is applied to locate the distribution centers.

The result of the investigation will help visualize the applicability and practicality of algorithms regularly studied in industrial engineering when they are applied to real-world sanitary problems. The comparison between two models will allow quantify the cost of leaning toward one or another model when designing and planning a vaccination campaign. In both cases the main requirement is the complete satisfaction of the demand, *id est*, the supply of doses for all the target population.

1.1 Objective

Analyze and compare different approaches for planning and implementing vaccination campaigns by means of designing and implementing virtual supply chain simulation models using different criteria such as the gravity model and the service distance, or response time, to locate the distribution centers for temporary storage.

2. Literature Review

2.1 Gravity Model

In operations research the center of gravity method is a mathematical technique used to locate a centroid that minimizes transportation costs considering the location of the demand (markets), the volume of products being shipped to these markets, and the transportation costs (Ivanov et al. 2019). The coordinates of the centroid o center of mass can be calculated as follows:

$$coordinate\ x = \frac{\sum_i d_{ix} Q_i}{\sum_i Q_i}$$

$$coordinate\ y = \frac{\sum_i d_{iy} Q_i}{\sum_i Q_i}$$

where d_{ix} = coordinate x of location i
d_{iy} = coordinate y of location i
Q_i = quantity of goods transported from or to location i

2.2 Service Distance

An alternative to the gravity model for determining the centroid location is the criterion of the responsiveness. In this case the volume of the demand or markets is not relevant, only their locations are considered. Although it might not be the most efficient alternative, this method will provide a limited response time to reach any of the markets as they are equidistant from the centroid (Figure 1).

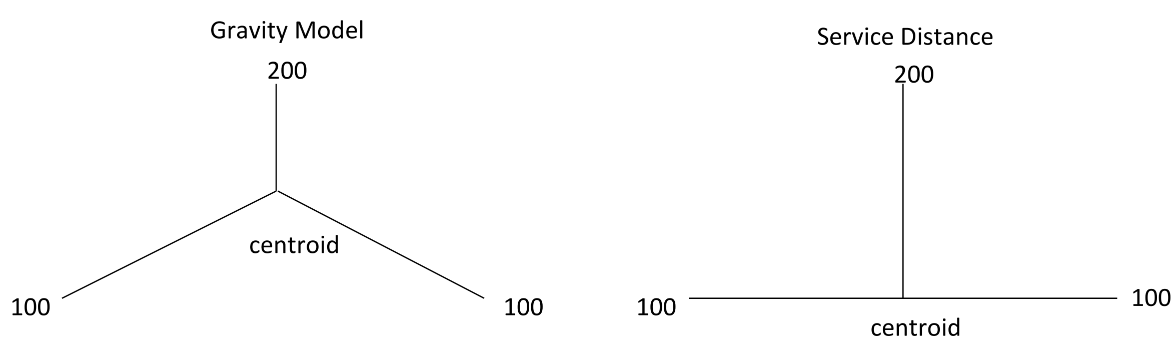

Figure 1. Centroid location

While the gravity model focuses on the efficiency, this approach does it on the responsiveness (Figure 2).

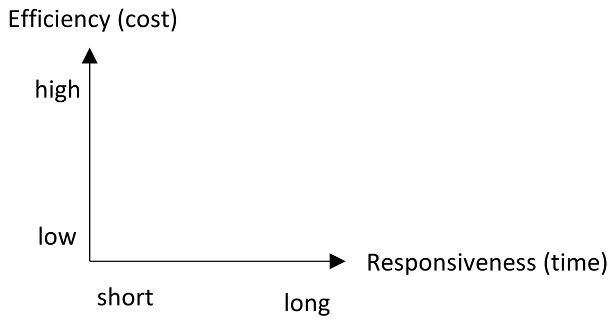

Figure 1. Efficiency and responsiveness

3. Methods

The present work is carried out following a classic 4-stage methodology (Figure 3).

