Supply Chain Disruptions Preparedness Measures Using a Dynamic Model

---

Abstract:

Supply chain risk management has recently seen extensive research efforts, but questions such as "How should a firm plan for each type of disruption?" and "What are the strategies and the total cost incurred by the firm if a disruption occurs?" continue to deserve attention. This chapter analyzes different disruption cases by considering the impacts of disruptions at a supplier, a firm's warehouse, and at the firm's production facility. The firm can prepare for each type of disruption by buying from an alternate supplier, holding more inventory, or holding inventory at a different warehouse. The Wagner-Whitin model is used to solve the optimal ordering strategy for each type of disruption. Since the type of disruption is uncertain, we assign probabilities for each disruption and use the Wagner-Whitin model to find the order policy that minimizes the firm's expected cost.

Keywords: Supply chain disruption, preparedness, Wagner-Whitin Model.

1. Introduction

Disruptions are unpredictable events and can occur at any facility location of a plant at any point of time. A supply chain is vulnerable to different types of disruptions, which can take the form of supply disruptions, operational problems at warehouses, demand uncertainty, transportation difficulties, or catastrophic events that close a firm's manufacturing facilities. Since a firm does not know what type of disruption will occur, if any, planning for disruptions should account for this uncertainty.

This chapter addresses disruptions occurring at three major locations: a supplier, a warehouse, and a firm's production facility. Two important questions are: (1) How should a firm plan for each type of disruption? and (2) How should a firm prepare for the possibility of all three disruptions? This chapter presents a model that seeks to answer these questions by exploring the firm's planning horizon and preparation strategies. First, the firm can prepare itself from calamity by holding inventory, possibly at different locations. Second, the firm can have an alternate supplier for its product.

Preparation strategies may also account for how the firm and other entities may respond if a disruption occurs. For example, a multinational firm may be able to rely on suppliers from other countries that are not impacted by a disruption. For example, if the firm's manufacturing plant is located in one part of world, the firm could increase productions at other facilities. Selecting international suppliers as an alternate supplier may incur higher ordering cost, however.

Each of the preparation strategies has a cost, and the cost of implementing all these strategies might be higher than the disruption itself. This chapter models this decision using the Wagner-Whitin model to incorporate the uncertainty around the type of disruption and to select a strategy that minimizes the firm's expected cost. This research is novel because we look at preparedness strategies of a firm during disruptions, which will reduce the overall disruption losses. It uses the idea of the Wagner-Whitin model to think about different disruption scenarios. A firm can use this Wagner-Whitin model with disruptions to make profitable decisions before and after a disruption.

Section 2 reviews the literature on supply chain disruptions. Section 3 introduces the supply chain model, the Wagner-Whitin algorithm, and the three disruption scenarios. Section 4 applies probabilities to each disruption and finds the firm's order policy that minimizes its expected cost. Section 5 discusses the results of this analysis.

2. Literature Review

Supply chain risk management and supply chain disruptions have received a lot of attention both in academia and in industry. A supply chain disruption can be defined as an internal or external event that alters the normal or planned flow of goods and services in a supply chain. Literature reviews on supply chain disruptions and supply chain risk management can be found in Tang (2006), Snyder et al. (2006), Vakharia and Yeniparzarli (2008), Natarajarathinam et al. (2009), Schmitt and Tomlin (2012), and Snyder et al. (2016). Supply chain disruptions can take many different forms, including production difficulties or operational risks (Xia et al., 2004), wholesale prices impacted by cost fluctuations (Xiao and Qi, 2008), supply shortages (Xiao and Yu, 2006), and sudden drops in demand based on the market conditions (Xiao et al., 2005). Much of the academic literature on supply chain disruptions focuses on understanding and modeling strategies that firms can use to mitigate a disruption, such as holding inventory (Song and Zipkin, 1996; Tomlin, 2006) purchasing from alternate suppliers (Tomlin, 2006; Song and Zipkin, 2009;

Babich et al., 2007; Hopp et al., 2009), rescheduling production (Bean et al., 1991; Adhyitya et al., 2007), rerouting transportation (MacKenzie et al., 2012), and producing at an alternate facility (MacKenzie et al., 2014). A firm can attempt to build a supply chain resilient to disruptions (Sheffi, 2005) by reconfiguring resources or improving its infrastructure (Ambulkar et al., 2015).

Understanding characteristics that make firms more or less vulnerable to supply chain disruptions is another important area of research. Bode and Wagner (2015) empirically found that the complexity of a supply chain, to include the horizontal and vertical complexity, can increase the frequency of disruptions and exacerbate them. Make-to-order supply chains may be more vulnerable to disruptions than make-to-forecast supply chains (Papadakis, 2006). Supply chain disruptions may be more severe for firms that are more geographically diverse or undertake a lot of outsourcing (Hendricks et al., 2009). This chapter explores some of the potential impacts that could occur in a complex supply chain with multiple suppliers and different warehouses.

The model in this chapter uses the model developed by Wagner and Whitin (1958) which provides a production or ordering plan with varying but known demand. If demand and order lead time are uncertain to small extent, a modified Wagner-Whitin model can still be applied (Kazan et al., 2000; Jeunet and Jonard, 2000). The Wagner-Whitin model was recently extended to situations with variable manufacturing and remanufacturing cost (Richter and Sombrutzki, 2000; Richter and Weber, 2001). To our knowledge, no research has extended the Wagner-Whitin model to supply chain disruptions to understand how a firm can use a manufacturing resource planning system to prepare for potential disruptions.

