Hub Location Problem for Medical Care During Epidemic Outbreaks

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Abstract. This paper presents a proposal for the Hub location for medical care during epidemic outbreaks. A problem of coverage of medical services that offers a radius of medical attention to the population is analyzed. Two criteria are shown for the location of health services. Finally, based on public health policy recommendations, the solution is proposed for a hypothetical case.

Keywords: Facility location · Health systems · Supply chain

1 Literature Review

In the case of a Health system such as that of Mexico that has structural problems and a 70% full supply of medicines, facing a public health challenge such as the COVID-19 pandemic implies making value-added proposals that allow face contingencies like the current one. The design of a resilient medicine supply chain that can serve as a response to unexpected risks in the health system requires the participation of the different agents involved in the supply chain, in addition to the stewardship of the health department that allows the integration of wills and joint actions.

In the framework of an epidemic, it is necessary to guarantee medical supplies (medicines, vaccines, supplies, etc.) in addition to basic products (food, water, etc.). To guarantee the supply and supply of these products, it is necessary to have strategic storage and distribution centers that communicate with the expected demand points in the event of a contingency. It is precisely a problem of designing an emerging logistics network in the face of disruptive events. For this, it is necessary to define the number and location of distribution and collection centers, unloading places and the location of demand centers, and the selection of optimal distribution algorithms that guarantee the best performance of the network. As well as the definition of the required optimal inventory levels, replacement policies, transportation, and distribution according to the health contingency that is being faced.

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For the proper design of a network of this nature, it is necessary to have precise estimates of the demand required according to the contingency. Studies have been carried out combining demand estimation models related to epidemiological models of disease progression. Authors such as [5] propose a multi-objective programming model for the selection of emergency centers and the quantities of drugs to be transported from the supply sources to the demand points. In [14], they extend the vision of multi-objective programming towards a stochastic model using genetic algorithms for its solution. In [6], they integrate the analysis of system dynamics to model the dynamic behavior of the refueling, reception, and dispensing sources in the case of an anthrax attack. In [9], they propose a dynamic optimization model with variable replacement and transport times using heuristic methods for its solution. Other approaches consider logistics network designs with one-time supply and replenishment points [17]. Similarly, there are different versions of the modeling depending on the objective of the network, which can be to minimize inventory and transport costs or to minimize response time as a priority [15] and [19].

Various studies use the hybrid approach where they combine disease modeling through simulation and supply chain design through optimization models, [7] applies this approach to an anti-bioterrorism system. In [18], they analyze the distribution of medical supplies in affected areas considering a desirable minimum level of supply as well as maximum response times in addition to the associated costs. Similarly, vehicle routing problems are integrated into a context of epidemic control, works such as [4,8] and [12] have addressed this problem in their logistics designs.

In [2], they show the development of a coordinated supply chain for the distribution of the influenza vaccine. Taking into account the non-linear demand given the behavior of the disease and the most effective immunization strategies, combining the epidemiological model with the supply chain. In addition to the necessary coordination between the government and the vaccine provider, through shared risk schemes.

The study shows in [13] presents a systematic review of the health and disaster supply chain literature, especially in the case of natural disasters. They highlight the development of methodologies to abort the problem, based on operational management, information technology, inventory and control management, strategic management, and service management. As well as the application of new technologies for inventory management such as the use of RFID.

In [1], they develop a systematic review of relief distribution networks. Highlighting the contributions made about three stages defined in an emergency: a) preparedness and mitigation, b) response, and c) recovery. To attend to each stage, methodological contributions focused on location and network design, transportation (relief distribution and casualty transportation), and location and transportation are distinguished. Through exact and heuristic methods.

In [3], they present a literature review focused on epidemic control and logistics operations. Highlighting as a necessary attribute in the face of a health contingency the need for a quick response and coordination between the sectors involved to guarantee the supply of medical supplies, human and financial resources. Highlighting the time horizon in which you intervene, pre-event, or post-event. Bioterrorism, natural outbreaks, and disaster aftermath are considered as possible catastrophic events. The intervention considers as basic stages: 1) Preparedness, 2) Outbreak, 3) investigation, 4) Response, and 5) Evaluation. Table 1 shows the main logistical operations and decisions during the phases of an epidemic outbreak. The main methods used to analyze the problems associated with the health supply chain are simulation, game theory, mathematical modeling, economic analysis, cost-effectiveness analysis, optimization, and analysis of multi-criteria decisions.

