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A Simulation-Optimisation Approach to Assess the Impact of Covid-19 Movement Control Orders on Supply Chain Resiliency

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Abstract

The Covid-19 pandemic has impacted economies worldwide, particularly the supply chains (SCs) of various industries. This research was aimed at investigating the impact of the Covid-19 pandemic on the manufacturing SC in Malaysia. The study employed an optimisation model to simulate the effects of various movement control orders (MCOs) on the SC. Through an analysis using the SC disruption simulation model, it became evident that an optimal recovery plan depends largely on both the recovery duration and manufacturing capacity. The longer the recovery duration, the longer the optimal recovery plan that is needed if the manufacturing capacity is not considerable. Moreover, the number of backorders and sales lost will increase as well if the disruption cannot be recovered within a short period of time. Based on the simulation results, some suggestions have been proposed to mitigate the impact of an adverse disruption and strengthen the SC. These include having emergency stock to prevent stock-outs and utilising inventory strategies to overcome the issue of raw material shortages. In addition, manufacturers can reduce the total cost of recovery by adjusting the optimal manufacturing capacity to ensure customer demand can be met with minimal losses.

Keywords
Supply chain; Covid-19; Movement control order; Simulation-optimisation.

1. Introduction
A supply chain (SC) is defined as a network of organisations and their suppliers to produce and distribute a specific product to the final purchaser. This network involves a range of operations, individuals, organisations, knowledge, and services. The SC often reflects the steps taken to get the product or service from its original state to the consumer (Donne, 2012; Ganeshan & Harrison, 1995; Gupta, 2014; Kenton, 2020). The SC is effectively a major tool that enables a company to save on costs and stay competitive in a business (Kenton, 2020). According to Janvier-James (2011), a SC plays an important role in improving the efficiency of a business. This is because it facilitates processes such as production, trade, transport, and supplies worldwide.

During the Covid-19 pandemic, the demand for healthcare products increased dramatically, causing drastic shortages in healthcare products from around the world and disruptions to the medical SC. Therefore, the effect of the pandemic on the SC was unpredictable. Moreover, this pandemic led to a drop in productivity as people failed to perform in their respective companies and industries. This was because employees, especially those working in production lines, were unable to work as a consequence of the measures that were taken to prevent the spread of the disease; such as social distancing and closure of industrial facilities (Aday & Aday, 2020). Deliveries were also interrupted due to the movement control orders (MCOs).

Computer simulation is an effective method for assessing complex structures. These tests are generally based on answers to "what if" questions. The popularity of computer simulation has also been applied to answer “how-to” questions in recent years. "What if" questions include responses to such output indicators for a given set of values for the decision variables of a system. On the other hand, "How-to" questions seek optimal values for the decision variables of a system so as to maximise or minimise a given response or answer vector (Azadivar, 1992, 1999; Gavanelli et al., 2012). These decision variables may be quantitative variables; such as the number of machines required for a production line or the inventory level at a warehouse. A simulation-optimisation problem is an optimisation problem where the objective function and some constraints are responses that can only be evaluated by computer simulation (Azadivar, 1999; Gavanelli et al., 2012).

This research was aimed at investigating the effect of the pandemic on Malaysian manufacturing SCs. Besides that, the impact of the pandemic on the SCs of the manufacturing industry during the MCO was analysed through a simulation-optimisation method using LINGO. From the results of the simulation, some managerial insights have been proposed to overcome the impact of a pandemic.

Manufacturing and supply networks in most sectors were affected by the pandemic and the mitigation steps adopted by states, businesses, or health systems (Wuest et al., 2020). Manufacturers also faced challenges from social distancing, where they had to arrange for their employees to be kept at a distance of six feet (1.5 metres) from each other and be on the alert for employees who were sick or under quarantine (Wuest et al., 2020). Two key factors play an important role in SC management, namely production and delivery, which are also connected to the healthcare industry (Majid, 2020). Majid (2020) demonstrated that these two factors are highly dependent on humans to control the machines used in the steps of production. Meanwhile, delivery is important to ensure that the goods are received by the people and organisations. However, these two factors proved to be a huge challenge during the pandemic.

