ASSESSING THE IMPACT OF LEAN AND AGILE SUPPLY CHAIN STRATEGIES ON EFFECTIVE COVID-19-MASS VACCINATIONS

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ABSTRACT – A properly designed vaccine supply chain that uses suitable supply chain strategies can facilitate an effective mass vaccination that minimises COVID-19 infections and deaths. This study assesses the impact of two supply chain strategies which are Lean supply chain strategy and Agile supply chain strategy on effective mass vaccination using a two-stage approach. In the initial stage, we developed an optimal vaccine distribution network under both Lean and Agile supply chain strategies separately, for a selected scenario in Colombo, Sri Lanka. In the second stage, we have developed a Susceptible-Exposed-Infected-Recovered (SEIR) model for COVID-19 which reflects the impact on infections and deaths when using the two different supply chain strategies. Results of this study reflect that a higher percentage of lead time saving can be achieved when using the Agile supply chain strategy. Moreover, when using Agile strategy, a considerable reduction of infections and deaths can be expected for the considered scenario despite a cost accumulation of approximately 32%.

Keywords: supply chain strategy; lean vs. agile; COVID-19; vaccine distribution; SEIR model

1. INTRODUCTION

As an effective response for COVID-19 pandemic, most countries in the world stepped into mass vaccination programs. The success of mass vaccination is achieved when a considerable population in the country is immunised as fast as possible to exit from the pandemic [1]. Across the vaccine supply chain, maintaining speed and the flexibility of vaccine distribution is highly challenging. As a solution, the design phase of the vaccine supply chain should be focused on developing an effective distribution process that supports faster vaccine rollouts [2]. Further, it is important to identify optimal strategies for critical vaccine distribution specially in an adverse economic situation where the existing resources should be carefully utilised. There are different supply chain strategies that can be used to design the vaccine supply chain [3]. In this study we have considered the impact of 'Lean supply chain strategy' and 'Agile supply chain strategy' when designing a vaccine distribution network that supports faster vaccine rollout which will eventually minimise COVID-19 infections and deaths. The Lean supply chain strategy is focused on reducing costs and wastages while meeting the customer needs. On the other hand, the Agile supply chain strategy is a strategy that focuses on flexibility and faster responses to customer demand [4].

Several studies have considered mathematical modeling to design the optimal vaccine distribution network. The study of Lim et al.[5] has developed a mixed integer mathematical model to redesign a vaccine distribution network. In the study of Chen et al.[6], the authors have introduced a mathematical programming model as a planning tool for vaccine distribution. Moreover, the study of Sah et al. [7] has assessed the impact of accelerated vaccine rollouts on improving immunisation of populations. Amidst a pandemic, uncertainties and complexities in vaccine supply chains are inevitable. According to Lee [3], seeking the suitable supply chain strategy works as an 'uncertainty framework' that manages different levels of uncertainties. In the study of Goldsby [8], the trade-offs of lean and agile supply chain strategies are discussed considering a simple supply network. However, the existing studies have not paid attention on impact of different supply chain strategies on vaccine distribution. In our study, we have focused on connecting the optimal vaccine distribution under two affluent supply chain strategies namely Lean and agile, with the response of vaccination which is minimising infections and deaths.

2. MATERIALS AND METHODS

We have considered a simple vaccine supply chain scenario in Colombo District, Sri Lanka which includes one national level vaccine storage, 10 divisional level storages and 20 vaccination points that administer vaccines to people. Colombo district has a population of more than 1.6 million and a high population density of 3300 persons per square km, thus the region is highly exposed to the risk of COVID-19. Assuming it takes 9 months to vaccinate 80% of the population who are above 18 years of age, we determined the demand at each vaccine point based on the mentioned population in relevant Medical Officer of Health (MOH) areas. We conducted the study in two stages, where the first stage was focused on developing an optimal distribution network [9]. We developed optimal distribution networks for both lean supply chain strategy and agile supply chain strategy separately. Then, in the second stage we developed a Susceptible-Exposed-Infected-Recovered (SEIR) simulation model for COVID-19 considering the results of the first stage as an input.