3. Supply Chain Model and Illustrative Example

3.1 Model

We consider a supply chain (see Figure 1) in which a manufacturing firm requires several suppliers. These suppliers transform raw materials into goods that are delivered to the firm. The firm stores these supplies in a warehouse. The firm also operates two smaller warehouses that are located further away but can be used if the main warehouse is short of supplies or unusable. The firm depends on a single primary supplier for parts. An alternate supplier is also available to deliver parts at a more expensive price if the primary supplier cannot meet demand. Since this chapter assumes that at most one supplier is disrupted, the analysis focuses on the firm's ability to obtain parts for its manufacturing process.

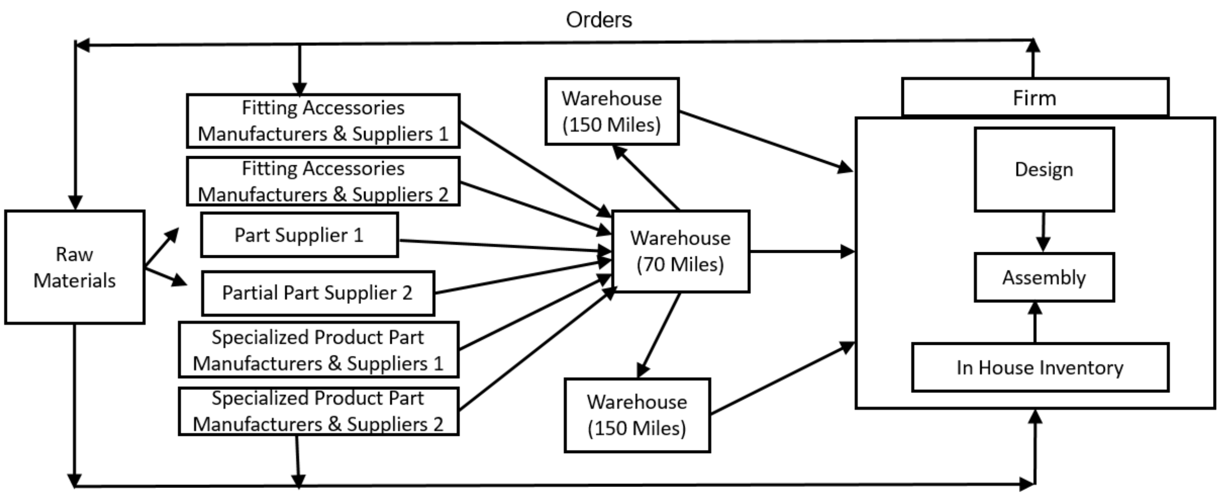

Figure 1: Supply chain map

We assume that the firm's forecasted demand D_t in time period t is deterministic but changes in each time period where $t = 1,2, \dots, T$ and T represents the planning horizon. The firm develops a plan to order quantity Q_t in each period in order to minimize its cumulative cost over the time horizon. The firm's cost is composed of a per-unit ordering cost C_t, a fixed cost per order A_t, and a per-unit holding or inventory cost H_t. All costs are in U.S. dollars. Given the assumptions in this framework, the model developed by Wagner and Whitin (1958) provides an appropriate solution for the firm's planning. The Wagner-Whitin model is a dynamic lot-sizing model that produces an optimal lot size for each period. A notional example is developed for a firm using the "RoadHog" example from Hopp and Spearman (pp. 58-64, 2008). The example without a disruption is explained first. We extend the example to three possible scenario disruptions: (1) a supplier disruption, (2) a firm closure, and (3) a warehouse disruption.

3.2 No Disruptions

Table 1 depicts the parameters for a 10-period model. The demand changes in each period, but the variable ordering cost, the fixed order cost, and the holding cost remain the same for each period. The cost in period t equals $A_t 1_{Q_t > 0} + C_t Q_t + H_t I_t$ where $1_{Q_t > 0}$ is in the indicator function that equals 1 if $Q_t > 0$ and where I_t is the amount of inventory being held from period t to $t+1$. We assume the revenue for the firm is the product of the demand and a per-unit selling price.

Table 1: Data representing demand, variable order cost, fixed order cost, and holding cost

Time period	1	2	3	4	5	6	7	8	9	10
D_t	20	50	10	50	50	10	20	40	20	30
C_t	10	10	10	10	10	10	10	10	10	10
A_t	100	100	100	100	100	100	100	100	100	100
H_t	1	1	1	1	1	1	1	1	1	1

Under an optimal lot-sizing policy, the inventory carried from period $t-1$ to t will be zero, or the order quantity in period t will be zero (Hopp and Spearman, 2008). In the Wagner-Whitin model, the per-unit ordering cost C_t is constant and can be ignored in the calculations. When no disruption occurs, C_t is constant, but as will be explained later, C_t can change during a supply chain disruption. Thus, C_t is included in this model's calculations. The basic recursive algorithm is outlined below. The algorithm goes forward in time by calculating $X_{\tau,t}$ the cost of ordering in period τ to satisfy demand in all periods from τ through t. The cumulative minimum cost Z_t^* in each period t is selected, and $j_t^* \epsilon \{1,2,\ldots,t\}$ represents the period in which to order parts to meet demand in t. The third and fourth steps in the algorithm ensures that the optimal order period j_t^* is selected in cost calculations.