2. Methodology

This section will describe the research method that was employed to achieve the objectives of this research. A simulation-optimisation method was employed to modify the SC disruption during the pandemic. As a result, it was decided to use nonlinear programming to create a simulation model. Nonlinear programming is a mathematical modelling technique that involves minimising or maximising a nonlinear objective function, subject to bound constraints, linear constraints, or nonlinear constraints that can be unequal or equal (Sobel, 2012). Therefore, LINGO 12.0 was used to create a simulation of a SC disruption during the pandemic. Through LINGO, the relationship between the optimum recovery plan, recovery duration, manufacturing capacity, backorders (Bq), and sales lost (Lq) was determined. Some suggestions were then formulated from the simulation analysis as to how this scenario could be overcome.

3. Results and Discussion

3.1 Optimisation Simulation

In this study, a two-stage production and inventory system consisting of a manufacturer and a retailer was considered. The manufacturer produces a product and maintains its inventory, and thus, follows the economic production quantity model, while the retailer only maintains inventory and follows the economic order quantity model. As mentioned before, the mathematical modelling was modified from the model of Hishamuddin et al. (2014). It is assumed that a random supply disruption occurs during a cycle that disables the production from running as scheduled. After the disruption occurs, a specified duration, known as the recovery time window, is allocated for recovery. Like other DM models, the term recovery is defined as restoring the original production schedule within a short time period, while minimizing the relevant costs. The objective of the model is to determine the optimal recovery schedule that consists of the manufacturing and ordering batch sizes for the manufacturer and retailer, as well as the optimal recovery duration, so that the expected total cost isminimized. The model can be classified as a constrained nonlinear programming model and is solved using LINGO. The parameters used in this paper are listed in Tables 1 and 2 below.

Table 1. The decision variables of the model.

Parameter	
n	Number of cycles in the recovery window
z	Number of optimal productions lost in the recovery window

Table 2. The parameters and notations used in the model.

Parameter	
q	Pre-pandemic production quantity in a cycle
A_1	Setup cost of Stage 1 (RM/setup)
A_2	Ordering cost of Stage 2 (RM/order)
H_1	Annual inventory cost of Stage 1 (RM/unit/year)
H_2	Annual inventory cost of Stage 2 (RM/unit/year)
P	Production rate (units/year)
D	Demand rate (units/year)
B_1, B_2	Backorder cost per unit per time in Stages 1 and 2 (RM/unit/time)
L_1, L_2	Cost of sales lost per unit in Stages 1 and 2 (RM/unit)
C_t	Transportation cost
f_1	Penalty for a delay in recovering to the original schedule in Stage 1
f_2	Penalty for a delay in recovering to the original schedule in Stage 2, handled by Stage 1
f_3	The penalty for a delay in recovering to the original schedule in Stage 2
W	Warehouse capacity in Stage 2 (units)
S_t	Setup time per cycle
Q	Number of units produced in the original schedule
B_q	Number of backorders
L_q	Number of sales lost
Tc	Total cost (RM)
Q_1	Number of units produced in Stage 1 in the original schedule (units)
Q_2	Number of orders in Stage 2 in the original schedule (units)
T_d	Disruption duration
u	Production downtime in a normal cycle
t_e	Start of recovery window
t_d	End of recovery window
T	Production cycle duration in a normal cycle (*Q/D*)
T_{1i}	Stage 1 production cycle duration during the recovery window
T_{2j}	Stage 2 production cycle duration during the recovery window
m	Number of sales lost in the recovery window
I_i	Inventory at the end of the cycle in the recovery window