In the first stage of our study, the vaccine distribution network was designed optimising the total logistics costs which includes transport costs from storage facilities to vaccine points and storage costs at divisional storages. Under agile supply chain strategy, we designed the vaccine distribution network, in a way that minimises the average lead time of vaccines. We used IBM CPLEX Optimisation Studio and Anylogistix Software to design the optimal distribution network. The objective functions, parameters and constraints are as follows.

Index sets

MS	Main storage, $m \in MS \mid m = \{1\}$
DS	Divisional storages, $s \in DS \mid s = \{1,2,3,\ldots..,10\}$
VC	Mass vaccination center, $v \in VC \mid v = \{1,2,3,\ldots..,20\}$
F	Replenishment frequency, $f \in F \mid \{$daily $(f=0)$, weekly$(f=1)\}$
H	Vehicles, $h \in H$

Parameters

C^T_{msh}	Transport cost per kilometer when using vehicle h, from main storage m to divisional storage s
C^T_{svh}	Transport cost per kilometer when using vehicle h, from divisional storage s to mass vaccination center v
C^S_m	Storage cost at main storage m
C^S_s	Storage cost at divisional storage s
P^T_h	Transport capacity per trip of vehicle h in vaccine doses
P^S_s	Maximum Storage capacity at divisional storage s measured in number of doses
P^S_b	Capacity in number of doses for a box containing vaccines
L^S_s	Minimum safety stock to be maintained at divisional storage s measured in number of doses
R_f	Number of replenishments in the total period at divisional storage s, $f \in F$ $\{if\ f=0, R_0=180 \mid if\ f=1, R_1=36\}$
D_{ms}	Distance from main storage m to divisional storage s
D_{sv}	Distance from divisional storage s to mass vaccination center v
S	Initial supply of vaccine doses at main storage m
K_v	Demand at mass vaccination center v measured in number of doses
t	Total number of days for vaccine distribution

t^* Total number of days that storage costs are considered for

T_{msh} Time to transport vaccines from main storage *m* to divisional storage *s* in vehicle *h*

T_{svh} Time to transport vaccines from divisional storage *s* to vaccination center *v* in vehicle *h*

HT_{ms} Handling time at main storage, when loading vaccines to vehicle *h*

HT_{sv} Handling time at divisional storage and vaccination center per box *b*

Decision variables

Q_{msf} Quantity of vaccine doses flow from main storage *m* to divisional storage *s*

Q_{sv} Quantity of vaccine doses flow from divisional storage *s* to mass vaccination center *v*

Model for cost minimization

Minimize logistics cost (Z) = $\sum_m \left(S - \sum_1^{R_f} Q_{msf}\right) C_m^S + t^* \sum_s \left(Q_{msF} - \sum_1^{t/R_f} Q_{msf}\right) C_s^S + R_f \sum_m \sum_s D_{ms} Q_{msf} \frac{C_{msh}^T}{P_h^T} + R_f \sum_s \sum_v D_{sv} Q_{sv} \frac{C_{svh}^T}{P_h^T}$

Model for lead time minimization

Minimize total lead time (T) = $\sum_m \sum_s \frac{Q_{msf}}{P_h^T} (T_{msh} + HT_{ms}) + \sum_s \sum_v Q_{sv} \left(\frac{T_{svh}}{P_h^T} + \frac{HT_{sv}}{P_b^S}\right)$

The constraints of the model can be identified as follows.

$\sum_m \sum_s Q_{msf} <= S_m$	For all m	The flow from the MS to DSs should be less than or equal to the initial supply
$\sum_m \sum_s Q_{msf} >= \sum_s \sum_v Q_{sv} + L_s^S$	For all s	The flows from MS to DS should be higher than or equal to the sum of flows from DS to VCs and minimum safety stock at each DS
$\sum_m \sum_s Q_{msf} <= P_s^S$	For all s	The flows from MS to DS should be less than the maximum capacity of DS s.
$\sum_s \sum_v Q_{sv} = K_v$	For all v	The flows from DS to VC should be able to satisfy the demand at each VC.

