

Production Planning and Emergency Inventory for Demand Surge in Healthcare Supply Chains for Pandemics like COVID-19

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Abstract: This research considers modeling production and inventory quantities in the presence of demand surge due to pandemics like COVID-19. The aim of this research is to help health care organizations better prepare and respond to a demand surge due to a pandemic. A large-scale pandemic such as COVID-19 can cause an overwhelming demand for urgent medical supplies in a very short notice. Well-established supply chain planning and modeling are necessary to avoid any national level or company-wide supply chain problems resulting from demand shortages. This paper addresses these issues from supply chain perspective. The need to be prepared for any surge in demand is addressed in terms of emergency inventories, including those of Work-in-Process and finished goods. Linear Programming models are developed to minimize the costs of production, inventories, and transportation of goods from one stage to the next in the supply chain. Several scenarios are tested out for various levels of demand, cost, and capacities.

Keywords: Pandemic, Production planning, Demand Surge

1. Introduction

The spread of Covid-19 pandemic has wreaked havoc all over the world. As of late March 2021, the total number of deaths due to this pandemic is fast reaching 3 million people (Worldometer, 2021). One of the main reasons for such a heavy toll is that this Corona virus is of recent origin, and the scientist and physicians neither knew how to treat the disease nor how to protect against it. In terms of commerce, a major trade entity to get affected was supply chains. A survey of small businesses by the Federal Reserve Bank of Cleveland (2020) shows the extent of disruptions in various sectors, as shown in Table 1.

Table 1. Are You Seeing Significant Supply Chain Disruptions That Are Hampering Your Operations?

	Percent of sector that responded “Yes”			
	March 23–30 (125)	April 17–20 (105)	July 13–20 (112)	October 19–26 (108)
Full sample	32.0	34.3	33.9	35.2
Retail	64.7	61.5	58.8	63.2
Transportation	50.0	25.0	44.4	50.0
Construction and real estate	44.0	57.9	42.9	66.7
Manufacturing	25.0	31.0	27.6	32.1
Other	11.6	16.7	23.3	5.4

Sources: Federal Reserve Bank of Cleveland (FRBC) and the US Census Bureau Small Business Pulse (SBP) Survey.

The disruptions were caused by various factors, such as disruptions of transportation across the continents, quarantine and lockdown of many countries, and unprecedented demand for certain commodities.

Healthcare supply chains faced even worse situation, compared to other supply chains. On the one hand, healthcare supply chains were to supply very essential supplies needed for pandemic, such as Personal Protection Equipment (PPE), equipment needed for hospital’s Intensive Care Units (ICU), sanitizers, etc., and on the other hand, they faced disruptions like other supplies.

The pandemic has exposed the vulnerability of supply chains in almost all the countries. As countries and companies struggle to establish supply chains, or bring them back to normal conditions, there has been a tremendous amount of research and published research on supply chains in parallel. The problems with supply chains and the remedial measures to be taken have been extensively addressed. This paper also addresses some of those issues and develops a mathematical model towards achieving the objective of a certain level of preparedness at minimum costs.

2. Literature Review

The World Health Organization (WHO) defined seven phases of the pandemic diseases, starting from Phase one of “animals’ infection only” to phase seven, which is the post-pandemic phase. These phases are given in Figure 2. The WHO has declared that as of March 2021, COVID-19 is in stage 6 (Red stage in Figure 2). Even though the organization declared COVID-19 as a pandemic in March 2020, and it has been more than a year since then, many of the supply chains continue to be in disarray.

Many articles have been written about supply chain disruption caused by COVID-19, with the remedies suggested at both strategic and tactical levels. Katsaliaki et al. (2020) give a comprehensive survey of papers on supply chain resiliency and offered important suggestions for a resilient supply chain. Zhu et al. (2020) suggest following strategies as diversification and dual sourcing, vertical integration, decentralization of manufacturing facilities, and improving supply chain visibility will reduce the response time to a surge in demand. Sheffi (2020) states that many healthcare supply chains had followed, in recent times followed cost efficient policies of Just in Time and this has hampered their response to the recent pandemic as they did not have any inventories for such contingencies.

International agencies like World Health Organization (WHO) and national agencies like Federal Emergency Management Agency (FEMA) are helping local governments to identify needed supplies and linking them with potential suppliers.

Sheffi (2020) suggested that for hospitals and healthcare suppliers need to always maintain emergency inventories to face any surge in demand during a COVID-like pandemic in future. He discusses the idea of healthcare organizations being

required to keep certain levels of inventory, much like Federal Reserve asking financial institutions to keep certain levels of reserves. Ivanov (2020) coins a new name, viable supply chain, and defines it as one that integrates agility, resilience, and sustainability. Ivanov argued that these viable supply chains should shape the future of healthcare since they are very resilient to demand surge on medical supplies.

There have been quantitative models addressing the design and operational aspects of supply chains for minimizing the effects of disruptions. Johnson et al. (2021) use mathematical and simulation models to design robust and resilient supply chains. Grubbström and Wang (2003) develop stochastic models for designing multi-location production and inventory models. Alsalem et al. (2019) consider the design of multi-echelon, multi-product supply chain for optimizing total costs of manufacturing and transportation.