<u>Wager-Whitin algorithm:</u>

1. Satisfy demand in first period D_1, $Z_1^* = X_{1,1} = A_1 + C_1 D_1 \quad j_1^* = 1$

2. Determine minimum cost for periods $t = 2,3,\ldots,T$

$$X_{\tau,t} = \begin{cases} X_{\tau-1,t} + D_t\left(C_\tau + \sum_{t'=\tau}^{t-1} H_{t'}\right) & \text{if } \tau < t \\ Z_{t-1}^* + D_t C_t + A_t & \text{if } \tau = t \end{cases}$$

$$Z_t^* = \min_\tau X_{\tau,t}$$

$$j_t^* = \underset{\tau}{\operatorname{argmin}} X_{\tau,t}$$

3. Begin with $t = T$ and continuing with $t = T-1, T-2, \ldots, 2$

If $j_t^* < j_\tau^*$ for any $\tau = j_t^*, \ldots, t-1$, then set $j_\tau^* = j_t^*$

4. For periods $t = 2,3, \ldots, T$, repeat calculation for $X_{\tau,t}$ from step 2 and set $Z_t^* = X_{j_t^*,t}$.

Table 2: Planning horizon with total costs for each possible ordering period

Last period with order	Planning horizon (t)									
	1	2	3	4	5	6	7	8	9	10
1	300	850	970	1620	2320	2470	2790	3470	3830	4400
2		900	1010	1610	2260	2400	2700	3340	3680	4220
3			1050	1600	2200	2330	2610	3210	3530	4040
4				1570	2120	2240	2500	3060	3360	3840
5					2170	2280	2520	3040	3320	3770
6						2320	2540	3020	3280	3700
7							2540	2980	3220	3610
8								3000	3220	3580
9									3300	3630
10										3620
Z_t^*	300	850	970	1570	2120	2240	2500	3000	3220	3580
j_t^*	1	1	1	4	4	4	4	8	8	8

As shown in Table 2 (which replicates the result from Hopp and Spearman, pp. 58-64, 2008), the firm should order 80 units in period 1 to satisfy demand in periods 1, 2, and 3; 130 units in period 4 to satisfy demand in 4, 5, 6, and 7; and 90 units in period 8 to satisfy demand in 8, 9, and 10.

3.3 Supplier Disruption

We first consider that a disruption occurs with the primary parts supplier in period 5 and lasts through the rest of the planning horizon. The firm is able to order from the secondary parts supplier, but the ordering cost C_t increases from 10 to 20 for periods 5 through 10. All other values from Table 1 remain the same. If we assume that the firm knows the primary supplier will be disrupted in period 5, we can use the Wagner-Whitin algorithm to calculate the optimal order period given this disruption.

Table 3: Optimal planning horizon with local supplier disruption

	Planning horizon (t)									
	1	2	3	4	5	6	7	8	9	10
Z_t^*	300	850	970	1570	2120	2240	2500	3060	3360	3840
j_t^*	1	1	1	4	4	4	4	4	4	4

When the cost is 20 the firm should order 80 units in period 1 to satisfy demand in periods 1, 2, and 3; and 220 units in period 4 to satisfy demand in periods 4 through 10. It is cheaper for the firm to hold inventory than to purchase from the alternate supplier.

We explore the impact of changing the ordering cost from 10 to 20 for the alternate supplier. Figure 2 illustrates the relationship between total cost and the per-unit ordering cost. As the ordering cost increases, the total cost initially increases until the ordering cost equals 13, at which point the total cost remains the same. When the cost is 13, the firm changes its strategy from ordering in periods 1, 4, and 8 to ordering in periods 1 and 4 only. The cost of holding inventory from periods 4 through 10 is less than the cost of ordering in period 8 when the cost is 13 or greater. Since the firm is ordering all of its parts before the disruption in period 5, the total cost remains the same even when the ordering cost increases beyond 13.

Figure 2: Total cost as the ordering cost changes for period 5 through 10

3.4 Firm Disruption

The second type of disruption occurs when the firm itself is impacted and cannot produce. We model this type of disruption by setting $D_t = 0$ for those periods when the firm is disabled. The firm's revenue will be 0 until the firm recovers from the disruption. If the impact due to the disruption is large, the firm will take more time to recover from it. The purchase and holding costs remain the same as in Table 1. Table 4 illustrates the notional data in which the disruption takes place in period 5 and the firm recovers in period 9. The firm is disabled in periods 5 through 8.

Table 4: Demand with a firm disruption

t	1	2	3	4	5	6	7	8	9	10
D_t (units)	20	50	10	50	0	0	0	0	20	30

Table 5: Optimal planning horizon with firm disruption

	Planning horizon (t)									
	1	2	3	4	5	6	7	8	9	10
Z_t^*	300	850	970	1570	1570	1570	1570	1570	1870	2200
j_t^*	1	1	1	4	4	4	4	4	9	9

Since the firm is losing revenue when it is not producing, we examine the impact of the firm disruption on the firm's revenue and profit. We assume the firm receives a revenue of 50 for each unit it produces. Table 6 shows how the firm's profit changes based on when it recovers and resumes ordering and production. If the firm reopens in periods 6 or 7, the firm orders enough supplies in period 4 to cover the initial periods when it reopens. If the firm reopens in periods 8, 9, or 10, the firm holds no additional inventory from period 4 and orders supplies when it completely recovers.