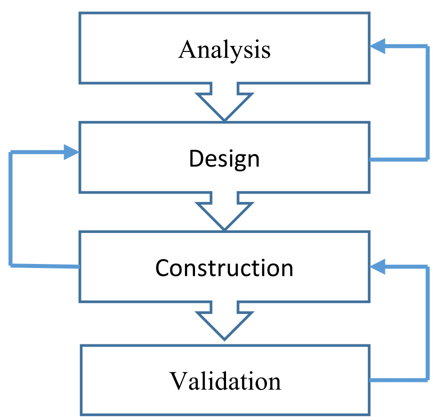

Figure 3. Four-stage methodology

During the analysis diverse sources of information are reviewed to estimate supply chain costs, geographic distribution of the population to be immunized, vaccine transportation requirements, and to select a suitable software for the simulations, which in this case is the academic version of anyLogistix PLE.
During the design, the requirements and approach to develop the chain supply models were defined along with the KPIs to compared them afterwards. Operational considerations such as lead time, number of shipments during the campaign, number of distribution centers (DC) and their inventory policy, capacity and transportation speed of the vehicle fleet, and the location of vaccination points are also defined at this moment.
Since a vaccination campaign is expected to make full use of all resources of the public health infrastructure, both vaccines' storage and vaccination itself will take place at public health center, therefore no inventory costs at DCs will be considered.
The following two assumptions will be applied during the investigation:

- the vaccination campaign has a duration of eight weeks, and
- the immunization will consist of only one dose.

To simulate the prioritization of high-risk groups such as elderlies, chronic patients, medical personnel, paramedics, and schoolteachers, every week a fixed percentage of the population receives the vaccine at a specific vaccination point according to a predefined schedule (Table 1).

Table 1. Stratified 8-week vaccination plan

Week	% of population

1	5
2	5
3	10
4	10
5	15
6	15
7	20
8	20

The construction of all models was completed entirely using anyLogistics PLE. At this moment, all the characteristics of the supply chain models are implemented. For both models several simulations were carried out to adjust and fine-tune the supply chain. Among others, it was necessary to define:

- Location of vaccination points and weekly vaccine demand.
- Location of distribution centers and their inventory policy. Even though arbitrary, five DCs were defined for both models.
- Capacity and travelling speed of the distribution vehicles.
- Transportation costs per kilometer.
- Allocation of vaccination points to each DCs, *id est*, the sourcing policy.
- Number of shipments during the campaign.
- KPIs to measure the effectiveness of the proposed supply chains.

The basic configuration of the supply chain to carry out the vaccination campaign consists of three echelons: supplier, distribution centers and vaccination points. The supplier is supposed to be a centralized source of vaccines, DCs are the temporary storage facilities, and the vaccination points are the places where the people's immunization will take place (Figure 4).

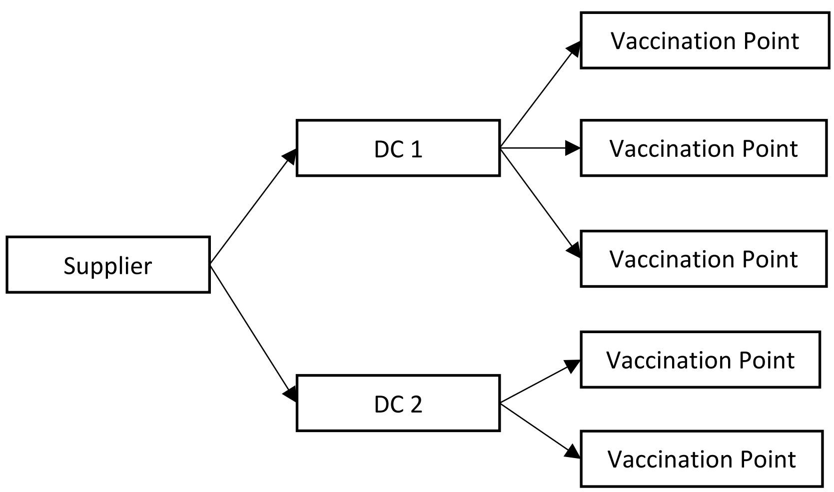

Figure 4. Three-echelon supply chain model

During the stage of validation, KPIs and summary tables are used to verify the quantity of doses delivered from the supplier to every DCs and from there each of the vaccination points, and to assure DCs are supplying their previously allocated vaccination points, which is the result of applying an optimization algorithm.

4. Data Collection

For the purposes is this investigation and due to the limitations of the simulation software's academic version only twenty vaccination points were considered, each located at the largest cities of central southern Chile (Figure 5). One of the reasons for selecting this specific region is the availability of an extensive road network so different distribution routes can be tried and compared. The vaccination plan was defined considering actual Chile's population (Table 2).