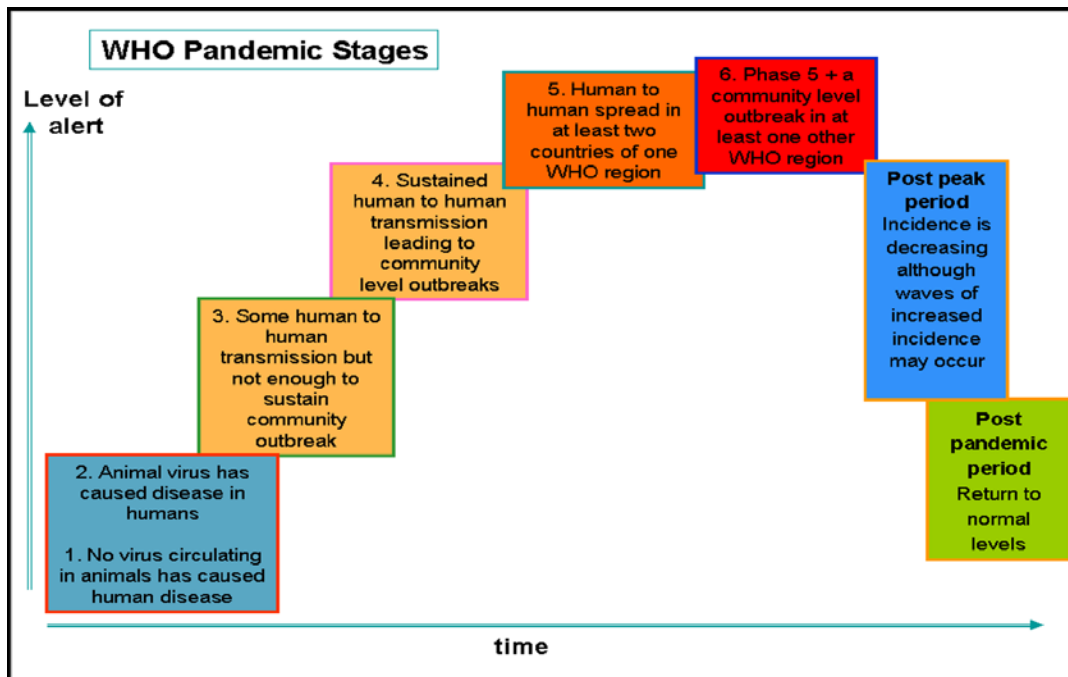


Figure 2. Pandemic stages by WHO

As mentioned earlier, while many industries faced supply chain disruption due to COVID-19 pandemic, healthcare suppliers in particular faced the challenge of responding to the massive surges in the demand for the products. Some of the literature relevant to supply chain challenges to fulfill the surging demands is covered now. Given that demands for medical supplies surge multifold during a pandemic, current supply chains lack the power to rapidly plan to meet the scaled-up demand (Sheffi 2005). Osterholm (2005) mentioned that in addition to the lack of rapid distribution plan during pandemic, a huge employees’ absenteeism was observed for due to illness, fear, transportation problems, and taking care of other sick family members. Consequently, the distribution of critical medical supplies is affected during the pandemic.

3. Development of Mathematical Models

In this section, we first describe some of the strategic and tactical factors that need to be considered when planning for a surge in demand. Then, we discuss two mathematical models that we developed to address the planning level decisions in supply chains.

3.1 An Approach to Meeting Demand Surge

Supply chains need to be prepared for any demand surge in the event of natural disasters and pandemics. In this research, we follow Sheffi (2020) and suggest that it is important for governments and companies to keep inventories so they can face any surge in demand. However, keeping inventory of finished products is very expensive. In addition, having large inventory of finished products will produce a significant amount of waste because all the work in process parts needed to produce the product are already assembled. Hence, companies can only sell those finished products and won't be able to use the work in process parts to manufacture other products that needs those parts. In addition, there are other problems including the need for larger storage space to store finished products and finished products loss of quality. Finished goods inventories are usually more expensive compared to component or raw material level inventories. In this research, we suggest that emergency inventory needs to be spread through the entire supply chain, starting from the raw material stage, all the way to the finished goods.

If a product is going to be stored at various completion stages, then a discussion is needed keeping in view the push/pull interfaces.

3.1.1 Push-Pull Interface

The push-pull interface is where, in any a given supply chain, the product is waiting in the inventory. Until that point, it is pushed, that is it is made to stock, in anticipation of demand. At this interface, it will be pulled downstream based on actual demand. How far this point is, from the end customer, depends on the company's competitive strategy. We will follow the general concepts about this interface to design our supply chains to face demand surge.

If this interface is closer to the customer, that is closer to finished goods stage, the delivery of the product will be faster. On the other hand, the closer the product is to the finished goods, then it will be more expensive to store compared to the product that is inventory upstream. The reasons being certain materials are not yet added, and additional labor charges are not yet accrued to the product. Another disadvantage is that the closer the work in process part is to being a finished good, the less fixable it is to fit into other product types because it is already differentiated as a product. For example, when there is large inventory of large size PPE gowns, and there is a demand for clothes of small size, will render it useless. The product has more potential for modifications and changes, when it is more upstream. Keeping the product closer to raw material stage will help in keeping inventory costs low and improves the flexibility to make any changes to the product. However, keeping the product at such upstream levels keeps the response time very high. There needs to be a good balance between how much back in the supply chain the product needs to be stored to keep low inventory costs and fast response time. In this work, a trade-off between the level of preparation and the incurred costs is required (Lodree and Taskin, 2008).

3.2 Proposed Models

The problem can be stated as, 'Given a known demand surge pattern in the near future, how much storage do we need to store at the different stages of the supply chain?'

The proposed models will use deterministic linear programming for single and multi-facility, multi-stage supply chain networks. The models aim to determine the optimal inventory level of Work-In- Process (WIP) and Finished Goods (FG), shipment size, and production quantity at each stage of the supply chain for each period at each location to meet the demand surge.

Two variations are developed, by adding extra constraints and decision variables to a basic model, to understand and verify the models. Initially, a simple model for a multi-stage supply chain with two decision variables (inventory level and production quantity) is introduced. Then, this model is expanded by adding more decision variables to cover different options and scenarios.

Several assumptions are made to develop these models:

- The demand is deterministic, and it gradually increases over time and then it becomes stable.
- The unit holding cost is deterministic and increases while moving down in the supply chain.
- The unit production cost is deterministic and decreases over time until the demand becomes stable.
- The rest of the parameters are deterministic and fixed over time.
- The lead time for the product to progress from one stage to the next stage is equal and constant along the supply chain.

The following notations are used:

Indices

- n Index for the stage (stage) number $n = 1, 2, \dots, N$
- t Index for the period number (time index) $t = 1, 2, \dots, T$

Parameters

- N Total number of the stages included in the study
- T Length of the planning horizon
- I Total number of supply chain locations
- $h_{n,t}$ WIP unit holding cost at stage n for period t
- $H_{n,t}$ Finished good unit holding cost at stage n for period t
- $C_{n,t}$ Unit shipping cost at stage n for period t
- $p_{n,t}$ Unit transportation cost at stage n for period t

Decision variables

- $W_{n,t}$ WIP inventory level at stage n for period t
- $F_{n,t}$ Finished good inventory level at stage n for period t
- $M_{n,t}$ Shipment size from stage n to stage $n+1$ for period t
- $X_{n,t}$ Production quantity at stage n for period t

A base model is introduced in the following section. The model is then expanded to cover all the objectives of this study.

3.2.1 Model I (Basic Model)

Model I is a general inventory and production planning model. This model helps the managers to better allocate the resources and the workload of the supply chain to satisfy the expected demand. The product must go through several processes (number of stages) before it is shipped to the consumer. These stages may include a part/all of the common supply chain’s stages (suppliers, manufacturers, distributors, retailers, and customers) or several consecutive processes in a manufacturing plant. Figure 3 illustrates model I.

The objective of this model is to minimize the total holding and production cost for a multi-stage supply chain. The purpose of model I is to determine the optimal inventory level and production quantity at each stage of the supply chain, given the unit inventory holding cost and unit production cost. Based on the previous assumptions and notations, the developed model is as follows:

$$\text{Minimize } \sum_{n=1}^N \sum_{t=0}^T W_{n,t} h_{n,t} + \sum_{n=1}^N \sum_{t=0}^T X_{n,t} p_{n,t} \tag{1}$$

Subject to:

$$X_{N,t} \geq D_t \quad \forall t = 0, \dots, T \tag{2}$$

$$h_{n-1,t-1} \geq X_{n,t} \quad \forall n = 2, \dots, N \ \& \ t = 1, \dots, T \tag{3}$$

$$h_{n,t} = h_{n,t-1} + X_{n-1,t-1} - X_{n,t} \quad \forall n = 2, \dots, N \ \& \ t = 1, \dots, T, \tag{4}$$

The first term in the objective function (1) represents the total holding cost of the supply chain for the planning horizon while the second term is the total production cost. Constraint (2) guarantees that the demand at each period is always satisfied since the production quantity at the final stage is equal to or more than the demand in any specific period. Constraint (3) implies that the inventory level should enough is to satisfy the production quantity. Constraint (4) represents the inventory level at each stage for each period.

