Building up Resilience in a Pharmaceutical Supply Chain through Inventory, Dual Sourcing and Agility Capacity

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Abstract

This paper is inspired by a risk management problem faced by a leading pharmaceutical company. Key operational risk mitigation measures include Risk Mitigation Inventory (RMI), Dual Sourcing and Agility Capacity. We study the relationship between these three measures by modeling the drug manufacturing firm that is exposed to supply chain disruption risk. The firm determines optimal RMI levels for assumed Dual Sourcing and Agility Capacity. We quantify the decrease in RMI levels in the presence of Dual Sourcing and Agility Capacity. Furthermore, using an example, we analyze RMI, Dual Sourcing and Agility Capacity decisions jointly. It turns out that RMI and Agility Capacity can be substitutes as long as no Dual Source is available. Once the Dual Source is available, Agility Capacity and Dual Sourcing appear to be substitutes. We further show that for long disruption times, the optimal Dual Source production rate may decrease in the disruption time. Within our modeling framework, we introduce an operational metric that quantifies Supply Chain Resilience. Supply chain disruptions can have a severe business impact and need to be managed appropriately.

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1. Introduction

During the past decade, a significant increase in drug shortages has been observed by the U.S. Government Accountability Office (GAO). Between 2007 and 2012 the number of active drug shortages in the U.S. grew from 154 to 456. The U.S. agency sees supply disruptions as the direct cause of supply shortages (GAO, 2014). In Switzerland, where the pharmaceutical industry plays an important role in the national economy, the government proposes that all relevant drug shortages should be centrally reported (Schweizer Radio und Fernsehen, 2014). Although pharmaceutical companies are committed to providing a secure and continuous supply of medical products, they also face shareholder pressure to operate cost-effectively.

The pharmaceutical industry is not unique. The focus on boosting efficiency in global supply chain networks has led to increasing vulnerabilities across industries (Sodhi and Tang, 2012). Managing supply disruptions appropriately and building resilient supply chains have thus emerged as important business challenges (WEF, 2013, 2012). While Supply Chain Resilience seems to be a high priority for top management, many companies still appear to manage supply disruptions in an ad hoc manner rather than viewing them as an integrated part of operations (Seifert and Lücker, 2014). The lack of clear Resilience metrics and quantitative decision tools contributes to many companies' hesitation when it comes to defining and implementing a holistic Supply Chain Resilience strategy.

In this paper we use the pharmaceutical industry as an example to analyze optimal risk mitigation strategies for a single firm that is exposed to supply chain disruption risk. The main risk mitigation levers are: holding additional inventory, so-called Risk Mitigation Inventory (RMI), and adding process flexibility (Simchi-Levi et al., 2015). RMI is designed to be used to meet customer demand in the event of a supply disruption. Our research focuses on analyzing RMI and process flexibility decisions jointly for a pharmaceutical firm. In this context, process flexibility refers to: 1) Establishing and qualifying a second manufacturing site (Dual Source) in addition to the disruption-prone first manufacturing site (primary site). In the pharmaceutical industry "qualifying" means that the facility is registered for all/major markets with the regulatory authorities. 2) Keeping a reserve capacity at the primary site for emergency production, so-called Agility Capacity.

We develop mathematical models that determine analytically the optimal RMI levels for an exogenously given process flexibility in terms of Dual Sourcing and Agility Capacity. We show numerically that RMI and Agility Capacity can be substitutes as long as no Dual Source is available. Once the Dual Source is available, Agility Capacity and Dual Sourcing appear to be substitutes. We further show that for long disruption times, the optimal Dual Source production rate may decrease in the disruption time. Within our modeling framework, we introduce an operational metric that quantifies Supply Chain Resilience. Our models incorporate pharma-specific regulatory constraints and production assumptions that are motivated by a research collaboration with a leading pharmaceutical company. Our work was then applied to pilot projects to assess the Supply Chain Resilience of life-saving drugs.

Our main contribution to the literature is to jointly analyze RMI and process flexibility decisions in the context of disruption risks. While RMI and process flexibility have been studied separately in the literature, little work has been undertaken to analyze them holistically. In particular, we provide novel insights on the sensitivity of the optimal risk mitigation strategy in model parameters such as disruption time or Resilience metric.

In the next section we describe the business setting of the pharmaceutical company and state our research questions. In section 3, we provide a literature review that focuses on Supply Chain Resilience and the pharmaceutical supply chain. We then present our mathematical models in section 4. We distinguish between a general model and two specific cases which arose in our research collaboration with the pharmaceutical company. To foster additional managerial insights, we provide numerical examples in section 5. Finally, we conclude this paper with recommendations for future research.

2. Business motivation and research questions

Having collaborated from the outset with a leading pharmaceutical company, we had the opportunity to analyze its Supply Chain Resilience strategy in detail. Given that the implementation of such a strategy not only has direct implications for patients' safety but also requires substantial capital expenditures and data collection, Supply Chain Resilience is a topic that has board level attention. The company's motivation to address Supply Chain Resilience is multifold, ranging from financial aspects (high product margin) to regulatory requirements to ethical aspects (reliable supply of life-saving drugs to patients).

To put costs into perspective, we cite the 2015 annual report of another pharmaceutical company, Pfizer (`http://www.pfizer.com/investors`): the innovative pharmaceutical segment has an average cost of sales of 11.2% of revenues (page 42). Annual sales of products in this segment typically exceed 1 bn USD. For example, Pfizer's Lyrica drug generated 4.8bn USD revenue in 2015, resulting in potential stockout costs of several million dollars per day if demand could not be met because of a disruption. Our industrial partner focuses its Supply Chain Resilience strategy on its key products from a financial and patient safety (life-saving drugs) perspective.

Resilience measures are predominantly implemented during the mature stage of the product life cycle, when the demand rate is stationary and can be approximated as constant for limited time periods. During the growth phase of the product life cycle, when the product faces non-stationary stochastic demand, practitioners focus their efforts on meeting demand and building up production capabilities. At the end of the product life cycle (decline phase), divestment strategies are undertaken.

To achieve Resilience, our industrial partner focuses on three risk mitigation levers, which are under the company's direct control (see Table 1): Dual Sourcing, Agility Capacity, and Risk Mitigation Inventory (RMI).

To assess Supply Chain Resilience on a product level, the company sets targets for each Resilience lever separately. The Dual Sourcing lever is measured in terms of market coverage of the Dual Source with respect to market registrations. An Agility Capacity of 20% is targeted for the various manufacturing sites, and RMI is determined by covering the 95^{th} percentile of a so-called *Disruption Risk Profile* (see below). The company has no methodology in place to determine how the Resilience levers relate to one another, e.g. to what extent RMI can be decreased in the presence of Dual Sourcing and Agility Capacity.

The idea behind the *Disruption Risk Profile* is to assess a manufacturing site's ability to recover from a variety of operational and catastrophic events. Such an event could be a biological contamination within the manufacturing site, a quality issue, or a natural hazard. These events are typically rare (less than 5% probability that such an event will occur in a given year), but they

	Dual Sourcing	Agility Capacity	RMI
Definition	Establish a 2^{nd} manufacturing site and register this site with the regulatory authorities for all/major markets.	Reserve capacity, quantified as the difference between "standard employed capacity" and "operating capacity" in hours.	Additional inventory on top of cycle inventory, work-in-progress and safety stock.
Time-horizon of implementation	Strategic: Implementation often takes up to 5 years due to regulatory complexity.	Tactical: Implementation in the long-range-planning for years 2+.	Operational: Implementation in the short term; RMI is built up during uptime.
Effectiveness	Dual Sourcing comes with an additional price tag for emergency production; in addition, Dual Source only becomes available after a time delay of 3 to 5 weeks for ramp-up.	The Agility Capacity at the primary site can produce goods immediately after the disruption with a production rate a, if the Agility Capacity is not interrupted (only certain disruptions can be mitigated, like a quality issue with a batch).	If stored at a safe distance, RMI can be used immediately to mitigate disruption risks.