Table 6: Recovery period and ordering strategy in case of a firm disruption (~ means the firm is closed)

Recovery period	Cost	Revenue	Profit	Ordering strategy j_t^*
No disruption	3580	15000	11420	1, 1, 1, 4, 4, 4, 4, 8, 8, 8
6	3030	12500	9470	1, 1, 1, 4, ~, 4, 4, 8, 8, 8
7	2910	12000	9090	1, 1, 1, 4, ~, ~, 4, 8, 8, 8
8	2650	11000	8350	1, 1, 1, 4, ~, ~, ~, 8, 8, 8
9	2200	9000	6800	1, 1, 1, 4, ~, ~, ~, ~, 9, 9
10	1970	8000	6030	1, 1, 1, 4, ~, ~, ~, ~, ~, 10

3.5 Main Warehouse Disruption

The third type of disruption occurs when the main warehouse is impacted. If the main warehouse is closed, the firm will need to arrange for additional warehouse space. We assume that the firm can use one of its two other warehouses as depicted in Figure 1, but using either of these facilities increases H_t the holding cost. Table 7 illustrates the increase in holding cost when the main warehouses closes from periods 5 through 10.

Table 7: Holding cost with a main warehouse disruption

t	1	2	3	4	5	6	7	8	9	10
H_t	1	1	1	1	5	5	5	5	5	5

If the holding cost is 5 beginning in period 5, the firm is incentivized to make more frequent orders. As depicted in Table 8, the firm should order 80 units in period 1 to satisfy demand in periods 1, 2, and 3; 110 units in period 4 to satisfy demand in periods 4, 5, and 6; 20 units in period 7 to satisfy demand in period 7; 60 units in period 8 to satisfy demand in periods 8 and 9; and 30 units in period 10 to satisfy demand in period 10.

Table 8: Optimal planning horizon with warehouse disruption

	Planning horizon (t)									
	1	2	3	4	5	6	7	8	9	10
Z_t^*	300	850	970	1570	2120	2280	2580	3080	3380	3780
j_t^*	1	1	1	4	4	4	7	8	8	10

Figure 3 shows the relationship between the firm's total cost and the holding cost. Not surprisingly, as the holding cost increases, the total cost also increases. When the holding cost increases from 5 to 6, the ordering strategy changes from 1, 4, 7, 8, 10 to 1, 4, 7, 8, 9, 10 as represented in Table 9. As the holding cost increases, it is cheaper to order more frequently.

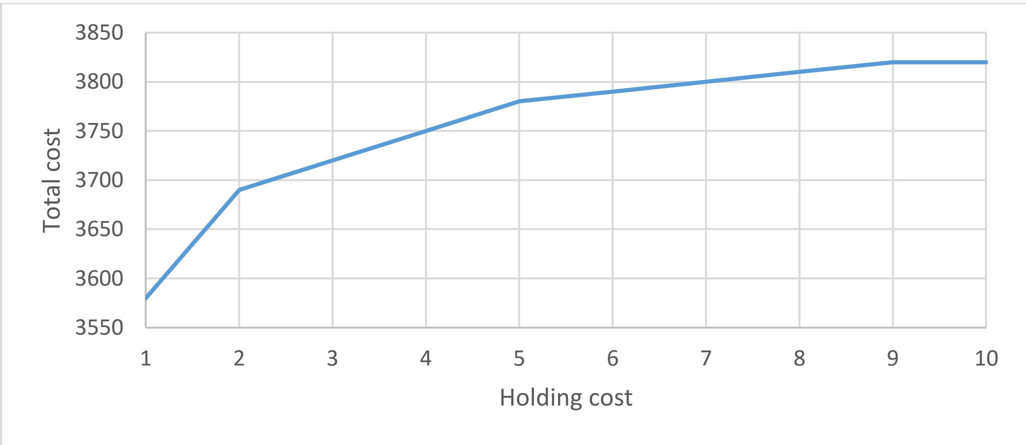

Figure 3: Total cost as the holding cost changes for periods 5 through 10

Table 9: Optimal planning horizon with warehouse disruption

Holding cost	Ordering strategy j_t^*
1	1,1,1,4,4,4,4,8,8,8
2	1,1,1,4,4,4,4,8,8,10
3	1,1,1,4,4,4,7,8,8,10
4	1,1,1,4,4,4,7,8,8,10
5	1,1,1,4,4,4,7,8,8,10
6	1,1,1,4,4,4,7,8,9,10
7	1,1,1,4,4,4,7,8,9,10
8	1,1,1,4,4,4,7,8,9,10

3.6. Disruption occurs in different periods

The previous section assumes that the disruption always occurs in period 5, but the disruption could occur in any period. This section analyzes the impact on the firm's cost and profit if the disruption occurs in different periods for each of the three types of disruptions.

3.6.1 Supplier Disruption

The initial period in which the primary parts supplier experiences a disruption is varied from periods 3 through 8. The primary supplier is always closed through period 10. As in Section 3.3, the firm can order from the secondary parts supplier, but the ordering cost increases to 20. The holding cost and fixed cost are the same as in Table 1. Figure 4 illustrates the relationship between the firm's total cost and when the disruption begins. The last ordering period for the firm should occur in the previous immediately prior to the disruption.