The first stage's average total cost for the recovery plan is represented as follows:

$$TC_1(X_i,n,z) = \left[\frac{(A_1\cdot(z)) + \left(H_1\left(\frac{1}{2P}q^2 + qT_d + \sum_{i=1}^{z}\left(I_{i-1}+\frac{1}{2}X_i\right)\cdot\frac{X_i}{P}\right)\right) + f_1\left(n^2\right) + f_2\left(n^2\right)}{nT}\right] + B_1\left(u+\frac{q}{P}+T_d+\frac{X_1}{P}-\frac{Q}{D}\right)\left(\frac{Bq}{2}\right) + (L_1(Lq)). \quad (1)$$

The total relevant costs of the recovery plan for the second stage is:

$$TC_2(S_i,n,z) = \left[\frac{(A_2\cdot(z-1)) + \left(\frac{H_2}{2D}\left(Q^2+(S_1-Bq)^2+\sum_{i=2}^{z-1}S_i^2\right)\right) + f_3\left(n^2\right)}{nT}\right] + \left(B_2\left(u+\frac{q}{P}+T_d+\frac{X_1}{P}-\frac{Q}{D}\right)\left(\frac{Bq}{2}\right)\right) + (L_2(Lq)). \quad (2)$$

The optimal recovery plan is obtained by solving the following mathematical problem, which minimizes the total cost of recovery for the two-stage system:

$$Min\ (TC) = TC_1 + TC_2 \quad (3)$$

Subject to the model's constraints.

It is empirical to note that the manufacturing capacity of the production line was modified based on the respective MCO phases. Table 3 lists the manufacturing capacity at each phase of the pandemic:

Table 3. The manufacturing capacity at each phase of the pandemic.

Phase	Start Date	Duration (Days)	Manufacturing Capacity
MCO	18 Mar 2020	54	20%
Enhanced MCO (EMCO)	11 May 2020	21	12%
Conditional MCO (CMCO)	1 Jun 2020	30	50%
Recovery MCO (RMCO)	1 Jul 2020	184	90%

Tables 4, 5, 6, and 7 present the results of the recovery duration of every phase while Figure 3 and 4 plot the results.

Table 4. The *TC* of the MCO recovery duration.

Recovery Duration (n)	***TC***
4	6910130
5	6876888
6	**6844266**
7	7066998

Table 5. The *TC* of the enhanced MCO (EMCO) recovery duration.

Recovery Duration (n)	***TC***
2	**2909644**
3	2909806
4	2920606

Table 6. The *TC* of the conditional MCO (CMCO) recovery duration.

Recovery Duration (n)	***TC***
3	3689300
4	3411976
5	3206719
6	3001691
7	2797483
8	2649750
9	2547648
10	**2482268**
11	2881139

Table 7. The *TC* of the recovery MCO (RMCO) recovery duration.

Recovery Duration (n)	***TC***
10	23282450
11	22660990
12	22040630
13	**21633400**
14	21728950
15	21824840
16	21920030
17	22014610
18	22108700
19	22202370
20	22295680
21	22388690