Table 1: Main risk mitigation levers

can have a significant impact by causing a long disruption time (i.e. typically longer than four weeks). As a first step, the following data is collected for all relevant risk events that might cause supply disruptions: probability of the event and impact in terms of length of supply disruption. Probability and impact are determined for three scenarios: best, worst, and most likely case. This data is based on past records, a survey with the manufacturing sites, and commercially bought insurance data. The results are fed into a Monte Carlo simulation leading to a so-called *Disruption Risk Profile* that provides the cumulative probability distribution function for the maximal disruption time in a given year. The company has conducted this *Disruption Risk Assessment* for several key sites. Given the range of input factors being considered, management has decided to cover the 95^{th} percentile of a *Disruption Risk Profile* with RMI.

Based on our experience with the company, we formulate our main research questions:

1. Can we define a holistic quantitative Resilience metric that considers RMI and process flexibility jointly?
2. What are optimal RMI levels if process flexibility is exogenously given in terms of Dual Sourcing and Agility Capacity?
3. How does the optimal risk mitigation strategy depend on parameters such as disruption time and Resilience metric?

3. Literature review

Two major literature streams are relevant to our research: the managerial and academic literature on Supply Chain Resilience, which serves as the main motivation for our work, and the operations management literature related to disruption risk management, inventory control systems, Agility Capacity and Dual Sourcing.

The Supply Chain Resilience literature introduces different definitions, which we briefly summarize. A supply chain disturbance is defined as "a foreseeable or unforeseeable event, which directly affects the usual operation and stability of an organization or a supply chain" (Barroso et al., 2008). These disturbances concern not only the flow of goods but also information and financial flows. In this context, it is common to define supply chain vulnerability "as the incapacity of the supply chain, at a given moment, to react to the disturbances and consequently to attain its objectives" (Azevedo et al., 2008).

Disturbances make a supply chain more vulnerable and they might affect a company's performance not only in terms of direct financial losses but also in terms of negative corporate image and loss in demand. Hendricks and Singhal (2005a, 2005b) use an empirical approach to quantify the effect of supply chain disruptions on the long-run stock price performance. Analyzing a period starting one year before the disruption and lasting until two years after the disruption, they find that the average abnormal stock return after disclosing a supply disruption was nearly -40%. Furthermore, share price volatility, which can be taken as an indicator of equity risk, increased by 13.50% during the subsequent two years.

In order to address the problem of vulnerability, scholars describe the concept of Resilience in the supply chain as "the ability [of a supply chain] to return to its original state or move to a new, more desirable state after being disturbed" (Christopher and Peck, 2004). While risk management often focuses on high probability, low impact operational risks, Supply Chain Resilience addresses low probability, high impact catastrophic risks. The probability of these risks is considered to be increasing because of the inter-connectivity of global supply chain networks (WEF, 2013). A key lever for achieving Resilience is seen in operational risk management, which is identified as the “most important risk domain” (van Opstal, 2007) and is the focus of this paper.

For a general overview of risk management we refer to the relevant literature. Tang (2006) presents a general overview of supply chain risk management and mitigation strategies, whereas Dong and Tomlin (2012) provide a literature review of the operational disruption management literature. While some authors analyze inventory management for single systems (Moinzadeh and Aggarwal, 1997) or multi-location systems (Schmitt et al., 2015), this paper focuses on analyzing jointly the operational measures of RMI, Dual Sourcing and Agility Capacity. The relevance of balancing inventory and capacity decisions is pointed out by Chopra and Sodhi (2004).

Within the operations management literature, several authors have linked Dual Sourcing with inventory decisions, or capacity decisions with inventory decisions under specific circumstances. On the procurement side, Tomlin (2006) analyzes a firm that can source from two suppliers and explores parameters like reliability of the supplier and volume flexibility. This work complements papers that analyze Dual Sourcing decisions, e.g. (Ramasesh et al., 1991; Chen et al., 2012; Silbermayr and Minner, 2014; Allon and Van Mieghem, 2010; Berger et al., 2004; Ruiz-Torres and Mahmoodi, 2007; Yu at al., 2009; Sawik, 2014). These models provide powerful tools for analyzing procurement decisions. However, our research focuses on Dual Sourcing within the manufacturing process, for which the assumptions and parameters differ from the abovementioned models. Capacity and inventory decisions under seasonal demand are analyzed in (Bradley and Arntzen, 1999), where the authors use a mixed-integer program to maximize return on assets.

The propagation of disruption in a network is analyzed by Liberatore et al. (2012). Similarly, Simchi-Levi et al. (2015) analyze supply chain robustness for different network configurations in terms of process flexibility and inventory. Their work is based on a two-stage robust optimization model.

The interface between operational measures and business insurance is analyzed by Dong and Tomlin (2012). The authors include inventory decisions and emergency sourcing in their model. However, some assumptions differ from our purely operational model. Some parameters that are relevant to our model, such as time delay and finite production rate of the Dual Source, are not considered because of their focus on insurance policies.

While there is some academic literature on modeling disruption risks, linking the three mitigation measures in the context of risk management seems to be relatively unexplored. The need for a Resilience metric is pointed out in various managerial journals (WEF, 2012).

4. Mathematical model

The model we present in this section assumes that the firm produces a single product and that the production is subject to disruption risk. Such a disruption could have an internal cause such as a biological contamination at a productions site or an external cause such as an earthquake. To mitigate a disruption, the firm builds up RMI and process flexibility. RMI is used to serve unmet demand instantaneously during a potential disruption. The Dual Source and the Agility Capacity (process flexibility) allow for production after a disruption has occurred.

RMI is typically considered an efficient risk mitigation lever for short disruption times. For long disruption times, Dual Sourcing or Agility Capacity are efficient risk mitigation levers because carrying excessive RMI over time is less economical.

We assume that the primary site of a single firm is exposed to a severe disruption of length τ during a cycle of length T with $\tau < T$. The disruption occurs with probability ω. Given the low probability for such a disruption ($\omega < 5\%$), we assume that only one disruption occurs during a cycle. This assumption is in line with prior literature that explicitly excludes the case that two disruptions occur simultaneously (see, for example, Simchi-Levi et al. (2014); Hu and Kostamis (2015); Asian and Nie (2014); and Simchi-Levi et al. (2015), p. 7 for a discussion of this assumption). During the disruption we assume that approximate constant demand takes place, since we are focusing on the mature stage within the life cycle of the key product.

We develop mathematical models that analytically determine optimal RMI levels for an exogenously given process flexibility. We choose the RMI level as our main decision variable because this variable can most easily be adapted in practice (operational decision). Decisions regarding process flexibility are often of a strategic/tactical nature and are not taken solely based on a mathematical model. For completeness, however, we provide numerical results for a specific case that jointly evaluates optimal RMI, Dual Sourcing and Agility Capacity decisions. Our mathematical model assumes the following:

1. The primary site of a single firm is exposed to a disruption during a cycle, with probability ω and disruption time τ.
2. The Dual Source can produce goods in an emergency case with a production rate d. This Dual Source only becomes available after a time delay t_D (Table 1).
3. The Agility Capacity at the primary site can produce goods immediately

after the disruption with a production rate a, if the Agility Capacity is not interrupted.

4. For mature products, demand ξ is approximately constant during the disruption time.
5. The proportion of backlog orders to total demand is given by $\epsilon \in (0, 1]$.
6. RMI is held decentrally in a safe location (i.e. at the next manufacturing stage) and is thus not interrupted by the disruption.