Table 10: Total cost and ordering strategy with different period of disruption

Periods during which primary supplier is disabled	Total Cost	Ordering Strategy
3 – 10	4220	1, 2, 2, 2, 2, 2, 2, 2, 2, 2
4 – 10	4040	1, 1, 3, 3, 3, 3, 3, 3, 3, 3
5 – 10	3840	1, 1, 1, 4, 4, 4, 4, 4, 4, 4
6 – 10	3770	1, 1, 1, 4, 5, 5, 5, 5, 5, 5
7 – 10	3700	1, 1, 1, 4, 4, 6, 6, 6, 6, 6
8 – 10	3610	1, 1, 1, 4, 4, 4, 7, 7, 7, 7

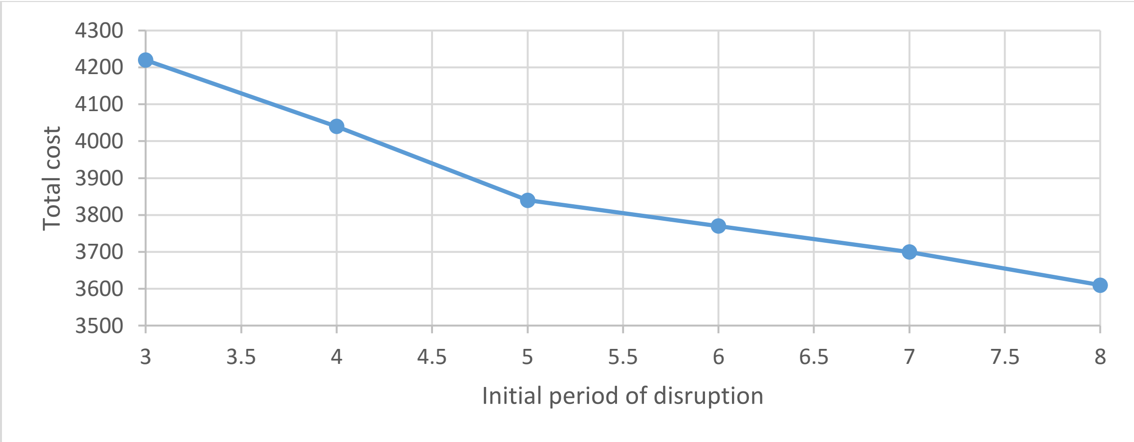

Figure 4: Total cost as the initial period of disruption changes from 3 through 8

3.6.2 Firm Disruption

The disruption disables the firm, and it cannot produce for a number of periods. The firm's revenue will be 0 until the firm recovers from the disruption, and we continue to assume that the firm recovers in the 10th period. The period in which the disruption begins is varied from periods 3 to 8. Table 11 and Figure 5 illustrate the relationship among the period in which the disruption begins, the firm's profit, and its ordering strategy. The firm's profit increases as the period in which the disruption occurs increases. The firm continues to order in periods 1 and 4 irrespective of the length of the disruption (as long as the disruption occurs after period 4).

Table 11: Profit and ordering strategy in case of a firm disruption with different periods of disruption (~ means the firm is closed)

Periods during which firm is unable to produce	Cost	Revenue	Profit	Ordering strategy j_t^*
3 – 9	1250	5000	3750	1, 1, ~, ~, ~, ~, ~, ~, ~, 10
4 – 9	1370	5500	4130	1, 1, 1, ~, ~, ~, ~, ~, ~, 10
5 – 9	1970	8000	6030	1, 1, 1, 4, ~, ~, ~, ~, ~, 10
6 – 9	2520	10500	7980	1, 1, 1, 4, 4, ~, ~, ~, ~, 10
7 – 9	2640	11000	8360	1, 1, 1, 4, 4, 4, ~, ~, ~, 10
8 – 9	2900	12000	9100	1, 1, 1, 4, 4, 4, 4, ~, ~, 10