Figure 5. Twenty vaccination points (blue points)

Table 2. Vaccination points (cities), population, and weekly demand

City (Vaccination point)	Population	Weekly Demand							
		1	2	3	4	5	6	7	8
		5%	5%	10%	10%	15%	15%	20%	20%
Rancagua	235,849	11,792	11,792	23,585	23,585	35,377	35,377	47,170	47,170
San Fernando	75,329	3,766	3,766	7,533	7,533	11,299	11,299	15,066	15,066
Rengo	63,820	3,191	3,191	6,382	6,382	9,573	9,573	12,764	12,764
Machalí	58,209	2,910	2,910	5,821	5,821	8,731	8,731	11,642	11,642
Talca	239,317	11,966	11,966	23,932	23,932	35,898	35,898	47,863	47,863
Curicó	150,024	7,501	7,501	15,002	15,002	22,504	22,504	30,005	30,005
Linares	91,372	4,569	4,569	9,137	9,137	13,706	13,706	18,274	18,274
Maule	71,691	3,585	3,585	7,169	7,169	10,754	10,754	14,338	14,338
Constitución	51,412	2,571	2,571	5,141	5,141	7,712	7,712	10,282	10,282

Concepción	228,779	11,439	11,439	22,878	22,878	34,317	34,317	45,756	45,756
Talcahuano	179,670	8,984	8,984	17,967	17,967	26,951	26,951	35,934	35,934
San Pedro	153,562	7,678	7,678	15,356	15,356	23,034	23,034	30,712	30,712
Coronel	120,729	6,036	6,036	12,073	12,073	18,109	18,109	24,146	24,146
Hualpén	114,833	5,742	5,742	11,483	11,483	17,225	17,225	22,967	22,967
Chiguayante	104,382	5,219	5,219	10,438	10,438	15,657	15,657	20,876	20,876
Tomé	55,760	2,788	2,788	5,576	5,576	8,364	8,364	11,152	11,152
Penco	52,695	2,635	2,635	5,270	5,270	7,904	7,904	10,539	10,539
Chillán	182,622	9,131	9,131	18,262	18,262	27,393	27,393	36,524	36,524
San Carlos	53,815	2,691	2,691	5,382	5,382	8,072	8,072	10,763	10,763
Los Ángeles	202,214	10,111	10,111	20,221	20,221	30,332	30,332	40,443	40,443

As aforementioned, two approaches for designing the supply chain were considered. In the first one, the location of the distribution centers to store temporarily the vaccines was based on the gravity model (Figure 6).

Figure 6. DCs location (red points) based on the gravity model

In the second supply chain model, the service distance was the criterion to locate the distribution centers despite the number of patients at each vaccination point (Figure 7).

Figure 7. DCs location (red points) based on the service distance

Both virtual models were configurated and fine-tuned to carry out completely the vaccination campaign in 2 months, shipping vaccines and medical supplies on a weekly basis so that vaccination points are to be restocked 8 times during the campaign. It is assumed that enough vaccines are always available at the supplier when needed and that they are sent to DCs where they are temporarily stored until they are dispatched to the vaccination points.
The impact of each approach on the supply efficiency noticeable.

For instance, the application of the gravity model locates one of the DCs nearby Concepción, largest of the 20 cities and the point of highest demand, which help optimize the transportations costs (Figure 8). It does not occur the same when the service distance criterion is applied (Figure 9). In this case, the DC is located far from Concepción, which means that the volume of the demand is not being considered now, but it is almost equidistant from every city withing a certain range.