To avoid trivial solutions, we further assume that $\tau \geq t_D$, $a < \xi$, and $a+d+p > \xi$. The time delay of the Dual Source (assumption 2) is due to scheduling restrictions and the lead time of production, including quality release. For a pharmaceutical company this delay can easily amount to 3 to 5 weeks. Regarding assumption 3, the availability of the Agility Capacity depends on the disruption type. For example, a quality issue represents a major risk in some pharmaceutical manufacturing stages within the supply chain. For such cases, the Agility Capacity can become a viable mitigation lever as the primary site itself is not necessarily affected. In our mathematical models, we can always switch off the Agility Capacity by setting the relevant parameters to zero. Assumption 6 ensures that RMI is not destroyed by the disruption. RMI is typically stored at the next manufacturing stage, which is geographically distant from the possible disruption location.

4.1. Analysis of the disruption phase and Resilience metric

In Figure 1 we display a single disruption that takes place at time $t = 0$. For a given level of RMI, we can immediately mitigate the disruption until RMI is depleted at time t_1. Starting at time t_D the Dual Source produces goods with production rate d (with $d > \xi$ being shown in Figure 1). At time τ the primary site produces goods at the maximal production rate p. The

Agility Capacity produces goods with a production rate a during t_0 and t_2 if the Agility Capacity is available. The backlog ends at time t_2.

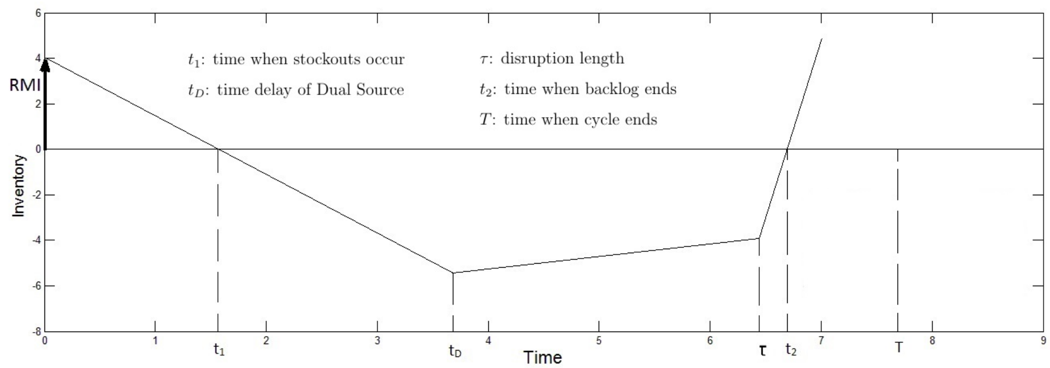

Figure 1: General model showing inventory levels over time

When defining a Resilience metric, we agreed with the pharmaceutical company that, together with the stockout quantity, the stockout time itself is important. Rather simplistic Resilience metrics such as two separate metrics for the relative stockout time (e.g. $\frac{t_1}{t_2}$, Figures 2, 3) and the projected service level during the stockout time might not lead to satisfactory results. A metric based on the relative stockout time might indicate a low Resilience score even if only a few stockouts occur, spread evenly over the disruption time. Hybrid performance measures that include stockout quantity and time have previously been studied in the context of the service level (Schneider, 1981). Motivated by these hybrid performance measures, we define the operational Resilience metric ρ as

$$\rho = \frac{M}{M+S}. \tag{1}$$

The surface S is defined as the *stockout surface* (quantity times time, see

Figures 2, 3 for an illustration),

$$S = -\int_{t_1}^{t_2} I(t)dt$$

where $I(t)$ is the RMI level at time t. Note that $I(t)$ can be negative for $t > t_1$. The surface M is the area that has been successfully mitigated (see Figures 2, 3 for an illustration).

$$M = M_1 + M_2 + M_3 = \int_0^{t_1} I(t)dt + \int_{t_D}^{\tau} tddt + \int_{\tau}^{t_2} t(d+p)dt,$$

where the first part originates from the RMI, the second part from the Dual Source and the third part from the primary site during the recovery phase. We have:

Lemma 1. *We have: $\rho \in [0,1]$, $\frac{d\rho}{dI} > 0$, and $\frac{d\rho}{da} > \frac{d\rho}{dd} > 0$. If no Dual Source is used we have: (i) $\rho = 0$ iff $I = 0$ and (ii) $\rho = 1$ iff $I = t_2\xi$. If no RMI is held, we have: (iii) $\rho = 0$ iff $d = 0$ and (iv) $\rho < 1$ if $d = \xi$.*

Proof. All results follow from $M = \frac{1}{2}\frac{I^2}{\xi} + (\tau - t_D)^2 d + \tau^2 a + (t_2 - \tau)^2(a + d + p)$ and $S = t_2^2\xi - M$. □

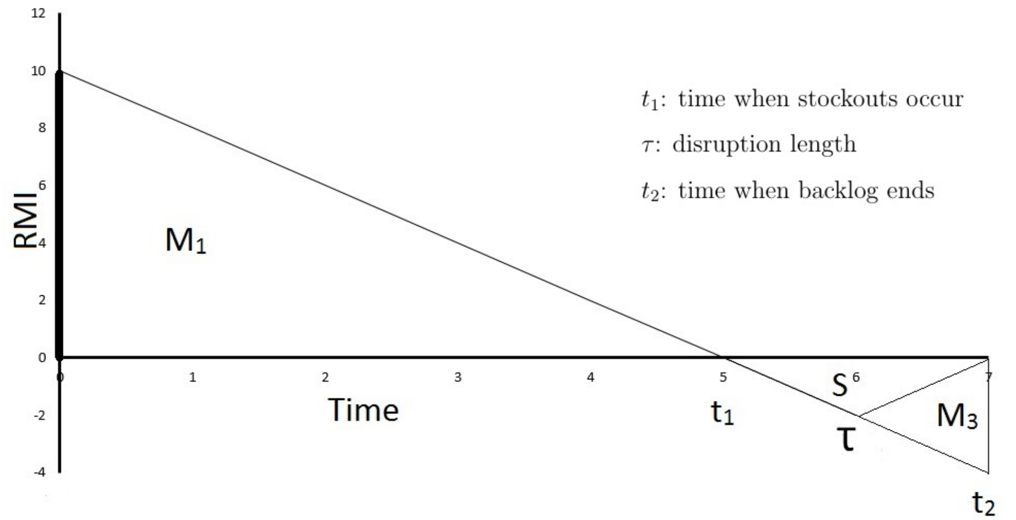

Figure 2: Stockout and mitigation surface without a Dual Source

Figures 2 and 3 illustrate that for an increased RMI or for a quicker and stronger Dual Source, the surface M increases, whereas the surface S decreases.

This metric is applied to the disruption time τ to visualize the company's capability to mitigate disruptions in a worst case scenario. Illustrative examples of the metric are presented in section 5.

To include the stockout time in our optimization problem, we define Resilience cost as

$$C_R = -\hat{R} \int_{t_1}^{t_2} I(t)dt, \tag{2}$$

with a penalty cost per item and time, $\hat{R}$. Note that RMI $I(t)$ is negative between time t_1 and t_2. This Resilience cost makes it possible to minimize the "surface of stockouts" (area of negative inventories between t_1 and t_2 in Figure 1) under further cost considerations. Such a penalty cost has been applied for different inventory control problems (Axsäter, 2006).