Table 1. Most important logistics operations and decisions during the phases of the outbreak

Phase	Most important logistic operations
Preparedness	Identification of sources Contract management Inventory management Periodical review and updating of medical supplies Facility location of stockpiling centers Network design transportation/distribution Selection of facilities/health Availability of funds
Outbreak investigation	Provision of appropriate materials Training of clinical workers Provision of commodities and resources to the outbreak response Collection, transportation, and storage of specimens Procurement, handling, storing and distribution of laboratory commodities
Response	Selection of facilities (PODs) Review and updating of supplies Transportation/distribution of supplies and commodities Procurement of supplies once depleted Dispensing of medical supplies, supplementary materials, and commodities to the public Establishment of a cold supply chain for essential medical supplies Management of human resources Scheduling available vehicles Adjustments to the capacity of health care facilities to hospitalize infected people Management of patients in triage centers
Evaluation	Identification and assessments of possible bottlenecks of delays Evaluation of timelines that should have been respected Follow-up and monitoring of patients for the effectiveness of treatments Identification of patients requiring dose modification of alternative treatment Development of indicators to evaluate the performance of logistics control operations Assessment coordination issues Establishment and operation of rehabilitation procedures

A recent study by [16] analyzes a reverse logistics network design for the treatment of medical waste, in the framework of the COVID-19 pandemic in Wuhan (China). The study is of great importance due to the identification of a high rate of contagion as well as the residence time of the virus in objects that had contact with infected patients. Rapid response to the management of these wastes represents an opportunity to contain the spread of the epidemic. A multi-objective and multi-period model of mixed-integer programming is proposed for the design of the reverse logistics network.

The challenge is not less considering the complexity in the prediction of epidemic outbreaks, however, based on historical data, it has been possible to adequately model the probability of occurrence and possible scenarios of the magnitude of the problem. Stochastic variables and different simulation approaches must necessarily be included to obtain robust models. From a technical point of view, it is necessary to integrate innovative elements in supply chain management, such as the integration of:

- Multi-paradigm simulation schemes
- Discreet simulation
- Dynamic simulation
- Agent-based simulation
- Optimization algorithms
- Disruption event modeling
- Risk analysis in the supply chain

The use of data science tools, simulation, and optimization methodologies will allow efficient and timely management of the supply chain for medicines and supplies in a contingency. Currently, there is a specialized software that allows integrating different paradigms into hybrid models that allow generating technical evidence for public health decision-making.

2 Resilient Supply Chain Model

In this section, we develop the supply chain design model for a resilient supply network. We consider the model into a generalized network. The model is a mixed-integer linear problem.

Let K be the set of manufacturing plants. An element $k \in K$ identifies a specific plant of the company. Let I be the set of the potential cross-docking warehouses. An element $i \in I$ is a specific cross-docking warehouse. Finally, let J be the set of distribution centers, a specific distribution center is any $j \in J$. Let $\mathbb{Z}$ denote the set of integers $\{0,1\}$.

2.1 Parameters

Q_k = Capacity of plant k.
β_i= Capacity of cross-docking warehouse i.
F_i = Fixed cost of opening cross-docking warehouse in location i.
G_{ki} = Transportation cost per unit of the product from the plant k to the cross-docking warehouse i.
C_{ij} = Cost of shipping the product from the cross-dock i to the distribution center (CeDis) j.
d_j = Demand of the distribution center j.

2.2 Decision Variables

We have the following sets of binary variables to make the decisions about the opening of the cross-docking warehouse, and the distribution for the cross-docking warehouse to the distribution center.