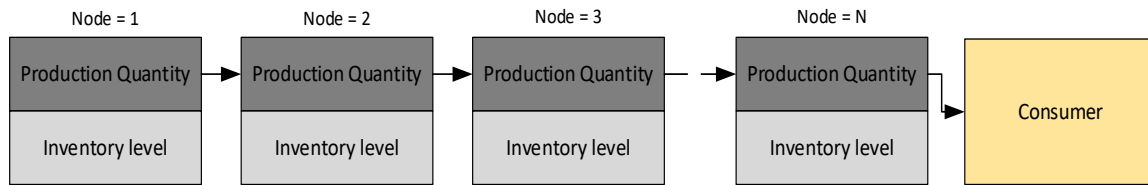


Figure 3. Flow chart of model I

3.2.2 Model II (Different Inventory/Transportation Costs)

Model II helps the decision-makers to specify the optimal shipment size moved from each stage to the next one. Moreover, this model is more comprehensive than model I because it not only determines the inventory level, but it also defines the inventory type (whether WIP or FG). WIP inventory level in each stage is the quantity of products in inventory that require additional activities to become FG and they are not ready to be transferred to the next stage. FG inventory level in each stage is the amount of products in inventory that do not require additional activities and they are ready to be transferred to the following stage in the supply chain.

The transportation cost is considered in model II and the inventory is divided into two types which are the WIP and FG. Three more decision variables are added to the model to consider these adjustments, in addition to extra the constraints. Following is the developed model:

$$Minimize \sum_{n=1}^N \sum_{t=0}^T W_{n,t} h_{n,t} + \sum_{n=1}^N \sum_{t=0}^T F_{n,t} H_{i,t} + \sum_{n=1}^N \sum_{t=0}^T M_{n,t} C_{n,t} + \sum_{n=1}^N \sum_{t=0}^T X_{n,t} p_{n,t} \tag{5}$$

Subject to:

$$W_{n,t} = W_{n,t-1} + M_{n-1,t-1} - X_{n,t} \quad \forall n = 2, \dots, N \ \& \ t = 1, \dots, T \tag{6}$$

$$F_{n,t} = F_{n,t-1} + X_{n,t} - M_{n,t} \quad \forall n = 1, \dots, N - 1 \ \& \ t = 1, \dots, T \tag{7}$$

$$F_{N,t} = F_{N,t-1} + X_{N,t} - D_t \quad \forall t = 1, \dots, T \tag{8}$$

$$F_{n,0} = X_{n,0} = M_{n,0} = A \quad \forall n = 1, \dots, N \tag{9}$$

$$X_{n,t} \geq 0 \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \tag{10}$$

$$M_{n,t} \geq 0 \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \tag{11}$$

$$W_{n,t} \geq 0 \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \tag{12}$$

$$F_{n,t} \geq 0 \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \tag{13}$$

$$F_{N,t} \geq 0 \quad \forall t = 0, \dots, T \tag{14}$$

$$W_{n,0} = A_n \quad \forall n = 1, \dots, N \tag{15}$$

The objective function (5) consists of four terms; the first term represents the WIP total holding cost, the second term is the total holding cost of the FG, the third term represents the total shipping cost, and the fourth shows the total production cost for the whole supply chain for the planning horizon.

Constraints (6) and (7) represent the WIP and FG inventory level, at stages 2,..., N and 1,...,N-1 for periods 1,...,T, respectively. Constraint (8) denotes the FG inventory level at stage N for periods 1,...,T. Constraint (9) shows the initial amount of the FG inventory level, the production quantity, and the number of parts shipped at each stage. Constraints (10), (11), (12), (13) and (14) are non-negativity constraints. Constraint (15) indicates that the initial WIP inventory level at each stage is constant and known. Figure 4 illustrates the flow and activities of model II.

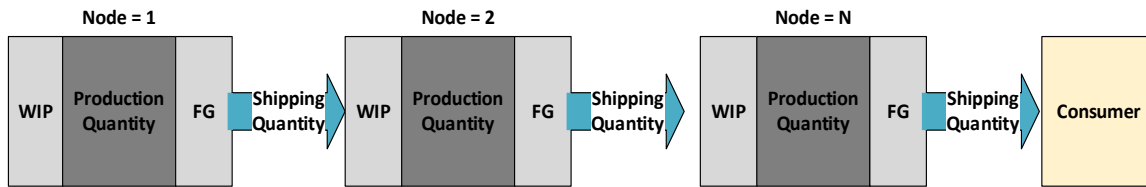


Figure 4. The flow chart of model II

4. Results and Discussion

4.1.1 Data for Model I

Period	0	1	2	3	4	5
Demand	100	200	300	400	500	600

The Demand

Holding Cost						
		Stage				
		1	2	3	4	5
Period	0	10	15	20	25	30
	1	14	20	25	27	32
	2	17	18	30	34	38
	3	20	21	26	27	34
	4	24	22	26	28	35
	5	29	28	27	30	40

Unit holding cost

Production Cost						
		Stage				
		1	2	3	4	5
Period	0	30	30	30	30	30
	1	28	28	28	28	28
	2	25	25	25	25	25
	3	20	20	20	20	20
	4	19	19	19	19	19
	5	18	18	18	18	18

Unit production cost for model I

4.1.2 Results for Model I

One basic scenario is implemented for model I provided in Section 3.2.1 with N=5 and T=5. The total cost obtained is \$378,300. The corresponding values for the decision variables (inventory level and production quantity) are provided in Figures 5 and 6, respectively.