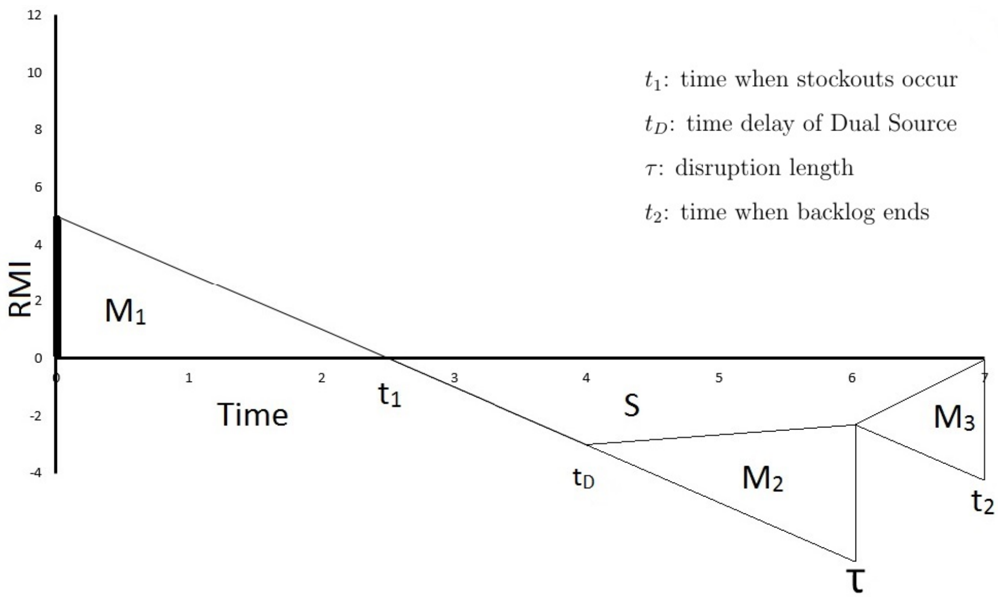

Figure 3: Stockout and mitigation surface with a Dual Source

4.2. General model

Our model is based on minimizing total costs over one cycle (e.g. one year) for a single firm that is exposed to disruption risk. The firm decides RMI levels before a disruption takes place. Process flexibility decisions are exogenously given. While some cost components (reservation cost for Dual Source and Agility Capacity) are incurred regardless of whether a disruption occurs, other cost components are only incurred when the disruption takes place (emergency production costs through Dual Source or Agility Capacity). Inventory holding costs C_I are only incurred as long as no disruption occurs. Further cost parameters are: Dual Source reservation cost C_D^0 and Dual Source production cost C_D, Agility Capacity reservation cost C_A^0 and Agility Capacity production cost C_A, a lost sales cost for stockouts C_P, and a Resilience cost for backlogs $\hat{R}$. All model parameters are given in Table A.2 in Appendix A.

The expected total cost function is

$$C(I_G) = \hat{C}_I(I_G) + \hat{C}_D(I_G) + \hat{C}_A(I_G) + C_P(I_G) + C_R(I_G). \tag{3}$$

We distinguish between two cases:

- *Short time delay*: $t_D < t_1$
- *Long time delay*: $t_D \geq t_1$

Note that t_1 depends on our decision variable I_G. In the following we assume that $t_D < t_1$. At the end of this section we fully characterize this case in terms of model parameters only. The case $t_D \geq t_1$, which follows a parallel analysis, will be treated in the appendix. In addition, we assume that $a + d < \xi$. This assumption will be relaxed in section 4.2.2.

The first cost component of Eq. 3 is the inventory holding cost, which is incurred over the entire cycle as long as no disruption occurs.

$$\hat{C}_I(I_G) = C_I I_G (1 - \omega) \tag{4}$$

where ω is the probability that a disruption occurs. Note that these inventory holding costs are only an approximation. For a more precise treatment, one could replace $C_I(1-\omega) \rightarrow C_I(1-\omega) + C_I\omega\frac{1}{2} + C_I\omega(1-\frac{\tau}{T})$. The $C_I\omega\frac{1}{2}$ term reflects the situation that inventory holding costs are incurred during the disruption time when inventory is carried for at least some of the disruption time. The $C_I\omega(1-\frac{\tau}{T})$ term reflects the situation that RMI might still be held for part of the disrupted cycle time. For simplicity, we will refer only to C_I, given the low probability for disruptions.

The Dual Source production cost consists of two components: a fixed amount for reserving the free capacity, which is incurred over the entire cycle regardless of whether a disruption occurs; and an additional production cost per item that is incurred only if the disruption takes place.

$$\hat{C}_D(I_G) = C_D^0 d + C_D d(t_2 - t_D)\omega. \tag{5}$$

Similarly, the Agility Capacity cost splits into two parts.

$$\hat{C}_A(I_G) = C_A^0 a + C_A a t_2 \omega. \tag{6}$$

The lost sales cost is incurred for the $(1 - \epsilon)$ part of the effective demand $(\xi - a - d)$ during the time interval (t_1, τ), when lost sales occur.

$$\hat{C}_P(I_G) = C_P(\xi - a - d)(1 - \epsilon)(\tau - t_1)\omega. \tag{7}$$

The Resilience cost consists of two parts. One part arises during the time interval (t_1, τ), before the primary site recovers. The other part originates from the remaining backlog once the primary site recovers (time interval (τ, t_2)).

$$C_R(I_G) = \hat{R}\Big(\epsilon \int_0^{\tau - t_1} (\xi - a - d)t dt + \int_0^{t_2 - \tau} (n + (\xi - a - d - p)t) dt\Big)\omega, \tag{8}$$

where n is the backlog at time τ,

$$n = [(\xi - a - d)(\tau - t_D) - I_G]\epsilon.$$

The starting time of stockouts t_1 is given by setting supply volumes equal to demand volumes.

$$I_G + at_1 + (t_1 - t_D)d = \xi t_1,$$

which becomes

$$t_1 = \frac{I_G - dt_D}{\xi - a - d}. \tag{9}$$

The time when the backlog ends, t_2, consists of two components. One is the disruption time τ and the other is the time to serve all outstanding backlogs once the site has recovered.

$$t_2 = \tau + \frac{n}{a + d + p - \xi}. \tag{10}$$

Our general model gives an explicit analytic expression for the optimal RMI level I_G^* depending on Dual Sourcing and Agility Capacity parameters. Using first and second order conditions for the expected total costs (Eq. 3) leads to

$$I_G^* = \frac{-C_I\frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon\frac{C_A a + C_D d}{a+d+p-\xi} + \hat{R}\epsilon(\epsilon\frac{(\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau + \frac{dt_D}{\xi-a-d})}{\hat{R}\epsilon(\frac{\epsilon}{a+d+p-\xi} + \frac{1}{\xi-a-d})}. \tag{11}$$

Note that $\hat{R} < \frac{C_I\frac{(1-\omega)}{\omega} - C_P(1-\epsilon) - \epsilon\frac{C_A a + C_D d}{a+d+p-\xi}}{\epsilon\frac{(\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau}$ would result in negative optimal RMI levels. Note further that the condition $t_D < t_1$ (*short time delay*) is satisfied if and only if

$$\frac{-C_I\frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon\frac{C_A a + C_D d}{a+d+p-\xi} + \hat{R}\epsilon(\epsilon\frac{(\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau + \frac{dt_D}{\xi-a-d})}{\hat{R}\epsilon(\frac{\epsilon}{a+d+p-\xi} + \frac{1}{\xi-a-d})(\xi-a)} > t_D. \tag{12}$$

We find in general:

Proposition 1. *For a positive Resilience cost per item and per time* $\hat{R} \geq$

$\frac{C_I \frac{(1-\omega)}{\omega} - C_P(1-\epsilon) - \epsilon \frac{C_A a + C_D d}{a+d+p-\xi}}{\epsilon \frac{(\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau}$*, and for an exogenously given process flexibility, the optimal RMI* I_G^* *is given by*

$$I_G^* = \begin{cases} \frac{-C_I \frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon \frac{C_A a + C_D d}{a+d+p-\xi} + \hat{R}\epsilon(\epsilon \frac{(\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau + \frac{d t_D}{\xi-a-d})}{\hat{R}\epsilon(\frac{\epsilon}{a+d+p-\xi} + \frac{1}{\xi-a-d})} & \text{for } \textit{short time delay} \\ \frac{-C_I \frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon \frac{C_A a + C_D d}{a+d+p-\xi} + \hat{R}\epsilon(\epsilon \frac{(\xi-a)t_D + (\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau)}{\hat{R}\epsilon(\frac{\epsilon}{a+d+p-\xi} + \frac{1}{\xi-a})} & \text{for } \textit{long time delay.} \end{cases} \quad (13)$$

Proof. We refer to Appendix B for the case *long time delay.* □

Numerical results and managerial insights are discussed in section 5. In collaboration with the pharmaceutical company we reached the conclusion that the following two cases are relevant for applications:

- Hot Standby case: the Dual Source is strong and the disruption ends before the primary site restarts production ($a + d > \xi$).
- Quick Recovery case: the disruptions ends immediately once the primary site starts producing goods again. This is relevant for applications in which large batch sizes are produced (e.g. the production of the Active Pharmaceutical Ingredient, API) and it is reasonable to assume that $p \to \infty$.