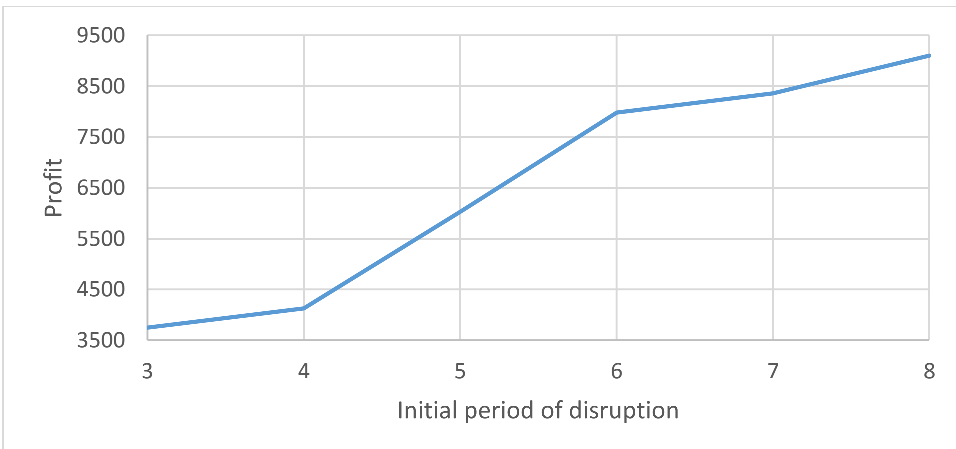

Figure 5: Profit as the initial period of disruption changes from 3 through 8

3.6.3 Main warehouse Disruption

If the firm's main warehouse is disrupted, we assume the firm can use alternate warehouses, but its holding cost increases to 10. The disruption can begin in periods 3 through 8 but always continues through period 10. The ordering cost and fixed cost remain the same as in Table 1. Table 12 and Figure 6 illustrate that the total cost decreases as the length of the disruption decreases. The firm should always order in periods 1 and 4, but whether or the not the firm orders in other periods changes as the length of disruption changes. For most cases, the firm should order in each period after the first disruption period. For example, if the disruption lasts from periods 5-10, the firm should order in each period from 6 through 10.

Table 12: Total cost, holding cost and ordering strategy in case of a main warehouse disruption with different periods of disruption

Periods during which main warehouse is closed	Total Cost	Ordering strategy j_t^*
3 – 10	3870	1, 1, 1, 4, 5, 5, 7, 8, 9, 10
4 – 10	3870	1, 1, 1, 4, 5, 5, 7, 8, 9, 10
5 – 10	3820	1, 1, 1, 4, 4, 6, 7, 8, 9, 10
6 – 10	3740	1, 1, 1, 4, 4, 4, 7, 8, 9, 10
7 – 10	3700	1, 1, 1, 4, 4, 4, 4, 8, 9, 10
8 – 10	3680	1, 1, 1, 4, 4, 4, 7, 7, 9, 10

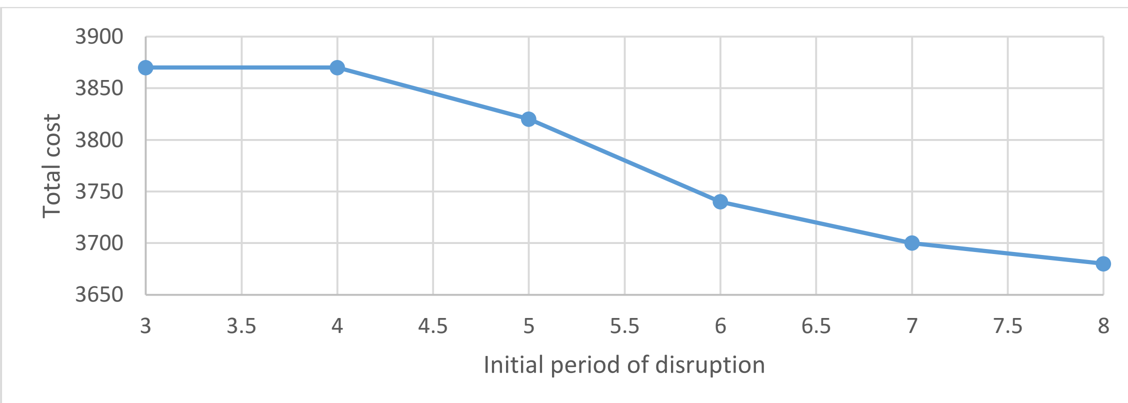

Figure 6: Total cost as the initial period of disruption changes from 3 through 8

4. Unknown disruption and period

The previous section assumes that the firm plans for each disruption individually and knows the type and timing of the disruption. In reality, the firm will not know which disruption, if any, will occur or when it will occur. This section explores how the chance and timing of one of these disruptions should impact the firm's planning. We assume that one of the three disruptions could occur: the local supplier disruption, the firm disruption, or the main warehouse disruption. Given that a disruption occurs, the probability the local supplier is disabled is 0.5, the probability the firm is closed is 0.2, and the probability the main warehouse is closed is 0.3. We assume there is an equal probability that the disruption will begin in period 3, 4, 5, 6, 7, or 8, equivalent to a 1/6 probability for each period. If the local supplier is disrupted, the firm can order from the alternate supplier at a per-unit cost of 20. If the firm is disrupted, we assume the firm cannot satisfy any demand while it is closed. If the main warehouse is disrupted, the firm can store inventory at the alternate warehouses, but the holding cost increases to 5. We use the probabilities of disruption to calculate the expected costs for each possible ordering strategy. The Wagner-Whitin algorithm is deployed to find the order policy that minimizes the firm's total expected cost. Since this is a planning problem, the firm establishes an order before knowing whether a disruption occurs, which disruption will occur, or when the disruption will occur.

We vary the probability of a disruption between 0 and 1. The optimal ordering strategy for the firm for different probabilities of disruptions is illustrated in Table 13. If the probability of a disruption is less than 0.3, the firm should not change its ordering policy from the case without a disruption. If the probability of a disruption is greater than or equal to 0.3, the firm should order in periods 1, 4, 8, and 10. It becomes optimal to order in period 10 because the firm is incentivized to plan for the firm being closed and for the main warehouse being closed. With such a large probability of disruption, it becomes more likely that the firm will have a disrupted warehouse, which increases its holding cost. Thus, it becomes more advantageous to hold less inventory and order in period 10. (If the disruption disables the primary supplier, the firm's cost of ordering does not change based on whether it orders in period 8 or 10 because both periods require ordering from the more expensive alternate supplier.) The expected profit decreases in a linear fashion as the probability of a disruption increases as displayed in Figure 7.