$Y_i = \begin{cases} 1 & \text{If location } i \text{ is used as a cross-docking warehouse,} \\ 0 & \text{otherwise,} \end{cases}$

$X_{ij} = \begin{cases} 1 & \text{If cross-dock } i \text{ supplies the demand of CeDis } j, \\ 0 & \text{otherwise,} \end{cases}$

W_{ki} = The amount of product sent from plant k to the cross-dock i is represented by continuous variables

We can now state the mathematical model as a (P) problem. See [10].

$$\min_{W_{ki}, Y_i, X_{ij}} Z = \sum_{k \in K} \sum_{i \in I} G_{ki} W_{ki} + \sum_{i \in I} F_i Y_i + \sum_{i \in I} \sum_{j \in J} C_{ij} d_j X_{ij} \quad (1)$$

Subject to constraints:

Capacity of the plant

$$\sum_{i \in I} W_{ki} \leq Q_k, \quad \forall k \in K \quad (2)$$

Balance of product

$$\sum_{j \in J} d_j X_{ij} = \sum_{k \in K} W_{ki}, \quad \forall i \in I \quad (3)$$

Single Cross-docking warehouse to distribution center

$$\sum_{i \in I} X_{ij} = 1, \quad \forall j \in J \quad (4)$$

Cross-docking warehouse capacity

$$\sum_{j \in J} d_j X_{ij} \leq \beta_i Y_i, \quad \forall i \in I \quad (5)$$

Demand of items

$$pY_i \leq \sum_{k \in K} W_{ki}, \quad \forall i \in I \quad (6)$$

$$p = min\{d_j\} \quad (7)$$

$$W_{ki} \geq 0, \quad \forall i \in I, \forall k \in K \quad (8)$$

$$Y_i \in \mathbb{Z}, \quad \forall i \in I \quad (9)$$

$$X_{ij} \in \mathbb{Z}, \quad \forall i \in I, \forall j \in J \quad (10)$$

The objective function (1) considers in the first term the cost of shipping the product from the plant k to the cross-docking warehouse i. The second term contains the fix cost to open and operate the cross-docking warehouse i. The last term incorporates the cost of fulfilling the demand of the distribution center j. Constraint (2) implies that the output of plant k does not violate the capacity of plant k. Balance constraint (3) ensures that the amount of products that arrive to a distribution center j is the same as the products sent from the plant k. The demand of each distribution center j will be satisfied by a single cross-docking warehouse i, this is achieved by constraint (4). Constraint (5) bounds the amount of products that can be sent to a distribution center j from an opened cross-docking warehouse i. Constraint (6) guarantees that any opened cross-docking warehouse i receives at least the minimum amount of demand requested by a given distribution center j. Constraint (7) ensures that the minimum demand of each distribution center j is considered. Finally, constraints (8), (9) and (10) are the non-negative and integrality conditions.

3 Case Study

In this section, we describe the case study. In particular, we consider the pharmaceutical supply chain in Mexico. The supply chain is made up of four echelons: two factories, one central-distribution center, three regional-distribution centers and thirty-two wholesale drug distributors. These facilities and clients are scattered throughout the country. Figs. 1 and 2 represent the current structure of the supply chain.

The case study consists of finding a resilient solution that allows the supply chain to react efficiently to a disruption. The distribution centers will be the facilities subjected to hypothetical scenarios of disruption.

Table 2 shows the disruption scenarios considered.

All network diagrams were implemented in cytoscape software, see [11].

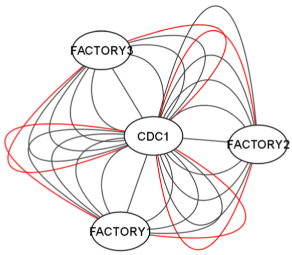

Fig. 1. CDC-Factory links.

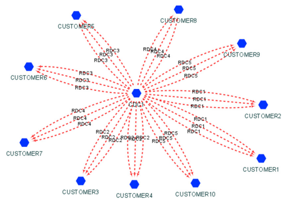

Fig. 2. CDC-RDC-CUSTOMER.

Table 2. Scenarios addressed in the case study

Scenario	Disruption	Breakdown time
I	One factory is closed due to health contingency	45 days
II	One DC is closed	30 days
III	All facilities are closed	15 days

3.1 Solution Methodology

The solution methodology used in this research is based on simulation-optimization. The anylogistix software was used to develop the "what if" methodology. This software uses CPLEX as an optimization engine to find the best solutions within a set of possible solutions. First, the current situation of the pharmaceutical company's supply chain is modeled. Subsequently, the elements or facilities that make up the supply network are optimized. Several operating policies of the chosen supply network are simulated. Finally, disruptive events are generated to test the resilience of the proposals to the previously defined disruption scenarios, see Fig. 3.