In the following we discuss these two cases.

4.2.1. Hot Standby case

Here we address the special case that the Dual Source is strong and the disruption ends before the primary site recovers, $a + d > \xi$ (see Figure 4). This can be the case, for example, when the Dual Source has sufficient excess capacity or when the demand rate is very low.

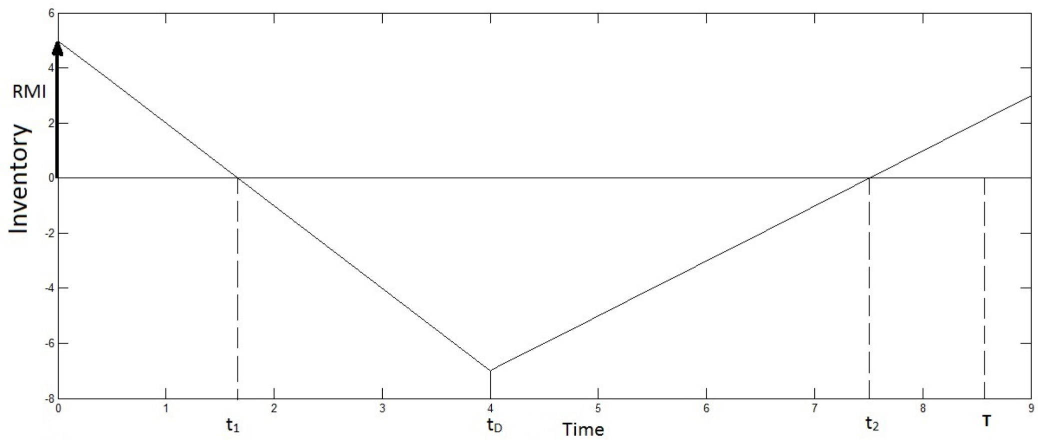

Figure 4: Hot Standby case: Dual Source/Agility Capacity takes over full production

The analysis of this case is similar to the general model. However, in contrast to Proposition 1, we only have to consider the case *long time delay* because the sum of the Dual Source and Agility Capacity production rates is assumed to be greater than the demand rate. Hence, stockouts only occur before the Dual Source starts production. Analogous to Proposition 1, the starting time of stockouts t_1 is given by

$$t_1 = \frac{I_H}{\xi - a}, \tag{14}$$

where I_H is the RMI level. The maximal backlog n is given by

$$n = (\xi - a)(t_D - t_1)\epsilon = ((\xi - a)t_D - I_H)\epsilon,$$

which leads to

$$t_2 = \frac{n}{a + d - \xi} + t_D = \frac{(\xi - a)t_D - I_H}{a + d - \xi}\epsilon + t_D. \tag{15}$$

Similar to the general model, we find:

Proposition 2. *For a positive Resilience cost per item and per time* $\hat{R} \geq \frac{C_I \frac{(1-\omega)}{\omega} - C_P(1-\epsilon) - \epsilon \frac{C_A a + C_D d}{a+d-\xi}}{\epsilon t_D (1+\epsilon \frac{\xi - a}{a+d-\xi})}$*, and for an exogenously given process flexibility, the optimal RMI* I_H^* *is given by*

$$I_H^* = t_D(\xi - a) - \frac{C_I \frac{(1-\omega)}{\omega} - C_P(1-\epsilon) - \epsilon \frac{C_A a + C_D d}{a+d-\xi}}{\hat{R}\epsilon(\frac{1}{\xi - a} + \frac{\epsilon}{a+d-\xi})}. \tag{16}$$

Proof. See Appendix C for a detailed proof. □

Note that for $\hat{R} \to \infty$ we have

$$I_H^* = t_D(\xi - a), \tag{17}$$

which means that there is sufficient RMI to cover the whole disruption until the Dual Source is qualified.

4.2.2. Quick Recovery case

In this case we assume that there are no more stockouts or backlogs once the primary site is fully functional again (see Figure 5). In the pharmaceutical industry this is the case, for example, when large batch sizes (e.g. API) are produced.

For the general case we can take the limit $p \to \infty$ and find:

Proposition 3. *For a positive Resilience cost per item and per time* $\hat{R} \geq \frac{C_I \frac{(1-\omega)}{\omega} - C_P(1-\epsilon)}{\epsilon \tau}$*, and for an exogenously given process flexibility, the optimal RMI* I_Q^* *is given by*

$$I_Q^* = \begin{cases} \frac{(-C_I \frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \hat{R}\epsilon(\tau + \frac{d t_D}{\xi - a - d}))(\xi - a - d)}{\hat{R}\epsilon} & \text{for } \textit{short time delay} \\ \frac{(-C_I \frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \hat{R}\epsilon\tau)(\xi - a)}{\hat{R}\epsilon} & \text{for } \textit{long time delay} \end{cases} \tag{18}$$

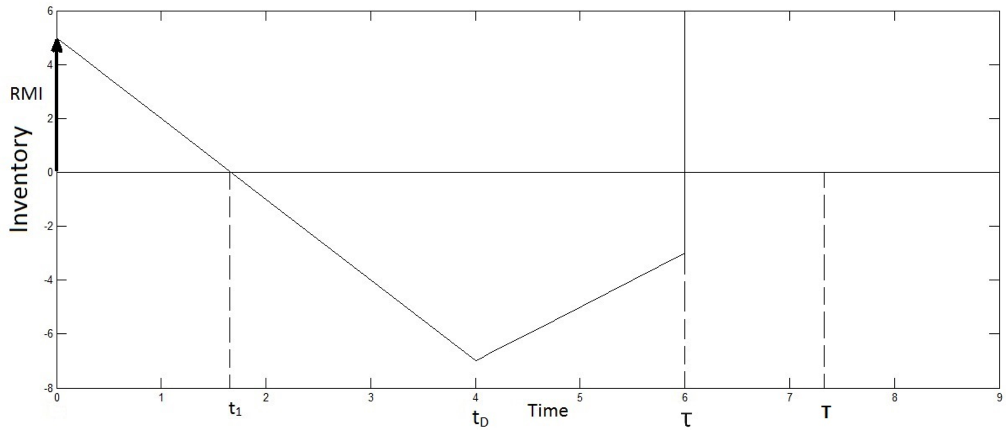

Figure 5: Quick Recovery case: Strong primary site

Proof. See Appendix D for a proof. □

Note that the condition $t_D < t_1$ (*short time delay*) is satisfied if and only if

$$\frac{-C_I\frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \hat{R}\epsilon\tau}{\hat{R}\epsilon} > t_D. \tag{19}$$

5. Numerical results

In this section we explore how different model parameters influence the risk mitigation strategy. First, we provide an illustration of the Resilience metric. Second, we analyze RMI and process flexibility decisions jointly. Third, we perform a sensitivity analysis of our decision variable in relevant model parameters.