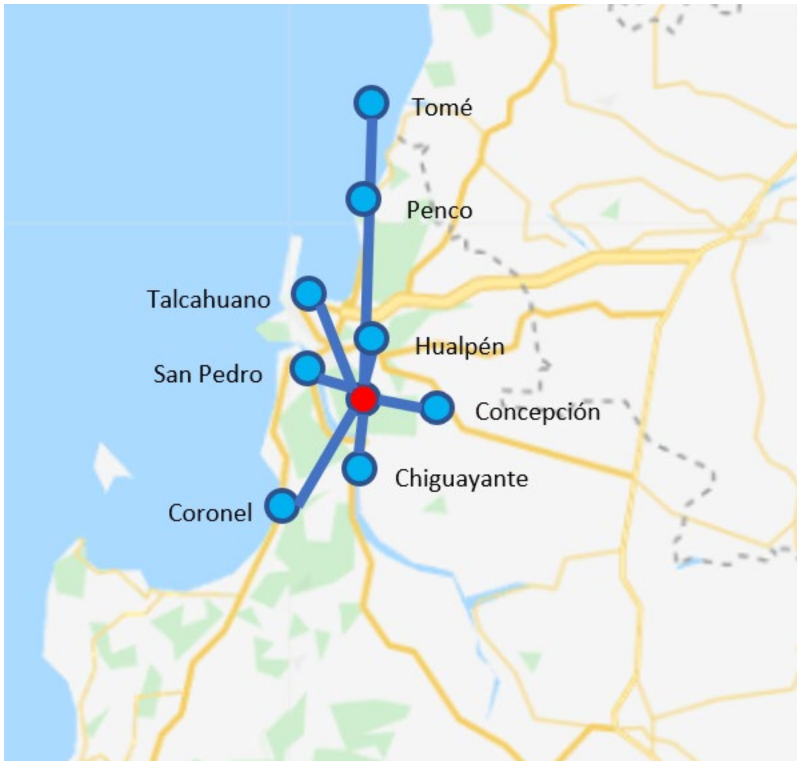

Figure 8. DCs located close to Concepción - Gravity model

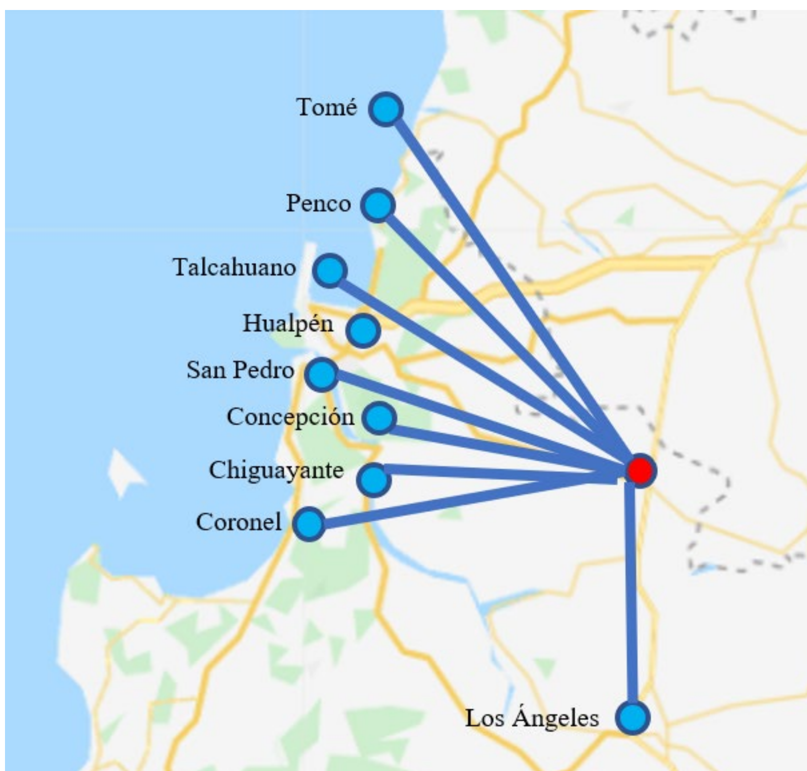

Figure 9. DC located far from Concepción - Distance service

5. Results and Discussion

Simulation results reveal that in the case of the supply chain based on the gravity model, distribution vehicles travel 14,300 km to deliver 2.48 million vaccines, the lead time is 0.33 days, and 8 vehicles are needed. In the case of the supply chain based on the response time, vehicles travel 21,050 km to deliver 2.48 million vaccines, the lead time is 0.83 days, and 13 vehicles are required. In both cases, 5 distribution centers are considered and 100% of the vaccines are delivered on time.

5.1 Numerical Results

The number of doses dispatched to each vaccination point is summarized in Table 3. Both models proved to be equally effective in carrying out the campaign successfully.