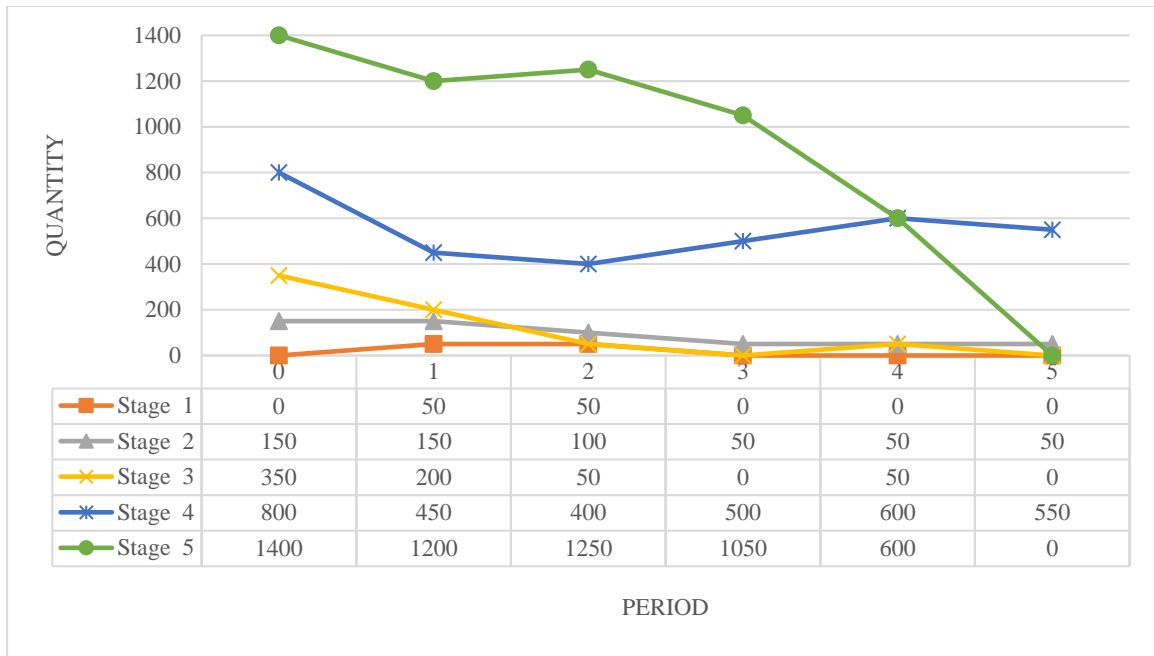


Figure 5. Inventory levels for model I

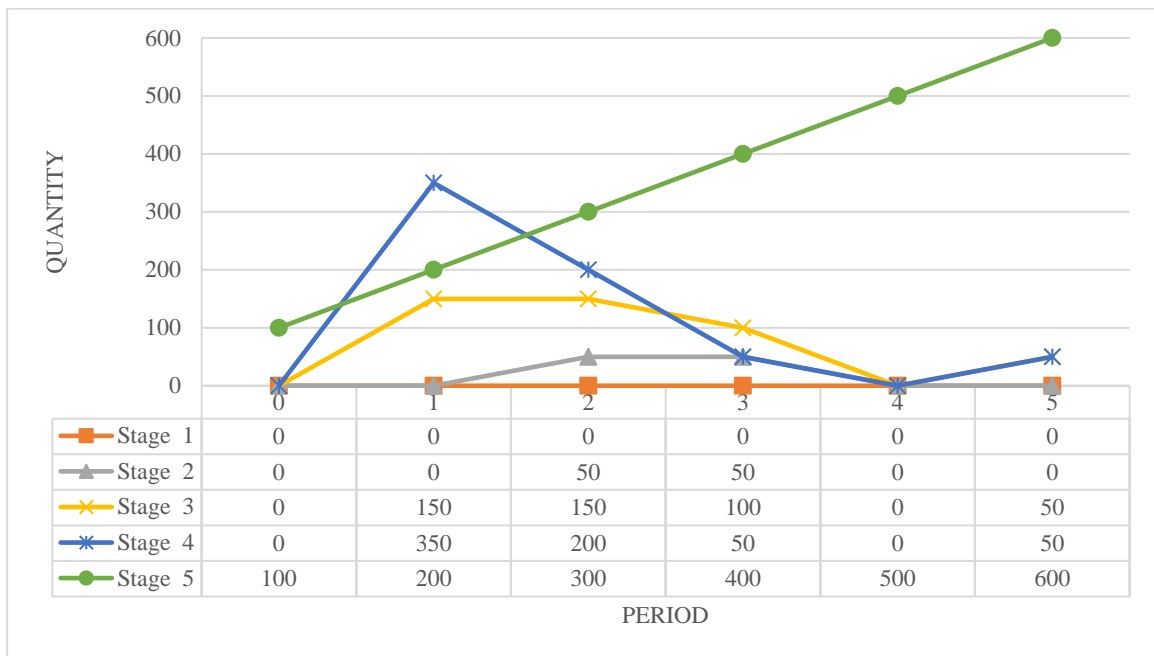


Figure 6. Production Quantities for model I

4.1.3 Data for Model II (Different Types of Inventory/Transportation Cost)

Two scenarios are tested for model II that is provided in Section 3.2.2. several data sets are used, and conditions (16), (17), (18), (19), (20), (21), (22), (23) and (24) are utilized to generate the data for the first scenario.

$$h_{n,t} = 0.10 V_{n,t} \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \quad (16)$$

$$H_{n,t} = 0.10 (V_{n,t} + p_{n,t}) \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \quad (17)$$

$$V_{n,t} = V_{n-1,t-1} + p_{n-1,t-1} + M_{n-1,t-1} \quad \forall n = 2, \dots, N \ \& \ t = 1, \dots, T \quad (18)$$

$$V_{1,t} \geq V_{1,t-1} \quad \forall t = 1, \dots, T \quad (19)$$

$$p_{n,t} = p_{n+1,t} \quad \forall n = 1, \dots, N \ t = 0, \dots, T - 1 \quad (20)$$

$$p_{n,t} < p_{n,t-1} \quad \forall n = 1, \dots, N \ \& \ t = 1, \dots, T \quad (21)$$

$$D_t > D_{t-1} \quad \forall t = 1, \dots, T \quad (22)$$

$$M_{n,t} = 1 \quad \forall n = 1, \dots, N \ \& \ t = 0, \dots, T \quad (23)$$

$$D_t = 0 \quad \forall t = 0, \dots, 4 \quad (24)$$

Conditions (16) and (17) imply that the unit holding cost is 10% of product's value. Condition (18) indicates that the value of the product is equal to the total cost of added value activities that are done on the product. Condition (19) implies that the raw material value (price) at the first stage increases over time due to the increase in demand. Condition (20) shows that the unit production cost for each period is the same at each stage of the supply chain. Condition (21) guarantees that the unit production cost decreases over time. The gradual increase in the demand is satisfied by Condition (22). Condition (23) indicates that the unit transportation cost between stages is equal to \$1 for the whole supply chain. Condition (24) implies that there is a five-week lead-time notice.

The same conditions are used to generate the data for the second scenario with a slight difference in Condition (25), which is substituted with Condition (14).

$$D_t = 0 \quad \forall t = 0, 1 \quad (25)$$

Condition (25) indicates that there is a two-week notice. The generated data is the same as the previous scenario, however the demand is different.

4.1.4 Results of Model II (Different Types of Inventory/Transportation Cost)

Two scenarios are tested in model II as provided in Section 3.2.1. In the first scenario, $N=5$, $T=15$, and the initial amount of WIP inventory level at each stage is constant and equal to zero. The solution has an objective function value of \$777,812.4. The values for the decision variables which are the WIP inventory level, the FG inventory level, shipment size, and the production quantity are provided in Figures 7, 8, 9 and 10, respectively.