5.1. Definition of metric

We recall that the Resilience metric ρ is defined by stockout quantity and stockout time. In Figure 6 we provide an illustrative visualization of the metric (an example calculation is given in Appendix E). We illustrate the performance of our resilience metric ρ (y-axis) depending on RMI (x-axis) for the Quick Recovery case. There are three groups of lines for the different Dual Sourcing scenarios ($d = 0.0$, $d = 0.3$, $d = 0.8$). Each group contains three lines for the different Agility Capacity scenarios ($a = 0.00$, $a = 0.05$, $a = 0.10$). The plot is based on the following further parameters: $\tau = 210,\ t_D = 30,\ \xi = 1,\ d = 0.0,\ 0.3,\ 0.8,\ a = 0.00,\ 0.05,\ 0.10,\ \epsilon = 1$.

Figure 6 illustrates the extent to which RMI can be reduced if disruptions are mitigated through Dual Sourcing and/or Agility Capacity if ρ is kept constant. For example, at $\rho = 0.8$, RMI can decrease from $RMI = 140$ units (no Dual Source or Agility Capacity) to $RMI = 7$ units ($d = 0.8$, $a = 0.10$). The graph also illustrates how Resilience ρ increases if Dual Sourcing and/or Agility Capacity increase while RMI is kept constant. For example, at $RMI = 50$ units, Resilience increases from $\rho = 0.1$ (no Dual Source or Agility Capacity) to $\rho = 1.0$ ($d = 0.8$, $a = 0.10$).

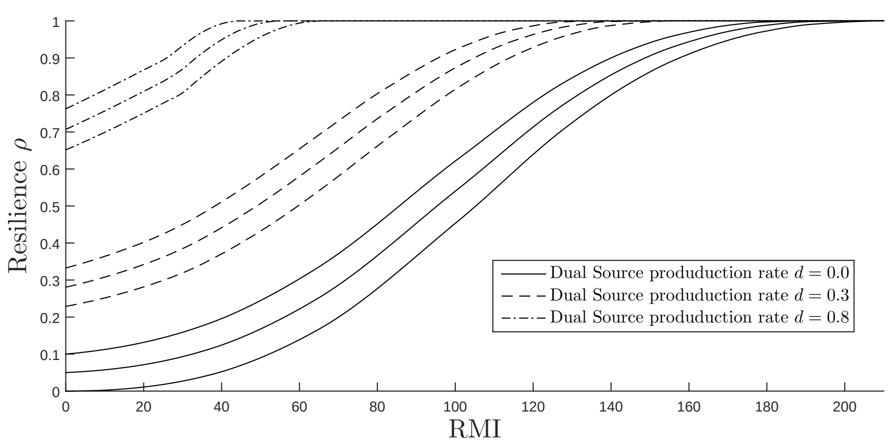

Figure 6: Resilience metric depending on RMI

5.2. Variable target Resilience ρ

So far we have considered the Dual Source production rate d to be exogenously given. In this section we minimize the total cost function (D.1) for the Quick Recovery case whereby we keep I_Q and d as independent decision variables and a as exogenously given:

$$C(I_Q, d) = \hat{C}_I(I_Q) + \hat{C}_D(I_Q, d) + \hat{C}_A(I_Q) + C_P(I_Q, d) + C_R(I_Q, d). \qquad (20)$$

We perform the numerical optimization with the fmincon solver from MATLAB. Figure 7 shows how RMI I_Q^* (y-axis) depends on the target Resilience ρ (x-axis). Likewise, Figure 8 shows how the Dual Source production rate d^* (y-axis) depends on the target Resilience ρ (x-axis). In both figures we display three plots for different Agility Capacity production rates respectively ($a = 0.00,\ a = 0.05,\ a = 0.10$). Figure 7 illustrates that RMI increases in Resilience ρ for $\rho < 0.55$, before the RMI reaches its maximum value in the range $0.55 < \rho < 0.65$ (depending on Agility Capacity production rate a). Afterwards RMI decreases in ρ as the Dual Source production rate d^* increases (Figure 8). Note that RMI does not decrease to 0 when the Dual Source covers 100% of the demand ($d = 1.0$) and when $\rho = 1.0$ due to the time delay of the Dual Source.

In Figure 7, for $\rho < 0.65$, RMI levels decrease in the Agility Capacity production rate a. For $\rho > 0.65$, RMI hardly changes in the Agility Capacity production rate. However, for $\rho > 0.65$, Dual Sourcing decreases in the Agility Capacity production rate a, revealing that Agility Capacity and Dual Sourcing are substitutes (Figure 8). It appears that RMI and Agility Capacity are substitutes as long as no Dual Source is available. Once the Dual Source is available, Agility Capacity and Dual Sourcing appear to be substitutes. The plots are based on $\hat{R} = 2,\ C_I = 4.2,\ C_D = 50,\ C_D^0 = 20,\ C_A = 20,\ C_A^0 = 40,\ \tau = 210,\ t_D = 30,\ \xi = 1$ and $\epsilon = 1$.

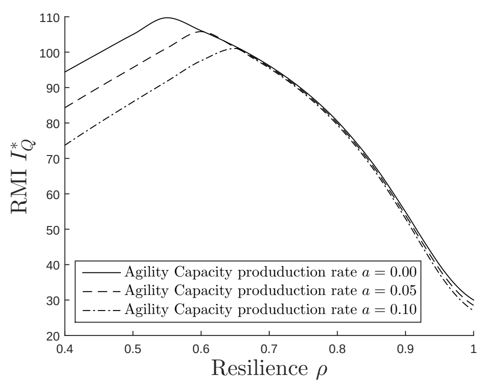

Figure 7: RMI depending on Resilience metric

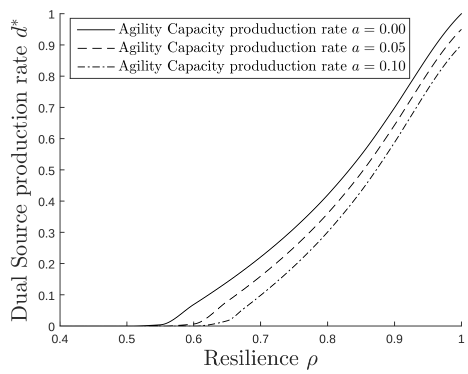

Figure 8: Dual Source production rate depending on Resilience metric

Following prior literature (for example, Tomlin (2006) and the literature cited therein), this numerical example does not consider fixed costs for the Dual Source. There are, however, two ways to incorporate such fixed costs for practical applications. One can either set an additional constraint on d (e.g. $d > 0.05$) or one can perform an additional NPV calculation (e.g. the discounted cash flow is calculated for each cycle minus the investment costs for the Dual Source) and then evaluate the value of Dual Sourcing.

5.3. Variable disruption time τ

As in section 5.2 we minimize the total cost function (D.1) for the Quick Recovery case whereby we keep I_Q and d as independent decision variables and a as exogenously given. However, we keep $\rho = 0.9$ constant and vary the disruption time τ. All other parameters are as above. Figure 9 shows that the Dual Source is only used for a minimal disruption time $\tau = 74$. For shorter disruption times the Dual Source reservation costs are too high compared to the inventory holding costs. For $\tau > 74$ the Dual Source production rate d^* increases in τ until a maximum is reached at $\tau = 150$. Interestingly, d^* decreases in τ for long disruption times. One might expect that long disruption times are optimally mitigated with a large Dual Source production rate. We recall that two cost components are associated with the Dual Source: a reservation fee $C_D^0 d$, and an emergency production cost $C_D d(t_2 - t_D)\omega$. As there is an extra price tag for emergency production through the Dual Source, Dual Sourcing may not be the optimal strategy for long disruption times τ. Instead, holding RMI over all the time may be cheaper than paying this extra price tag for emergency production.

Figure 10 shows that RMI increases in τ for $\tau < 74$. For $\tau > 74$, the Dual Source is in use and RMI I_Q^* decreases in τ. As a^* decreases in τ for long disruption times, RMI increases in τ as ρ is kept constant.