In the second stage we modeled the exposed, infected, recovered, and deceased populations using Anylogic simulation software. The parameters for the SEIR model were obtained using sources such as Our world in data, John Hopkins University Coronavirus Resource center, Department of census and statistics and Ministry of Health-Sri Lanka, [1].

3. RESULTS AND DISCUSSION

3.1. Optimal vaccine distribution network

According to the results shown in Table 1, when using Lean supply chain strategy, the storage costs are maintained at a minimum level which required daily replenishment of vaccine stocks at divisional storages. Thus, a cost saving can be achieved by using Lean supply chain strategy compared to Agile supply chain strategy. When using Agile supply chain strategy, the divisional level storages are allowed to keep maximum possible vaccine stocks in order to provide the vaccines to vaccine points quickly with a minimal lead time resulting in a lead-time saving. The results in Table 1, shows that the percentage saving of lead time achieved when using Agile strategy is higher than the percentage saving of costs when using Lean strategy.

Table 1. Costs, Lead time and savings when using Agile and Lean strategies

	Lean	**Agile**			**Saving %**
Total transport and storage costs for the period (USD)	2,970,165	3,927,148	Cost saving when using Lean strategy	USD 956,983	32%
Average lead time (hrs)	24.70	16.15	Lead time saving when using Agile strategy	8.55 hrs	53%

3.2. SEIR model reflecting vaccine response

As shown in Figure 1, SEIR model for COVID-19 simulates the susceptible, exposed, infected, recovered, and vaccinated populations for the considered period of time using System Dynamics simulation technique.

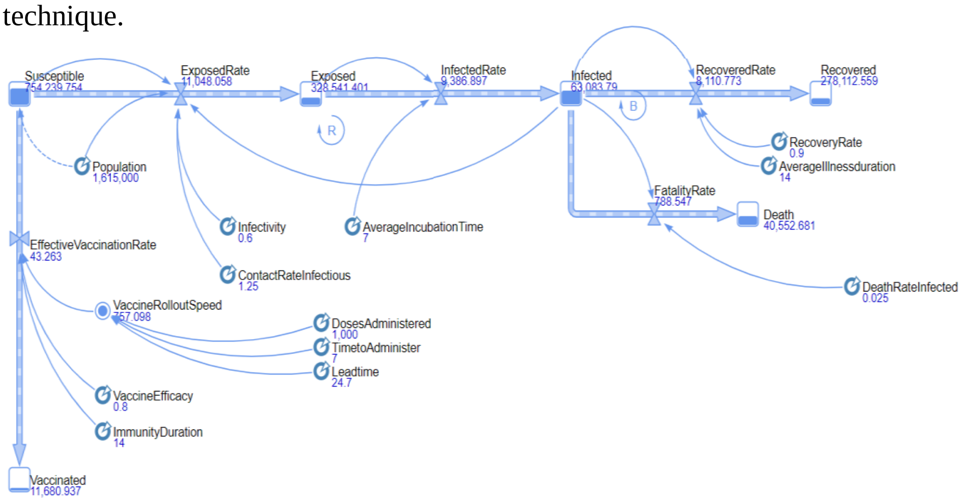

Figure 1. SEIR model for Covid-19

Table 2. Results of the SEIR model

Type of Population	When using Lean strategy	When using Agile strategy	Reduced amount when using Agile strategy	Increased amount when using Agile strategy
Infected	63084	62585	498	-
Deaths	4553	4217	336	-
Recovered	275809	278113	-	2303
Vaccinated	11681	15995	-	4314

The Table 2 shows that when using the Agile supply chain strategy, the infected population has reduced by 498 and the deaths have reduced by 336 when compared to the Lean strategy which is a very encouraging impact. Also, when using Agile supply chain strategy, the recovered population and vaccinated population has grown by 2303 and 4314 respectively.

4. CONCLUSION

From this study it is evident that having a properly planned vaccine supply chain using a suitable supply chain strategy can have a favourable impact on mass vaccinations. The results of our study reflect that

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Agile supply chain strategy is more suitable for vaccine distribution in Colombo, as it reduces the lead time of vaccines supporting faster rollouts which minimises infections and deaths. The study can be further extended to analyse the situation in the face of supply chain disruptions at storages that result in reducing the storage capacity.

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