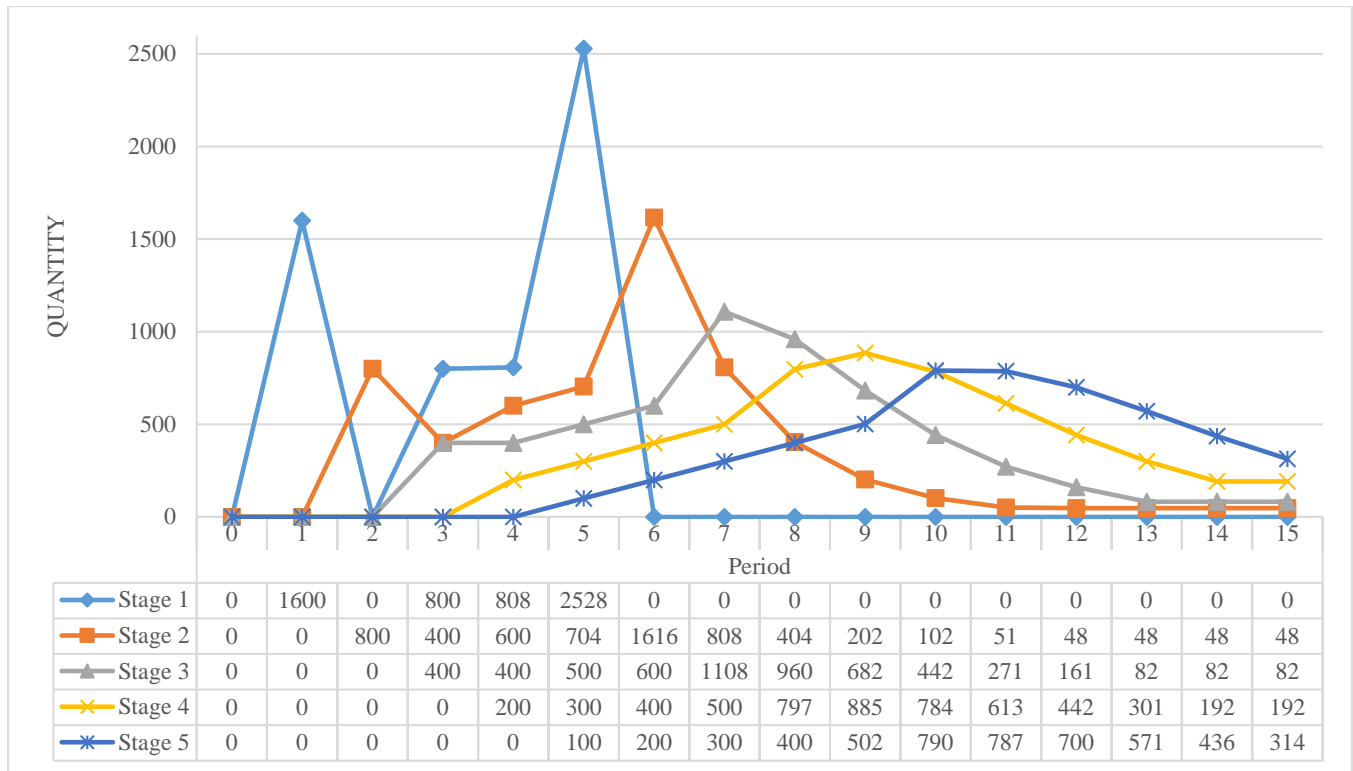


Figure 7. The WIP inventory level (W) for model II, first scenario

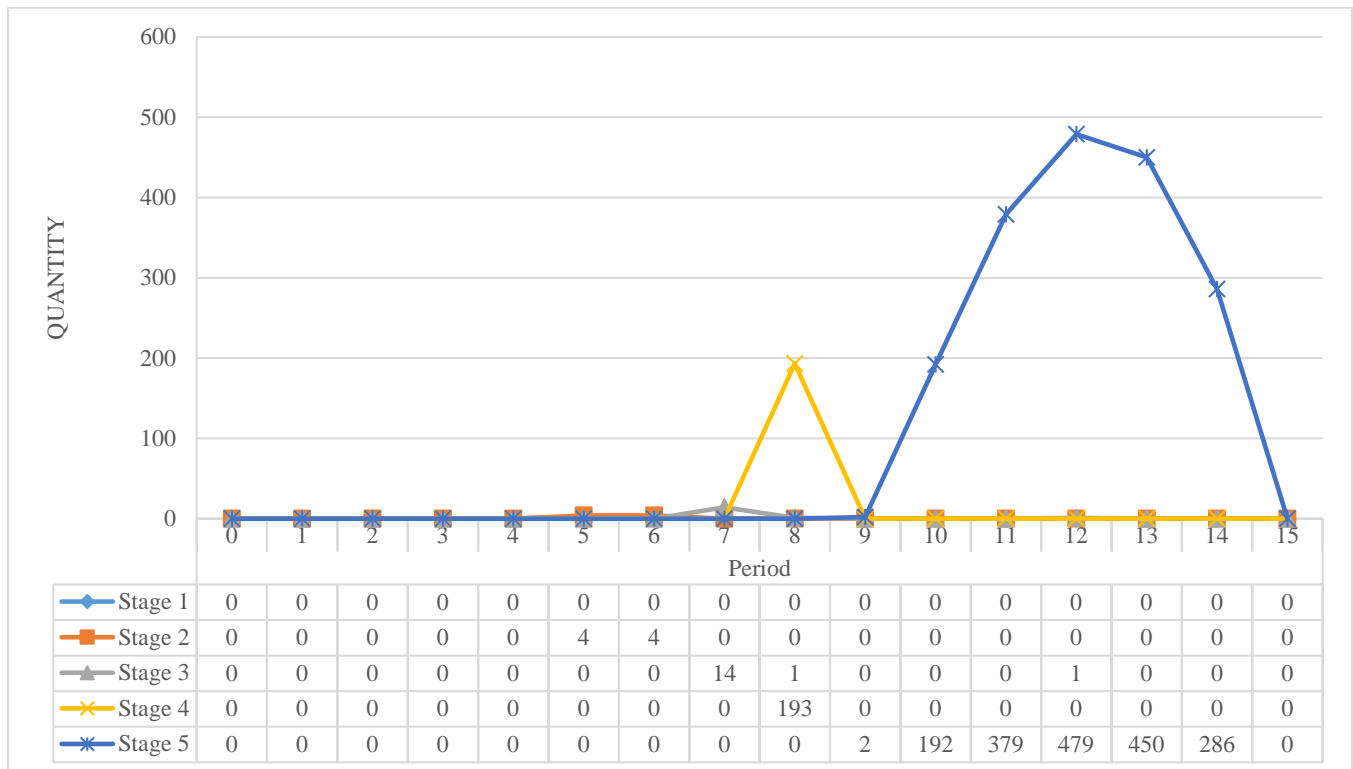


Figure 8. The FG inventory level (F) for model II, first scenario

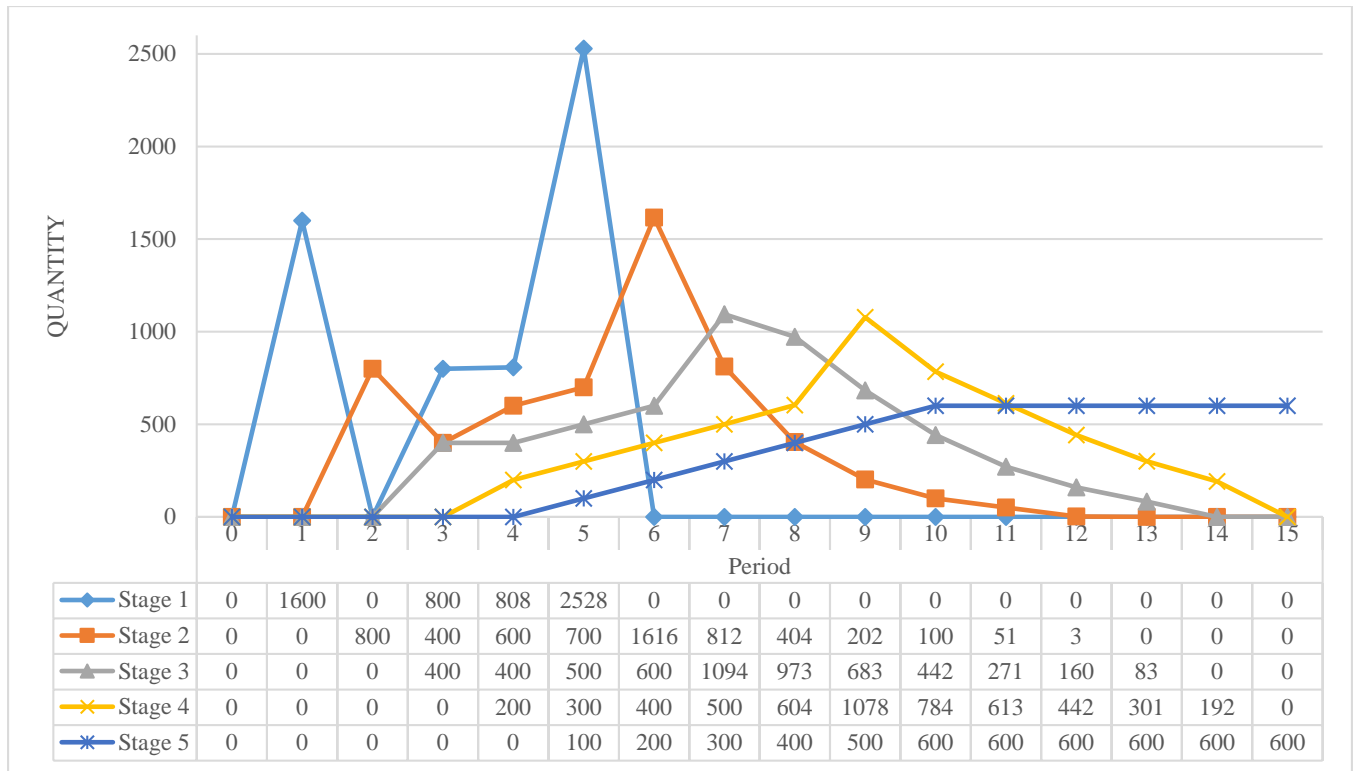


Figure 9. Shipment size (M) for model II, first scenario

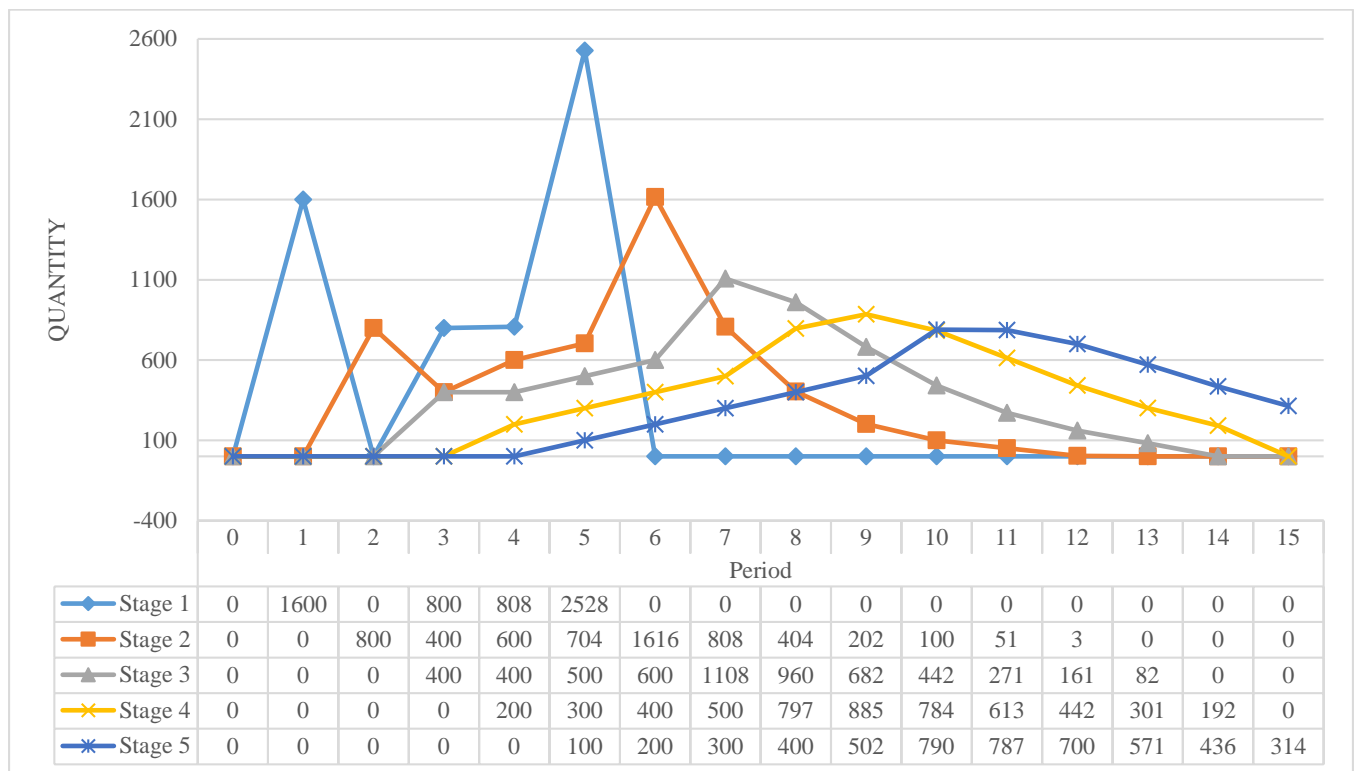


Figure 10. The production quantity (X) for model II, first scenario

The set of parameters for the second scenario are: $N=5$, $T=15$, and the initial amount of WIP inventory level at each stage is constant and set as follows ($A_1=200$, $A_2=300$, $A_3=400$, $A_4=500$, and $A_5=600$). The solution has an objective function value of \$964,455. The values for the decision variables are the WIP inventory level, the FG inventory level, shipment size, and the production quantity as shown in Figures 11, 12, 13 and 14, respectively.