Table 13: Probability of disruption and optimal planning for uncertain periods

Probability of disruption	Expected profit	Ordering strategy j_t^*
0	11420	1, 1, 1, 4, 4, 4, 4, 8, 8, 8
0.1	11318	1, 1, 1, 4, 4, 4, 4, 8, 8, 8
0.2	11215	1, 1, 1, 4, 4, 4, 4, 8, 8, 8
0.3	11121	1, 1, 1, 4, 4, 4, 4, 8, 8, 10
0.4	11035	1, 1, 1, 4, 4, 4, 4, 8, 8, 10
0.5	10949	1, 1, 1, 4, 4, 4, 4, 8, 8, 10

0.6	10862	1, 1, 1, 4, 4, 4, 4, 8, 8, 10
0.7	10776	1, 1, 1, 4, 4, 4, 4, 8, 8, 10
0.8	10690	1, 1, 1, 4, 4, 4, 4, 8, 8, 10
0.9	10603	1, 1, 1, 4, 4, 4, 4, 8, 8, 10
1	10517	1, 1, 1, 4, 4, 4, 4, 8, 8, 10

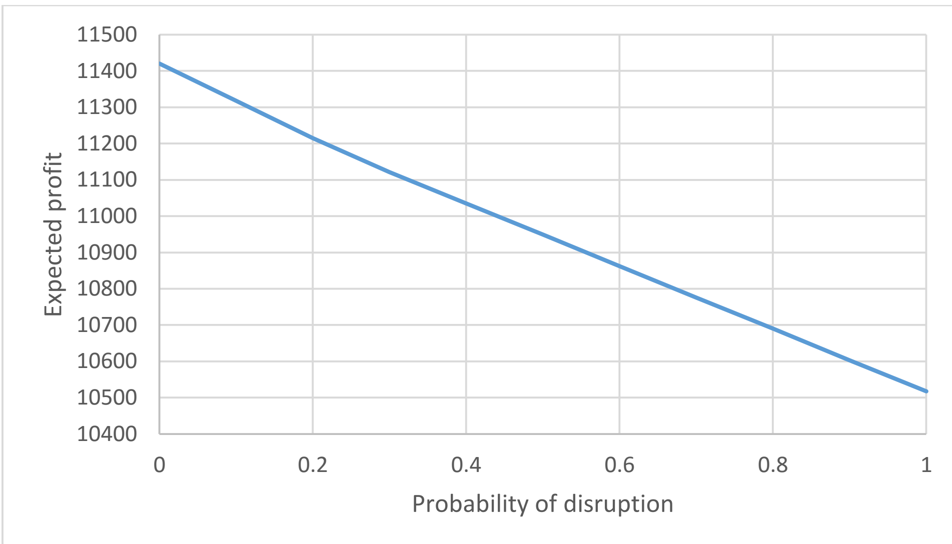

Figure 7: Expected profit as the probability of disruption changes from 0 through 1

5. Discussions and Conclusions

This research addresses an important question of how a firm should plan for the possibility of several disruptions. The Wagner-Whitin model is appropriate with the assumption that demand is varying but deterministic. Three possible disruption scenarios are studied: a supply disruption, a disruption in the firm's production facility, and a warehouse disruption. If the firm can anticipate that the supplier cannot deliver its supplies, the firm is incentivized to hold more inventory, depending on the cost of the alternate supplier. If the firm's primary warehouse closes, the firm should hold less inventory and order more frequently from its suppliers. The application explores how the firm's cost and order strategies change as the parameters change.

Since a firm will not know in advance which disruption occurs, it will need to decide for which, if any, disruption to plan. The period in which the disruption occurs is also uncertain. The model applies probabilities to each disruption and the timing, and the firm chooses an order policy in order to minimize its expected cost. Total profit is calculated based on the different probabilities of disruptions. The firm's ordering strategy may change as the probability of a disruption increases.

A firm who uses a manufacturing resource planning system that resembles the Wagner-Whitin model could forecast possible disruptive events and explore if its ordering and production schedule should change based on the possible disruptions. The incorporation of probability to account for the uncertainty in the type and timing of disruptions allows a firm to understand how the likelihood of a disruption should impact its planning and ordering strategy. For the illustrative example in this chapter, the firm should slightly modify its ordering strategy as the probability of a disruption occurs. Further research can seek to understand if generalized results can be derived from the model about how the probability of disruption should impact a firm's ordering strategy. Though the Wagner-Whitin model generates an optimal planning horizon, it has some drawbacks. It has a fixed setup cost and deterministic demand.

In the future, we plan to extend our methodology to more complex supply chains, which may involve multiple suppliers. Future extensions can apply the algorithm to a real case study rather than considering notional data. Having longer planning horizons and allowing the firm to respond based on what disruption occurs may also impact the firm's optimal planning.

6. References:

Adhyitya, A., Srinivasan, R., & Karimi, I. A. (2007). Heuristic rescheduling of crude oil operations to manage abnormal supply chain events. *American Institute of Chemical Engineers Journal*, *53*(2), 397-422.