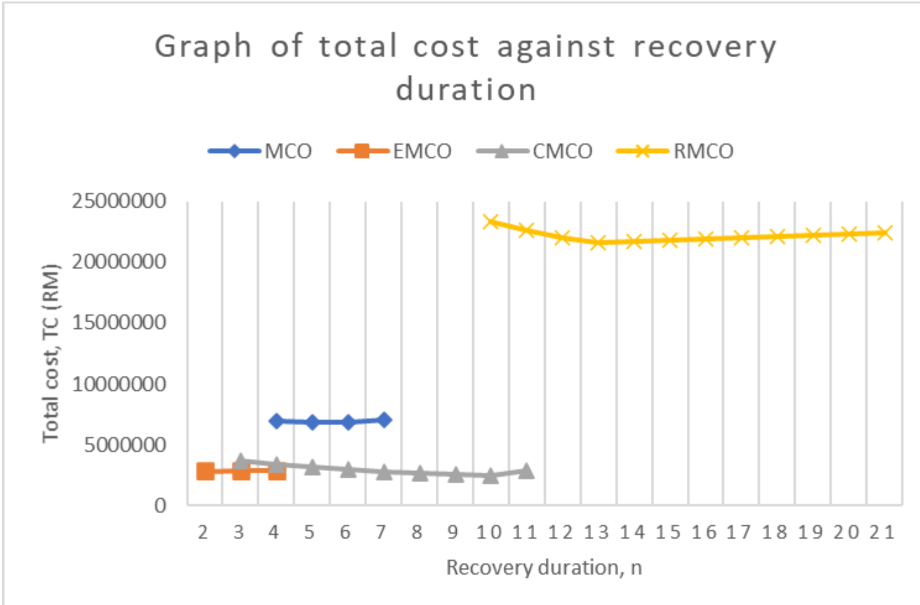

Figure 1. A graph of the *TC* due to the optimal recovery duration.

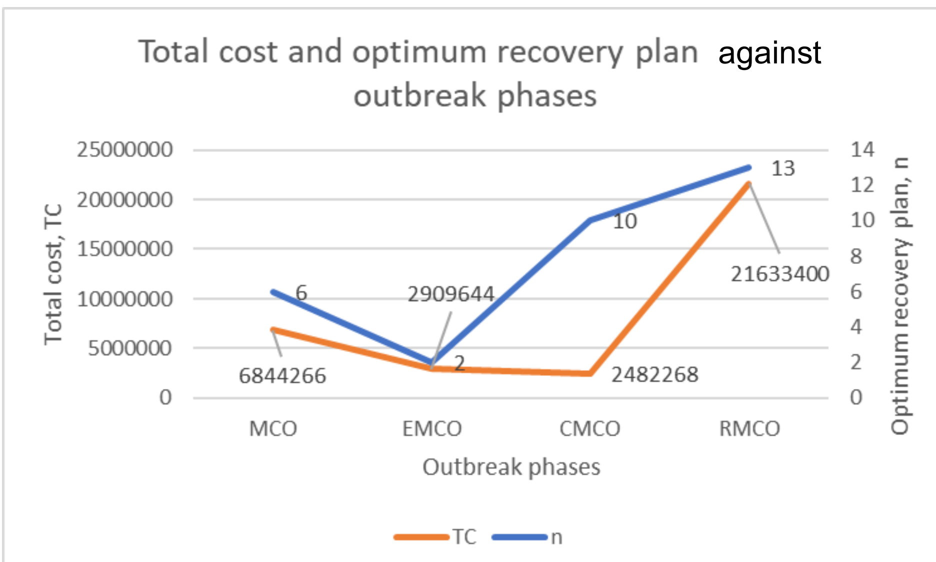

Figure 2. The *TC* and recovery duration due to the phases of the pandemic.

Figure 1 shows the graph of the total cost (*TC*) against the optimal recovery period. Based on the above graph in Figure 2, the EMCO had the shortest recovery duration, and even the manufacturing capacity during this phase was the lowest, while the RMCO had the longest recovery duration, but the manufacturing capacity was the highest among the other phases. The optimal recovery plan was strongly dependent on the recovery duration and the maximum manufacturing capacity. It can be concluded that the longer the recovery duration, the longer the optimal recovery plan that was needed. Therefore, more recovery plans were required when the recovery duration was longer, even though the maximum manufacturing capacity was at its highest. Furthermore, if the manufacturing capacity increased, the *TC* should have decreased. However, as seen in Figure 3, the *TC* continued to increase as recovery duration had a greater impact on the *TC* than manufacturing capacity. When normal production is disrupted, a factory will incur higher costs until production can restart at its previous level. The *TC* of the best recovery plan was mostly determined by the recovery duration and the maximum manufacturing capacity.

Tables 8, 9, 10, and 11 show the number of backorders (*Bq*) and lost sales s(*Lq*) at each phase of the recovery plan while Figures 5 and 6 plot them in line graphs.

Table 8. The *Bq* and *Lq* during the MCO recovery plan.

Recovery Plan, (n)	B_q	L_q
4	3020.52	56157.56
5	4027.36	55150.72
6	5034.20	54143.88
7	3801.84	55376.24

Table 9. The *Bq* and *Lq* during the EMCO recovery plan.