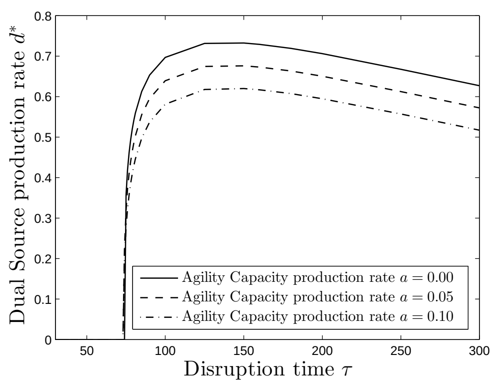

Figure 9: Dual Source production rate depending on disruption time

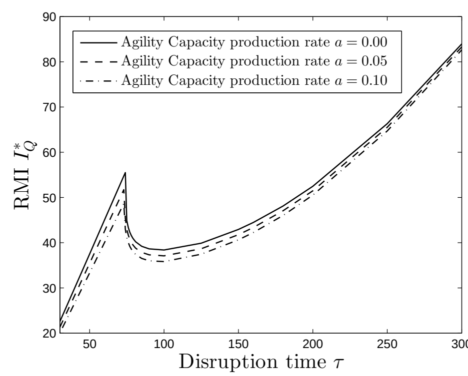

Figure 10: RMI depending on disruption time

5.4. Sensitivity analysis

We perform a sensitivity analysis in the optimal RMI I_G^* for the general model. I_G^* increases in C_P, C_A, C_D, ω, τ, and decreases in C_I. These results follow directly from Eq. (13). For the sensitivity in τ note that $\frac{dI_G^*}{d\tau} \geq (\xi - a - d) > 0$. As the probability for a disruption increases or as the disruption time increases, more RMI is built up. Likewise, if Dual Sourcing/Agility Capacity costs or penalty costs increase, RMI increases as well. RMI decreases in the inventory holding costs. I_G^* may decrease or increase in $\hat{R}$. For *short time delay* we have: $\frac{dI_G^*}{d\hat{R}} = -\frac{1}{\hat{R}^2} \frac{-C_I \frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon \frac{C_A a + C_D d}{a+d+p-\xi}}{\epsilon(\frac{\epsilon}{a+d+p-\xi} + \frac{1}{\xi-a-d})}$. The sign of the last term is ambiguous. Depending on the cost parameters, it could be that Dual Sourcing/Agility Capacity is more efficient than RMI as $\hat{R}$ increases. Regarding the sensitivity in ξ, d, a, p, t_D and ϵ, we refer to the relevant Quick Recovery case ($t_D < t_1$) as the economic insights can best be studied for this case: RMI increases in the Dual Source time delay t_D ($\frac{dI_Q^*}{dt_D} = d > 0$). As the time delay of the Dual Source increases, RMI increases by an amount that is proportional to the production rate of the Dual Source. For the sensitivity in the proportion of backlog orders to total demand ϵ, we find a sensitivity to the power of -2: $\frac{dI_Q^*}{d\epsilon} = \frac{C_I \frac{1-\omega}{\omega} - C_P}{\hat{R}\epsilon^2}(\xi - a - d)$. The sensitivity in the demand rate or production rate of Dual Source/Agility Capacity is given by: $\frac{dI_Q^*}{d\xi} = \frac{-C_I \frac{1-\omega}{\omega} + C_P(1-\epsilon)}{\hat{R}\epsilon} + \tau$, $\frac{dI_Q^*}{dd} = \frac{C_I \frac{1-\omega}{\omega} - C_P(1-\epsilon)}{\hat{R}\epsilon} - \tau + t_D$, $\frac{dI_Q^*}{da} = \frac{C_I \frac{1-\omega}{\omega} - C_P(1-\epsilon)}{\hat{R}\epsilon} - \tau$. The sensitivity of I_Q^* in the last four parameters is ambiguous. Depending on penalty costs, inventory holding costs, disruption probabilities, disruption times and proportion of backlog orders to total demand, I_Q^* may increase or decrease in the last parameters.

6. Conclusions and future research

In this research we have analyzed the three risk mitigation strategies RMI, Dual Sourcing and Agility Capacity. We find analytic results for optimal RMI levels if the characteristics for Dual Sourcing and Agility Capacity are exogenously given. In addition, we define a Resilience metric that allows a firm to track Supply Chain Resilience and assess trade-offs between risk mitigation levers in quantitative terms. This metric is based on the stockout time as well as the percentage of served demand during the disruption time. Our numerical results suggest that RMI and Agility Capacity can be substitutes as long as no Dual Source is available. Once the Dual Source is available, Agility Capacity and Dual Sourcing appear to be substitutes. We further show that for long disruption times, the optimal Dual Source production rate may decrease in the disruption time.

Our modeling work was validated by our industrial partner and subsequently applied to Supply Chain Resilience assessments for life-saving drugs. Single and Dual Sourcing scenarios (with and without Agility Capacity) were analyzed for the production in various production stages.

While these models are based on the practice and structure of a pharmaceutical supply chain, this work raises a couple of research questions to explore the generality of the analysis and the results across industries. It would be interesting to study if these results still hold under stochastic demand. This would also allow to explore the relation of RMI to safety stock in the context of the (Q, R) model. Further research extensions could address multi-echelon supply chains. In the pharmaceutical industry this would entail analyzing drug substance, drug product and finished goods production holistically.

Acknowledgments

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Appendix A. Decision variable and parameters of the model

Decision variable:	
$I \geq 0$	RMI level
Parameters:	
$C_I > 0$	Inventory holding cost per item
$C_D^0 > 0$	Dual Source reservation cost
$C_D > 0$	Dual Source production cost
$C_A^0 > 0$	Agility Capacity reservation cost
$C_A > 0$	Agility Capacity production cost
$C_P > 0$	Lost sales cost for stockouts
$\hat{R} > 0$	Resilience cost for backlogs
$t_D > 0$	Time delay of Dual source
$\xi > 0$	Deterministic demand during disruption
$d \geq 0$	Production rate of the Dual Source
$a \geq 0$	Production rate of the Agility Capacity
$p > 0$	Maximal production rate of the primary site
$\epsilon \in (0, 1]$	Percentage of stockouts that are backlogged
$\tau > 0$	Disruption time
$\omega \in (0, 1)$	Probability for disruption
Constraints: $\tau \geq t_D$, $a < \xi$, $a + d + p > \xi$	

Table A.2: Decision variable and parameters of the model

Appendix B. Proof of Proposition 1

Proof. For the case *long time delay* we have to consider the following changes: The lost sales cost for stockouts consists of two parts. One part arises during the time interval (t_1, t_D), before the Dual Source delivers goods. The other part arises during the time interval (t_D, τ).

$$\hat{C}_P(I_G) = C_P(1-\epsilon)\Big((\xi - a)(t_D - t_1) + (\xi - a - d)(\tau - t_D)\Big)\omega. \tag{B.1}$$

The Resilience cost consists of three parts. One part arises during the time interval (t_1, t_D), before the Dual Source delivers goods. Another part arises during the time interval (t_D, τ). The third part originates from the remaining backlog once the primary site recovers (time interval (τ, t_2)).

$$\begin{aligned} C_R(I_G) = \quad & \hat{R}\Big(\epsilon \int_0^{t_D - t_1} (\xi - a)t dt + \epsilon \int_0^{\tau - t_D} ((\xi - a)t_D - I_G + (\xi - a - d)t)dt \\ & + \int_0^{t_2 - \tau} (n + (\xi - a - d - p)t)dt\Big)\omega, \end{aligned} \tag{B.2}$$

where n is the backlog at time τ,

$$n = [(\xi - a)t_D + (\xi - a - d)(\tau - t_D) - I_G]\epsilon.$$

The starting time of stockouts t_1 is given by setting supply volumes equal to demand volumes.