Ambulkar, S., Blackhurst, J., & Grawe, S. (2015). Firm's resilience to supply chain disruptions: Scale development and empirical examination. *Journal of Operations Management*, *33*, 111-122.

Babich, V., Burnetas, A. N., & Ritchken, P. H. (2007). Competition and Diversification Effects in Supply Chains with Supplier Default Risk. *Manufacturing & Service Operations Management*, *9*(2), 123-146.

Bean, J.C., Birge, J.R.,Mittenthal, J. and Noon,C.E. (1991). Matchup scheduling with multiple resources, release dates and disruptions. *Operations Research*, *39*(3), 470–483.

Bode, C., & Wagner, S. M. (2015). Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. *Journal of Operations Management, 36*, 215-228.

Hendricks, K. B., Singhal, V. R., & Zhang, R. (2009). The effect of operational slack, diversification, and vertical relatedness on the stock market reaction to supply chain disruptions. *Journal of Operations Management, 27*(3), 233-246.

Hopp, W. J., Iravani, S. M. R., & Liu, Z. (2009). Strategic risk from supply chain disruptions. Working paper. Department of Industrial Engineering and Management Sciences, Northwestern University. Retrieved from http://webuser.bus.umich.edu/whopp/working%20papers/Strategic%20Risk%20from%20Supply%20Chain%20Disruptions.pdf

Hopp, W.J., & Spearman, M.L. (2008) *Factory Physics*, third edition, McGraw-Hill, Boston, MA.

Jeunet, J., & Jonard, N. (2000). Measuring the performance of lot-sizing techniques in uncertain environments. *International Journal of Production Economics*, *64*(1), 197-208.

Kazan, O., Nagi, R., & Rump, C. M. (2000). New lot-sizing formulations for less nervous production schedules. *Computers & Operations Research, 27*(13), 1325-1345.

MacKenzie, C. A., Barker, K., & Grant, F. H. (2012). Evaluating the consequences of an inland waterway port closure with a dynamic multiregional interdependence model. *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans, 42*(2), 359-370.

MacKenzie, C. A., Barker, K., & Santos, J. R. (2014). Modeling a severe supply chain disruption and post-disaster decision making with application to the Japanese earthquake and tsunami. *IIE Transactions, 46*(12), 1243-1260.

Natarajarathinam, M., Capar, I., & Narayanan, A. (2009). Managing supply chains in times of crisis: a review of literature and insights. *International Journal of Physical Distribution & Logistics Management, 39*(7), 535-573.

Papadakis, I. S. (2006). Financial performance of supply chains after disruptions: an event study. *Supply Chain Management: An International Journal, 11*(1), 25-33.

Richter, K., & Weber, J. (2001). The reverse Wagner/Whitin model with variable manufacturing and remanufacturing cost. *International Journal of Production Economics, 71*, 447-456.

Richter, K., & Sombrutzki, M. (2000). Remanufacturing planning for the reverse Wagner/Whitin models. *European Journal of Operational Research, 121*(2), 304-315.

Sheffi, Y. (2005). *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*. Cambridge: The MIT Press.

Schmitt, A. J., & Tomlin, B. (2012). Sourcing strategies to manage supply disruptions. In H. Gurnani, A. Mehrotra, & S. Ray (Eds.), *Supply Chain Disruptions: Theory and Practice of Managing Risk* (pp. 51-72). London: Springer.

Snyder, L. V., Atan, Z., Peng, P., Rong, Y., Schmitt, A. J., & Sinsoysal, B. (2016). OR/MS models for supply chain disruptions: A review. *IIE Transactions, 48*(2), 89-109.

Snyder, L. V., Scaparra, M. P., Daskin, M. S., & Church, R. L. (2006). Planning for Disruptions in Supply Chain Networks. *Tutorials in Operations Research*, 234-257.

Song, J.-S., & Zipkin, P. H. (1996). Inventory control with information about supply conditions. *Management Science*, *42*(10), 1409-1419.

Song, J.-S., & Zipkin, P. (2009). Inventories with multiple supply sources and networks of queues with overflow bypasses. *Management Science*, *55*(3), 362-372.

Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics, 103*(2), 451-488.

Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science*, *52*(5), 639-657.

Vakharia, A. J., & Yenipazarli, A. (2008). Managing supply chain disruptions. *Foundations and Trends in Technology, Information and Operations Management, 2*(4), 243-325.

Wagner, H. M. and T. M. Whitin (1958). Dynamic version of the economic lot size model. *Management Science*, 9, 1, 89-96.

Xia, Y., Yang, M.-H., Golany, B., Gilbert, S. M., & Yu, G. (2004). Real-time disruption management in a two-stage production and inventory system. *IIE Transactions*, *36*, 111-125.

Xiao, T. and Qi, X. (2008) Price competition, cost and demand disruptions and coordination of a supply chain with one manufacturer and two competing retailers. *Omega*, 36(5), 741–753.

Xiao, T. and Yu, G. (2006) Supply chain disruption management and evolutionarily stable strategies of retailers in the quantity-setting duopoly situation with homogeneous goods. *European Journal of Operational Research*, **173**(2), 648–668.

Xiao, T., Yu, G., Sheng, Z. and Xia, Y. (2005) Coordination of a supply chain with one-manufacturer and two-retailers under demand promotion and disruption management decisions. *Annals of Operations Research*, **135**(1), 87–109.