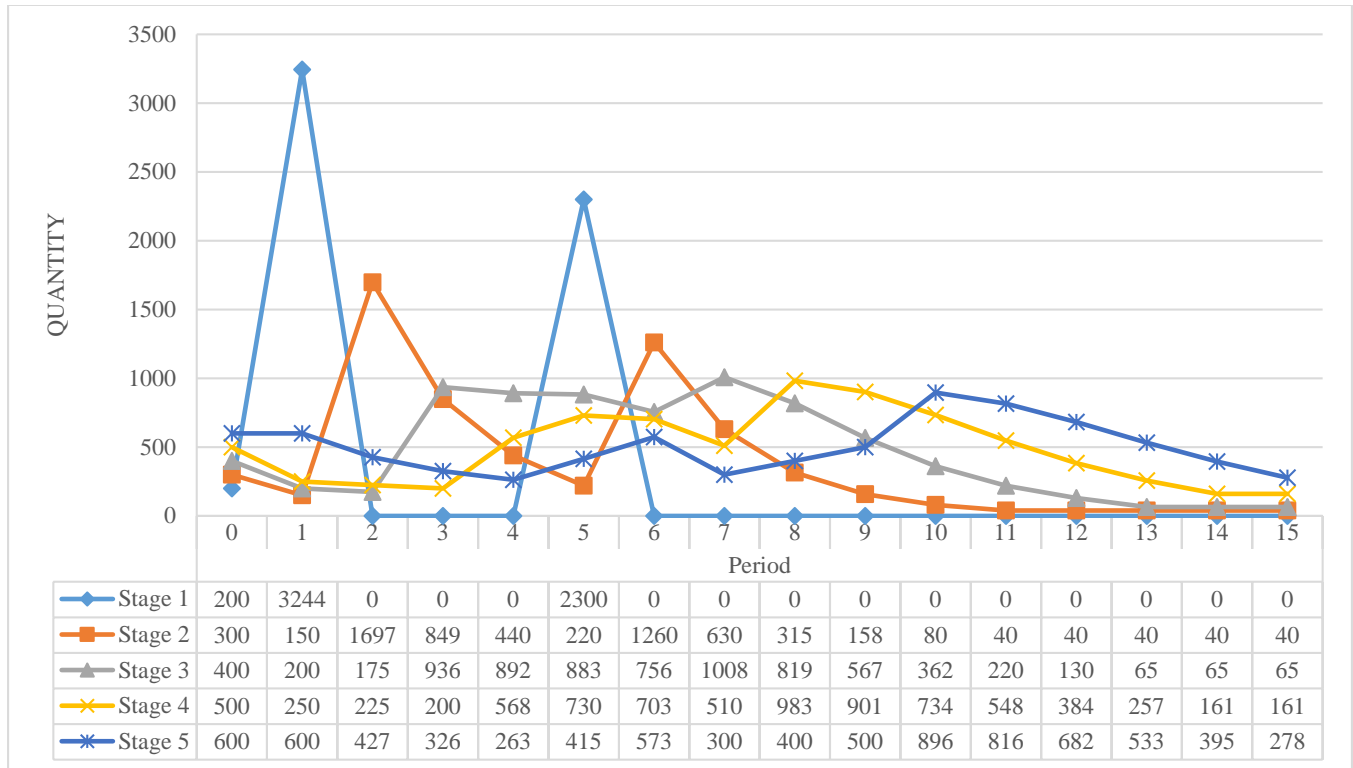


Figure 11. The WIP inventory level (W) for model II, second scenario

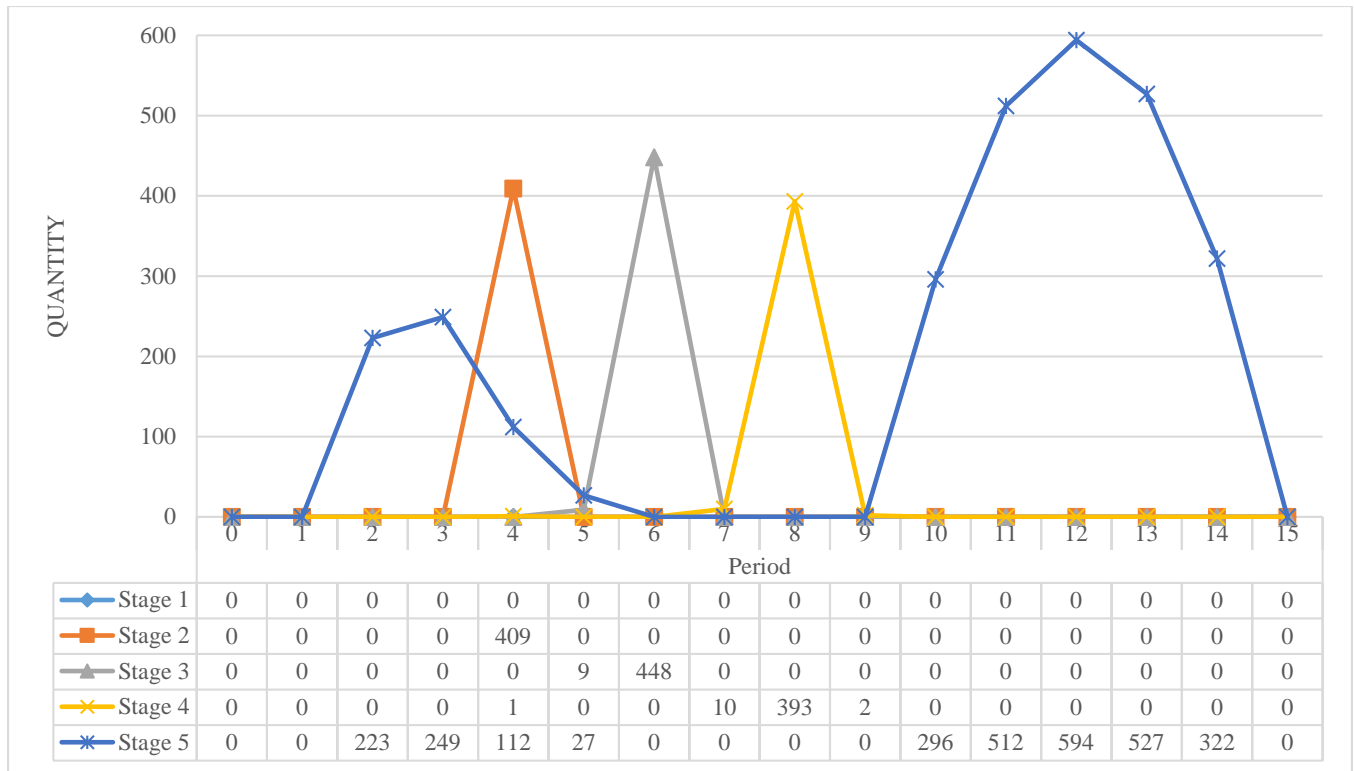


Figure 12. The FG inventory level (F) for model II, second scenario

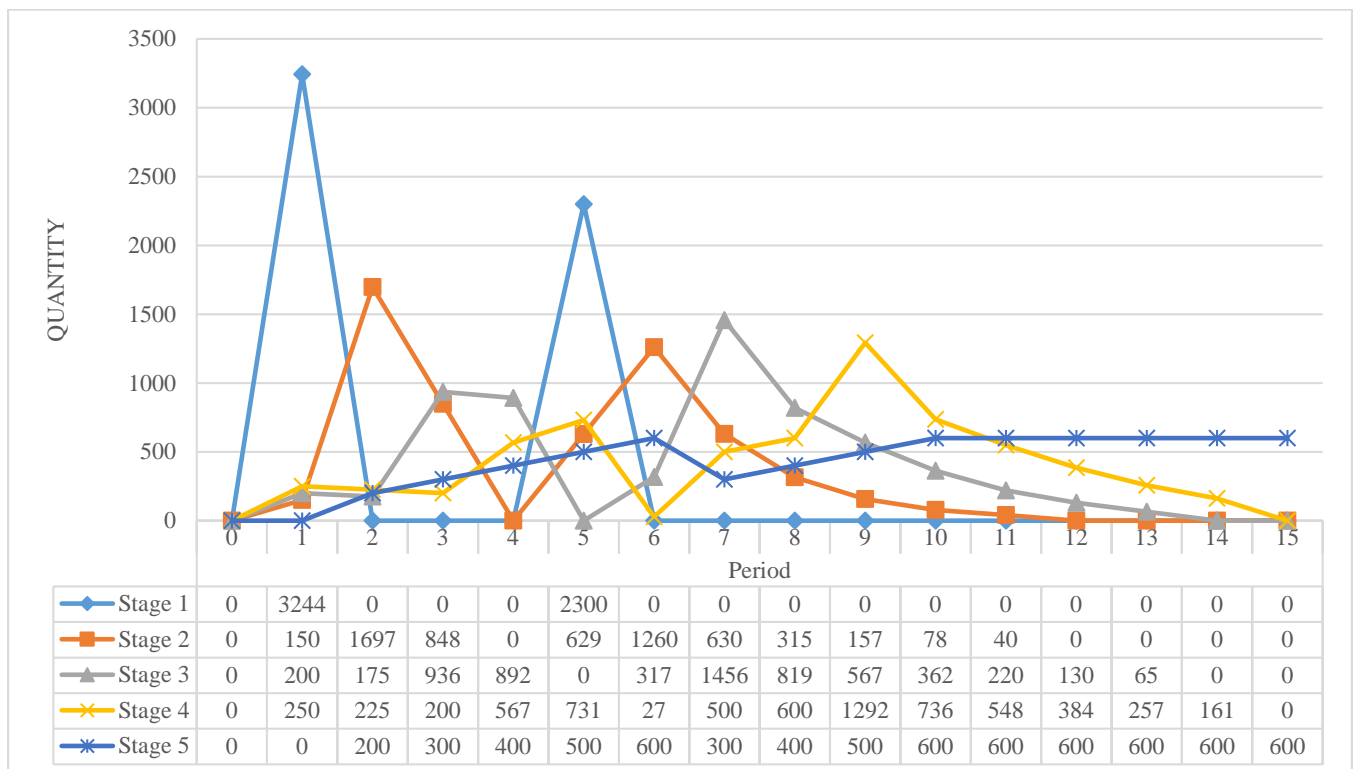


Figure 13. Shipment size (M) for model II, second scenario

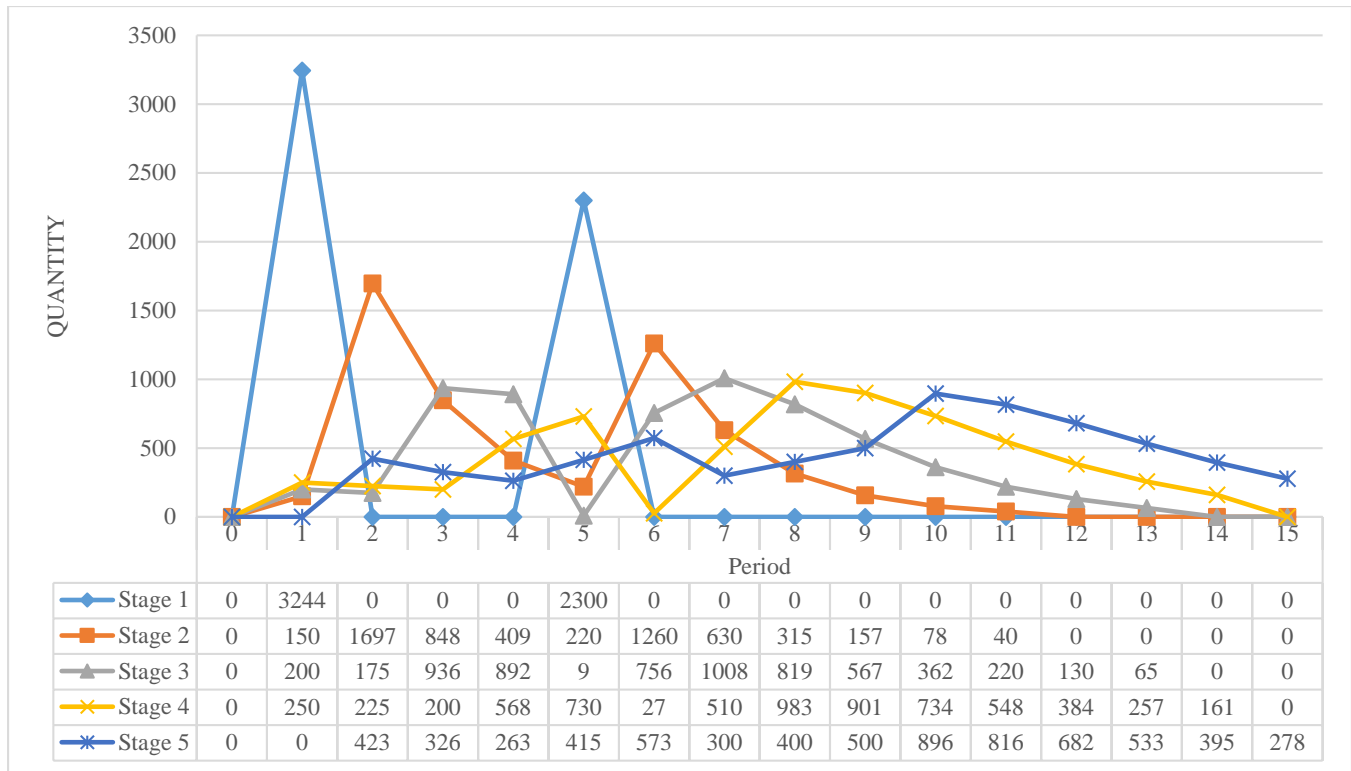


Figure 14. The production quantity (X) for model II, second scenario

5. Summary and Conclusions

This research addressed supply chain response to demand surge in pandemics like COVID-19, in particular, looking at the scenario of maintaining inventories at different stages of a product. This research explored single production location multi-stage supply chains. In pandemics, a demand surge for urgent medical supplies occurs with a very short notice. Robust supply chains are needed to cope with scaled up demand to prevent national health problems. This has led the healthcare organizations to focus on the readiness and preparedness of supply chains to deal with such outbreaks. In such demand surge, it is necessary to supply the medical supplies quickly and efficiently.

In this study, a well-established inventory allocation and production plans are derived to prepare for possible future demand surges for a pandemic such as COVID-19, H1N1, Ebola, or H5N1. Total-cost based general models were developed to aid the decision makers in allocating the supplies and capacities before and during outbreaks. Different scenarios were tested including changing the demand rates and time horizon.

The models were formulated as a linear programming problem for the single multi-stage supply chain. It determines the optimal inventory levels, shipment sizes, production quantities.

Based on the proposed models and scenarios the findings of this research are summarized in the following points:

- Higher levels of inventories are preferred in the upstream of the supply chain.
- Higher levels of WIP than FG inventories reduce the total supply chain cost.
- Similar patterns of the shipping amounts and production quantities which means:
 - Shipping the FGs to the next stage to be available for processing.
 - Faster response time.
- The extra needed capacity decreases moving downstream the supply chain.
- The total cost of the supply chain decreases as the notice period increases.
- The effect of the notice period on the total cost of the supply chain decreases over time.
- The total cost of the supply chain is lower when using extra capacity to store the SS than just using the existing capacity.

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