Recovery plan, (n)	B_q	L_q
2	539.33	22474.37
3	1208.20	21805.49
4	1812.31	21201.38

Table 10. The *Bq* and *Lq* during the CMCO recovery plan.

Recovery Plan, (n)	B_q	L_q
3	4366.33	28510.38
4	7551.30	25325.41
5	10068.41	22808.3
6	12585.51	20291.2
7	15102.61	17774.1
8	17116.29	15760.42
9	18727.24	14149.47
10	20016	12860.72
11	17288.83	15587.88

Table 11. The *Bq* and *Lq* during the RMCO recovery plan.

Recovery Plan, (n)	B_q	L_q
10	6223.837	195420
11	12516.59	189127.2
12	18809.35	182834.5
13	23272.29	178371.5
14	23225.86	178418
15	23166.94	178476.9
16	23107.81	178536
17	23048.68	178595.2
18	22989.54	178654.3

19	22930.41	178713.4
20	22871.27	178772.6
21	22812.14	178831.7

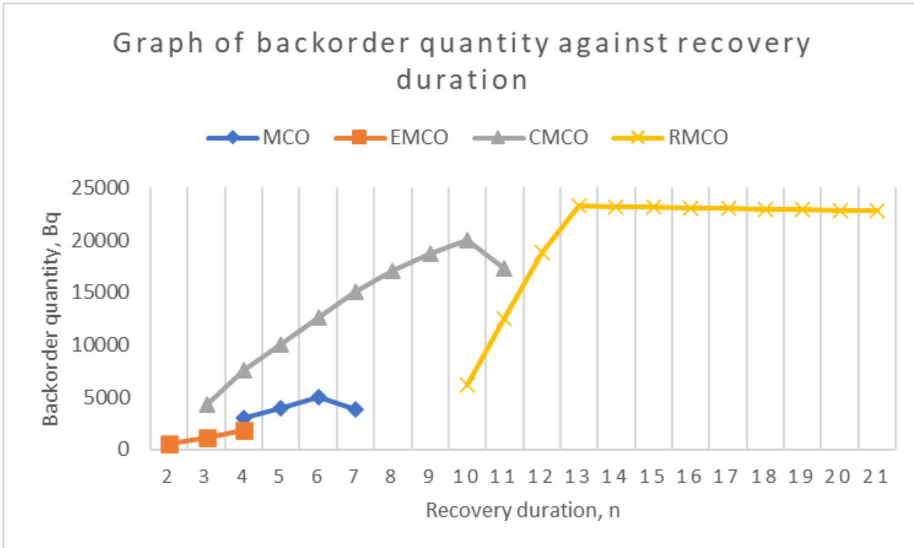

Figure 3. A graph of *Bq* against the recovery duration.