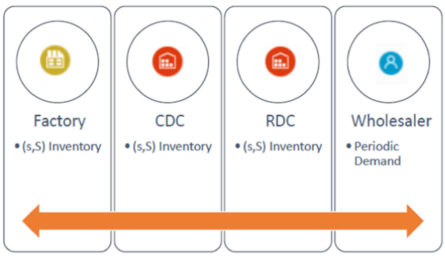

Fig. 3. Inventory policies and demand

3.2 Computational Results

Considering the three different scenarios, it was found that scenarios I and II are those that cause the greatest negative impact on the operation of the supply chain. For this, and for reasons of extension of the document, analysis of results shows the performance indicators for scenario I and scenario II. After running the optimization and simulation routines, the results obtained are as follows.

In the first instance, performance indicators for the current structure of the company were analyzed without disruption. Afterwards, the various scenarios were simulated. The variation experiment function, incorporated in ALX, was used to compare various key performance indicators. Figure 5 shows the current supply chain network structure.

For scenario I, the service level by product, the available inventory of all the facilities and the average delivery time are shown in Figs. 7, 8 and 9, respectively.

Scenario II, see Fig. 2, as mentioned above, was the one with the greatest disruptive effects and it is the scenario that generates less profits. As seen in Fig. 10, the level of service deteriorated to levels of 60% and 40% for each product. Figures 11 and 12, shows the available inventory and lead-time.

Once scenario II has been optimized, see Fig. 4, the results of the key performance indicators are reflected in Table 3. In this scenario, the highest profits are generated with a service level above 95%, see Fig. 13. The available inventory and lead time are shown in Figs. 14 and 15. Finally, the proposal to optimize scenario II is shown in Fig. 6.

Table 3. Key performance indicators of proposal solution

Available inventory	682342.6764	pcs
Demand (Products backlog)	0	pcs
Demand placed (Products) by customer	1061896.722	pcs
Demand received (Products)	2483056.467	pcs
Fulfillment received (Products On-time)	1050395.745	pcs
Fulfillment received (Products)	1421159.745	pcs
Fulfillment shipped (Orders)	393	Order
Peak capacity	989528	pcs
Products produced	1545502.421	pcs
Profit	3.52E+08	USD
Service level by products	0.989169401	Ratio
Total cost	3715253.767	USD
Transportation cost	3715253.767	USD
Traveled distance	41252.88728	km

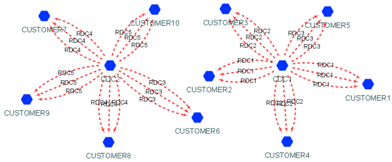

Fig. 4. Several CDCs.

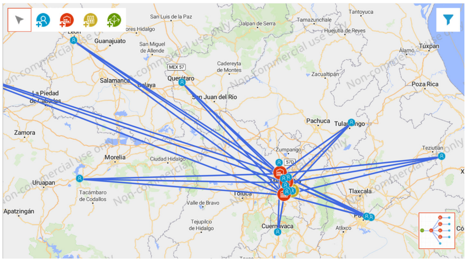

Fig. 5. Current supply chain network.

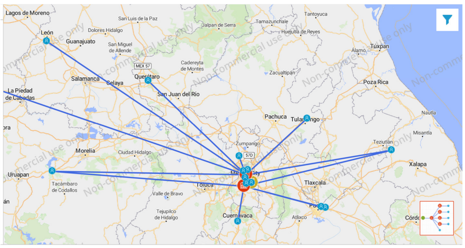

Fig. 6. Supply chain network proposal.

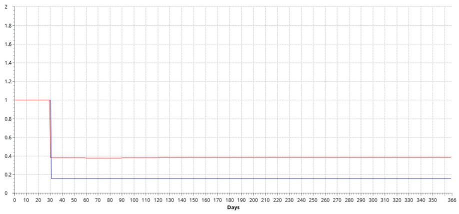

Fig. 7. Service level of Scenario I.

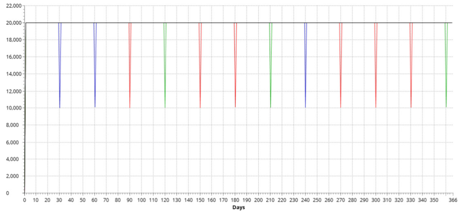

Fig. 8. Available inventory of Scenario I.