$$I_G + at_1 = \xi t_1,$$

which becomes

$$t_1 = \frac{I_G}{\xi - a}. \tag{B.3}$$

The time when the backlog ends, t_2, consists of two components. One is the disruption time τ and the other is the time to serve all outstanding backlogs once the site has recovered.

$$t_2 = \tau + \frac{n}{a+d+p-\xi}. \tag{B.4}$$

Using first and second order conditions for the expected total costs (Eq. 3) leads to

$$I_G^* = \frac{-C_I\frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon\frac{C_A a + C_D d}{a+d+p-\xi} + \hat{R}\epsilon(\epsilon\frac{(\xi-a)t_D + (\xi-a-d)(\tau-t_D)}{a+d+p-\xi} + \tau)}{\hat{R}\epsilon(\frac{\epsilon}{a+d+p-\xi} + \frac{1}{\xi-a})}. \tag{B.5}$$

Regarding the second order condition, it is sufficient to look at the Resilience cost because the other terms of the objective function are linear in I_G:

$$\frac{\partial C_R}{\partial I_G} = -\hat{R}\epsilon(\xi-a)(t_D-t_1)+(\xi-a-d-p)(t_2-\tau)\frac{-\epsilon}{a+d+p-\xi} - \frac{2n\epsilon}{a+d+p-\xi}$$

$$\begin{aligned}\frac{\partial^2 C_R}{\partial I_G^2} &= \hat{R}\epsilon(\xi-a)\frac{1}{(\xi-a)} + (\xi-a-d-p)\left(\frac{-\epsilon}{a+d+p-\xi}\right)^2 + \frac{2\epsilon^2}{a+d+p-\xi} \\ &= \hat{R}\epsilon + \frac{\epsilon^2}{a+d+p-\xi} > 0.\end{aligned}$$

□

Appendix C. Direct proof of Proposition 2

Proof. The proof is based on minimizing the total cost function

$$C(I_H) = \hat{C}_I(I_H) + \hat{C}_D(I_H) + \hat{C}_A(I_H) + C_P(I_H) + C_R(I_G). \tag{C.1}$$

The first cost component is the inventory holding cost.

$$\hat{C}_I(I_H) = C_I I_H(1-\omega). \tag{C.2}$$

The Dual Source production cost consists of a fixed component for reserving the free capacity and an additional production cost per item.

$$\hat{C}_D(I_H) = C_D^0 d + C_D d(t_2 - t_D)\omega. \tag{C.3}$$

Similarly, the Agility Capacity cost is given by

$$\hat{C}_A(I_H) = C_A^0 a + C_A a t_2 \omega. \tag{C.4}$$

The lost sales cost for stockouts is given by

$$\hat{C}_P(I_H) = C_P(\xi - a)(1-\epsilon)(t_D - t_1)\omega. \tag{C.5}$$

The Resilience cost is given by

$$C_R(I_H) = \hat{R}\Big(\int_0^{t_2-\tau}(n + (\xi - a - d)t)dt + \epsilon\int_0^{\tau - t_1}(\xi - a - d)tdt\Big)\omega, \tag{C.6}$$

where n is the backlog at time τ,

$$n = (\xi - a)(t_D - t_1)\epsilon = ((\xi - a)t_D - I_H)\epsilon.$$

t_1 is given by

$$t_1 = \frac{I_H}{\xi - a}.$$

Using first and second order constraints leads to

$$I_H^* = \frac{-C_I\frac{(1-\omega)}{\omega} + C_P(1-\epsilon) + \epsilon\frac{C_A a + C_D d}{a+d-\xi} + \hat{R}\epsilon t_D(1+\epsilon\frac{\xi-a}{a+d-\xi})}{\hat{R}\epsilon(\frac{1}{\xi-a} + \frac{\epsilon}{a+d-\xi})} \tag{C.7}$$

$$= t_D(\xi-a) - \frac{C_I\frac{(1-\omega)}{\omega} - C_P(1-\epsilon) - \epsilon\frac{C_A a + C_D d}{a+d-\xi}}{\hat{R}\epsilon(\frac{1}{\xi-a} + \frac{\epsilon}{a+d-\xi})}. \tag{C.8}$$

□

Appendix D. Direct proof of Proposition 3

Proof. The proof is based on minimizing the total cost function

$$C(I_Q) = \hat{C}_I(I_Q) + \hat{C}_D(I_Q) + \hat{C}_A(I_Q) + C_P(I_Q) + C_R(I_Q). \tag{D.1}$$

The first cost component is the inventory holding cost.

$$\hat{C}_I(I_Q) = C_I I_Q(1-\omega). \tag{D.2}$$

The Dual Source production cost consists of a fixed component for reserving the free capacity and an additional production cost per item.

$$\hat{C}_D(I_Q) = C_D^0 d + C_D d(\tau - t_D)\omega. \tag{D.3}$$

Similarly, the Agility Capacity cost is given by

$$\hat{C}_A(I_Q) = C_A^0 a + C_A a\tau\omega. \tag{D.4}$$

The lost sales cost for stockouts is given by

$$\hat{C}_P(I_Q) = \begin{cases} C_P(1-\epsilon)(\xi-a-d)(\tau-t_1)\omega & \text{for } \textit{short time delay} \\ C_P(1-\epsilon)\Big((\xi-a)(t_D-t_1)+(\xi-a-d)(1-\epsilon)(\tau-t_D)\Big)\omega & \text{for } \textit{long time delay.} \end{cases} \tag{D.5}$$

The Resilience cost is given by

$$C_R(I_Q) = \begin{cases} \hat{R}\Big(\epsilon\int_0^{\tau-t_1}(\xi-d-a)tdt\Big)\omega & \text{for } \textit{short time delay} \\ \hat{R}\Big(\epsilon\int_0^{t_D-t_1}(\xi-a)tdt+\int_0^{\tau-t_D}(m+(\xi-d-a)t)dt\Big)\omega & \text{for } \textit{long time delay,} \end{cases} \tag{D.6}$$

where the backlog m at time t_D is given by:

$$m = ((\xi-a)t_D - I_Q)\epsilon.$$

t_1 is given by

$$t_1 = \begin{cases} \frac{I_Q-dt_D}{\xi-a-d} & \text{for } \textit{short time delay} \\ \frac{I_Q}{\xi-a} & \text{for } \textit{long time delay.} \end{cases} \tag{D.7}$$

Using first and second order constraints leads to

$$I_Q^* = \begin{cases} \frac{(-C_I\frac{(1-\omega)}{\omega}+C_P(1-\epsilon)+\hat{R}\epsilon(\tau+\frac{dt_D}{\xi-a-d}))(\xi-a-d)}{\hat{R}\epsilon} & \text{for } \textit{short time delay} \\ \frac{(-C_I\frac{(1-\omega)}{\omega}+C_P(1-\epsilon)+\hat{R}\epsilon\tau)(\xi-a)}{\hat{R}\epsilon} & \text{for } \textit{long time delay.} \end{cases} \tag{D.8}$$

□

Appendix E. Calculation of Resilience metric

To illustrate how to calculate ρ we provide an example with $RMI = 105$, $d = 0.0$ and $a = 0.00$: $M = M_1 = \int_0^{t_1} I(t)dt = \int_0^{t_1} RMI - \xi tdt = RMI * t_1 - \frac{1}{2}\xi * t_1^2 = 5512.5$ with $t_1 = \frac{RMI}{\xi} = 105$ and $S = -\int_{t_1}^{t_2} I(t)dt = \int_{t_1}^{t_2} \xi tdt =$

$\xi \frac{1}{2}(t_2 - t_1)^2 = 5512.5$ leading to $\rho = \frac{M}{M+S} = 0.5$.

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