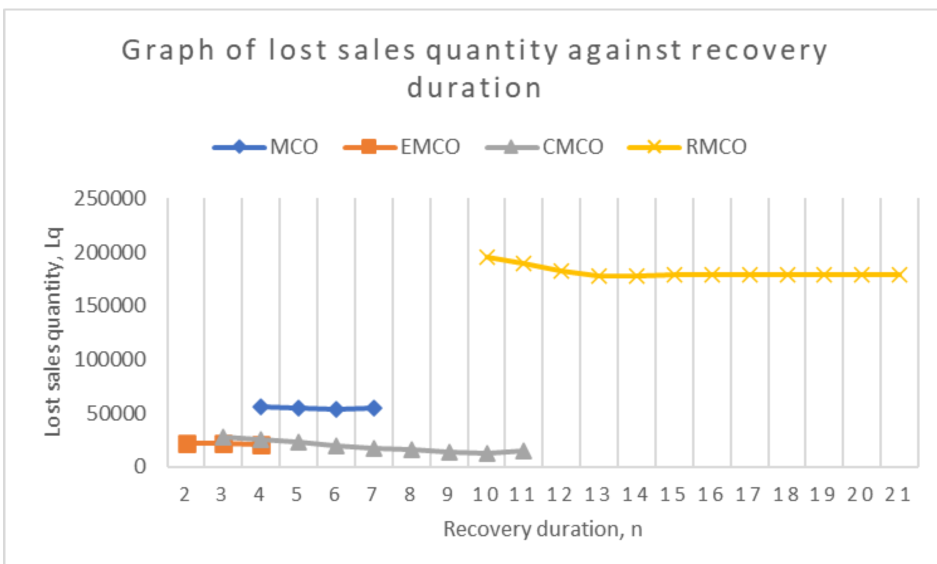

Figure 4. A graph of *Lq* against the recovery duration.

As can be seen in Figure 3, the *Bq* increased as the recovery duration increased, while Figure 4 shows a decreasing *Lq* as the recovery duration increased. When a longer recovery duration is needed, a factory will incur additional losses. As a result of the disruptions by the pandemic, the *Bq* continued to rise until the disruption was fully resolved. This is mainly due to customers preference who choose to cancel their orders instead of waiting for stocks to be replenished. However, from Phases 1 to 4, the *Bq* and *Lq* increased, which was a differed from the *TC* pattern.

The manufacturing capacity was lower during the recovery duration, forcing the companies to deal with the *B* and *L*. When the manufacturing capacity is disrupted, the *B* and *L* will be affected and increase. While customer demands can be maintained by the *B*, the *L* can result in the loss of customers. In contrast, a company will lose its customers as a result of *L*. The recovery duration is critical because *Bq* might become *Lq* if the recovery duration is prolonged.

3.2 Mitigating the Impacts of Supply Chain Disruptions

During the recovery duration, supply and demand will fluctuate. The sudden lack of supply and high demand will cause the SC system to have an out-of-stock issue. Most efforts are focused on two main scenarios: either all the demand during the stockout period is back-ordered, or all the demand during the stockout period is lost forever (Montgomery et al., 1973; Vakharia & Yenipazarli, 2008). According to Thomopoulos (2011), when customers refuse to wait for stocks to be replenished and cancel their orders, it is considered as a loss in sales. There are several suggestions for minimising the effect of stockouts. It is important to have a safety stock in the warehouse in case of an emergency. When the overall demand increases, the manufacturer can run production instantly to provide a better level of service by meeting the increasing demand with stocks and decreasing the back orders from the retailers. It is better to have a guideline from inventory management to balance the amount of supply and demand to prevent overstocking during a pandemic.

Furthermore, the disruption impact to the SC can be reduced by controlling the manufacturing capacity in order to minimise the total recovery costs. Hence, a match capacity strategy is suggested. In this strategy, smaller incremental modifications are made to the manufacturing capacity instead of boosting the demand ahead of time or increasing the demand after the existing capacity is depleted (Paton et al. 2011). This is done in response to changing market conditions. Despite its complexity, most producers will find this to be a safer bet than other capacity-planning strategies because it is considerably more risk-averse. To prevent the scenario of overcapacity and undercapacity, a company can make use of certain software programs such as enterprise resource planning (ERP) and warehouse management systems (WMS) to estimate a suitable capacity during a pandemic.

4. Conclusion

The impact of disruptions to the performance of SCs in relation to Covid-19 during the pandemic was investigated. The SC disruption model revealed that the recovery duration and manufacturing capacity were proportional to the optimum recovery plan and total costs incurred. Although the backorders increased with recovery duration, the lost sales decreased. Therefore, it can be concluded that the longer the recovery duration, the higher the cost that will have to be borne by the manufacturer. Several suggestions have been discussed to overcome this scenario. Manufacturers should have a safety stock in their warehouses to avoid a significant surge in demand. Moreoever, a match capacity strategy can be applied to manage manufacturing and production capacities based on demand during a pandemic.

Future research can be conducted to create simulation models with multi-stage SCs that include suppliers, manufacturers, warehouses, and consumers in order to replicate a more realistic situation. Furthermore, this model can be improved with more than one supplier and retailer to align the SC with reality.

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