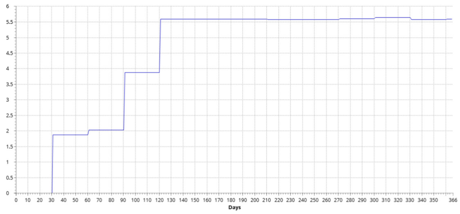

Fig. 9. Lead-time of Scenario I.

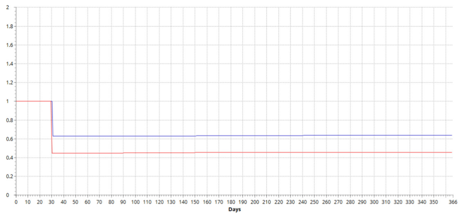

Fig. 10. Service level of Scenario II.

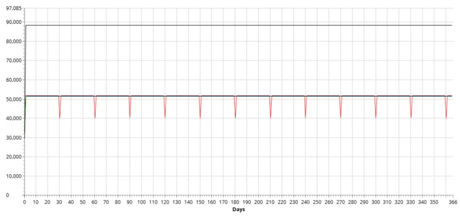

Fig. 11. Available inventory of Scenario II.

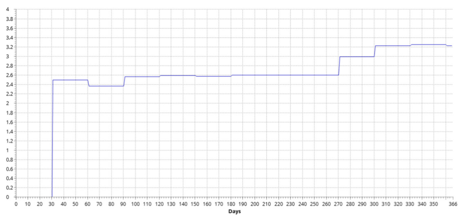

Fig. 12. Lead-time of Scenario II.

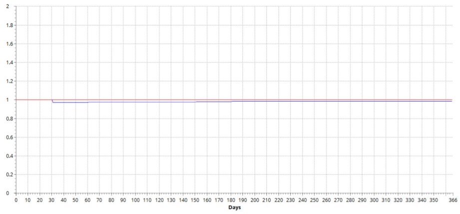

Fig. 13. Service level of Scenario II optimized.

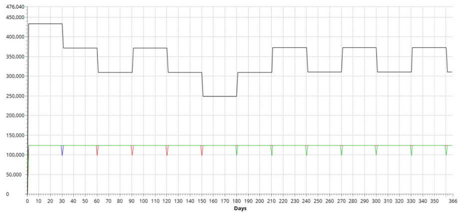

Fig. 14. Available inventory of Scenario II optimized.

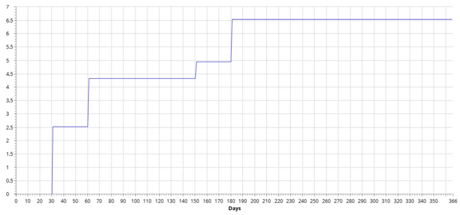

Fig. 15. Lead-time of Scenario II optimized.

4 Conclusions

According to the scenarios outlined for the company, the epidemic outbreak of COVID-19 in Mexico caused several disruptions in the supply chain of medicines.

The solution methodology based on a simulation-optimization approach, allows analyzing the impacts of the different recovery strategies for a subsequent epidemiological outbreak. Additionally, the proposed approach allows enable a comprehensive view of the supply network, as well as fast and efficient responses to risky situations and changing.

Mexico has great health challenges, it is going through a demographic and epidemiological transition where chronic degenerative diseases predominate. The public sector medicine supply chain in Mexico has several structural problems related to the characteristics of the Health System. In 2018, the percentage of a full supply of medications represented 70%, historically maintaining a percentage of prescriptions not filled, which implies that the patient must expend out-of-pocket expenses to acquire their medications or not take treatment.

Starting from this deficient structure of the medicine supply chain in the public sector, facing an epidemic such as the case of COVID-19 represents a very important challenge for the Mexican health system. The present pandemic has represented a significant increase in the demand for public health services. As of April 28, 2020, a total of 77 thousand probable cases were registered in the epidemiological surveillance system, of which 16,752 cases were positive with COVID-19. The crude mortality rate represented 93.3 deaths per 1000 inhabitants, and adults and older adults with some chronic disease are mainly affected.

In this context, the need for a supply chain for medicines and supplies that allows dealing with external events such as a pandemic is evident. For this, it is necessary to take into account innovative concepts of supply chain management, simulation, risk analysis, and optimization. Being able to have robust and efficient designs will allow us to react quickly to a contingency.

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