Table 3. KPI Vaccines delivered to vaccination points

City	Gravity Model	Service Distance
Chiguayante	104,275	104,275
Chillán	182,597	182,597
Concepción	228,551	228,551
Constitución	51,368	51,368
Coronel	120,599	120,599
Curicó	149,869	149,869
Hualpén	114,725	114,725
Linares	91,288	91,288
Los Ángeles	202,017	202,017
Machalí	58,141	58,141
Maule	71,628	71,628
Penco	52,647	52,647
Rancagua	235,604	235,604
Rengo	63,756	63,756
San Carlos	53,766	53,766
San Fernando	75,244	75,244
San Pedro de la Paz	153,406	153,406
Talca	239,080	239,080
Talcahuano	179,500	179,500
Tomé	55,704	55,704

Even though all vaccines are delivered according to schedule, one model is more efficient in terms of the transportation costs as the fleet needs to travel far less during the vaccination campaign (Table 4). All the results presented here correspond to one 8-week run or simulation. A more detailed research would require several runs to avoid the variation coming from the seed used to generate the pseudorandom numbers incorporated in the frequency of the demand. It must be clear that each weekly demand is the sum of distributed randomly daily demands.

Table 4. KPI Traveled distance

	Gravity Model	Service Distance
Traveled distance	14,272	21,049

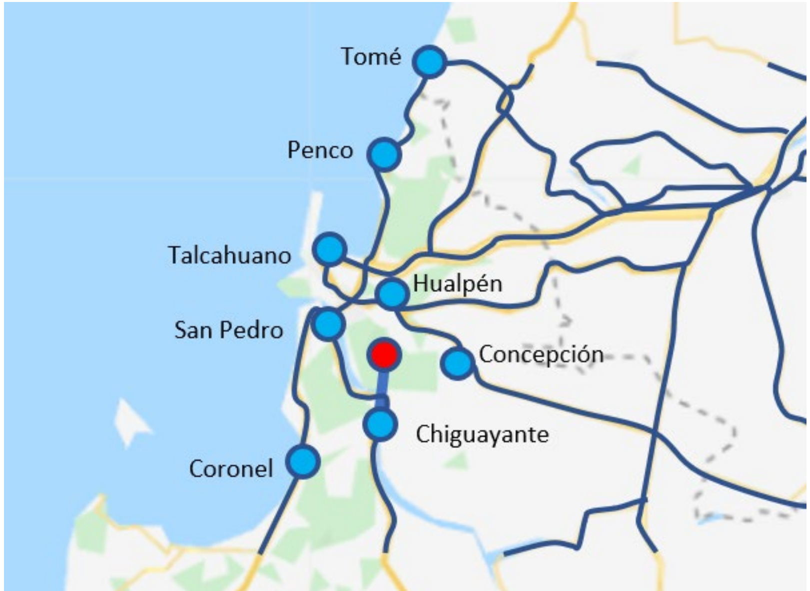

Figure 10. Actual roads and highways used in the virtual models

Although not visually clear from the previous figures, actual roads and highways are considered during the simulations to estimate the traveled distance (Figure 10).

6. Conclusion

This work presented in simple terms the application of optimization algorithms commonly used in industrial engineering and operations research to a real-world problem of crucial importance nowadays. Two distinctive approaches were adopted to model the supply chains and proper performance indicator helped visualized objectively the advantages and disadvantages of each proposal.
In conclusion, even though both proposed supply chain models allowed complete the vaccination campaign successfully, differences were found in their efficiency. The supply chain based on the gravity model proved to be more efficient in terms of transportation costs by a margin close to 30%. Although often laborious, the implementation of virtual models for simulating supply chain models can be useful when planning vaccination campaigns and making decision about resources' allocation.

References

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Biography

Carlos Hernández is an industrial engineer and professor in the Institute of Industrial Engineering at Universidad Austral de Chile, Valdivia, Chile. He earned Licentiate Degree in Engineering from Universidad de La Frontera, Temuco, Chile, Master of Sciences in Computational Engineering and Doctor of Engineering from Technische Universität Braunschweig, Brunswick, Germany. He is the author of several scientific and engineering articles. He has taught lectures in Discrete Event Simulation, Supply Chain Management, Engineering Economics, Corporate Finances, Financial Engineering, Business Analytics, Data Mining and Machine Learning for engineering students. He has developed a professional career working for big multinational companies (PricewaterhouseCoopers, BHP Billiton, and Merck Sharp & Dohme). He also worked as a scientific researcher in the Institut für Produktionsmesstechnik at TU Braunschweig, Germany. His research interests include assembling process techniques, manufacturing process simulation, urban traffic and transportation systems simulation, supply chain design and management, and machine learning for finances. He is a member of IEOM.