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DEVELOPMENT OF A SUPPLIER SEGMENTATION METHOD FOR INCREASED RESILIENCE AND ROBUSTNESS: A STUDY USING AGENT BASED MODELING AND SIMULATION

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DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By

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2017

ABSTRACT OF DISSERTATION

DEVELOPMENT OF A SUPPLIER SEGMENTATION METHOD FOR INCREASED RESILIENCE AND ROBUSTNESS: A STUDY USING AGENT BASED MODELING AND SIMULATION

Supply chain management is a complex process requiring the coordination of numerous decisions in the attempt to balance often-conflicting objectives such as quality, cost, and on-time delivery. To meet these and other objectives, a focal company must develop organized systems for establishing and managing its supplier relationships. A reliable, decision-support tool is needed for selecting the best procurement strategy for each supplier, given knowledge of the existing sourcing environment. Supplier segmentation is a well-established and resource-efficient tool used to identify procurement strategies for groups of suppliers with similar characteristics. However, the existing methods of segmentation generally select strategies that optimize performance during normal operating conditions, and do not explicitly consider the effects of the chosen strategy on the supply chain's ability to respond to disruption. As a supply chain expands in complexity and scale, its exposure to sources of major disruption like natural disasters, labor strikes, and changing government regulations also increases. With increased exposure to disruption, it becomes necessary for supply chains to build in resilience and robustness in the attempt to guard against these types of events. This work argues that the potential impacts of disruption should be considered during the establishment of day-to-day procurement strategy, and not solely in the development of posterior action plans. In this work, a case study of a laser printer supply chain is used as a context for studying the effects of different supplier segmentation methods. The system is examined using agent-based modeling and simulation with the objective of measuring disruption impact, given a set of initial conditions. Through insights gained in examination of the results, this work seeks to derive a set of improved rules for segmentation procedure whereby the best strategy for resilience and robustness for any supplier can be identified given a set of the observable supplier characteristics.

KEYWORDS: Resilience, Robustness, Supplier Relationship Management, Supplier Segmentation, Agent-Based Modeling and Simulation

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August 18, 2017

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1 Introduction and Motivation

1.1 Complexity of Supply Chain Management

In the text 'Supply Chain Risk: A Handbook of Assessment, Management, and Performance', Zsidisin and Ritchie (2009) defined a supply chain as the "linkage of stages in a process from the initial raw material or commodity sourcing through various stages of manufacture, processing, storage, and transportation to the eventual delivery and consumption by the end consumer" (ch.1). These linkages can exist between geographically dispersed entities of the same organization, or between a company and its external partners. Overall business capability is therefore a property of the supply chain system and must be measured as a function of the performance of every partner in the supply chain network (Fine 1999). Rather than existing as a series of linear connections between buyers and suppliers, these systems are complex and competitive advantage must be gained through the effective functioning of interconnected and overlapping networks (Lambert 2006). A failure at any node or linkage in the supply chain network will have a negative effect on the entire system.

Figure 1.1 represents a supply chain network and the different kinds of linkages that exist between entities in the network.

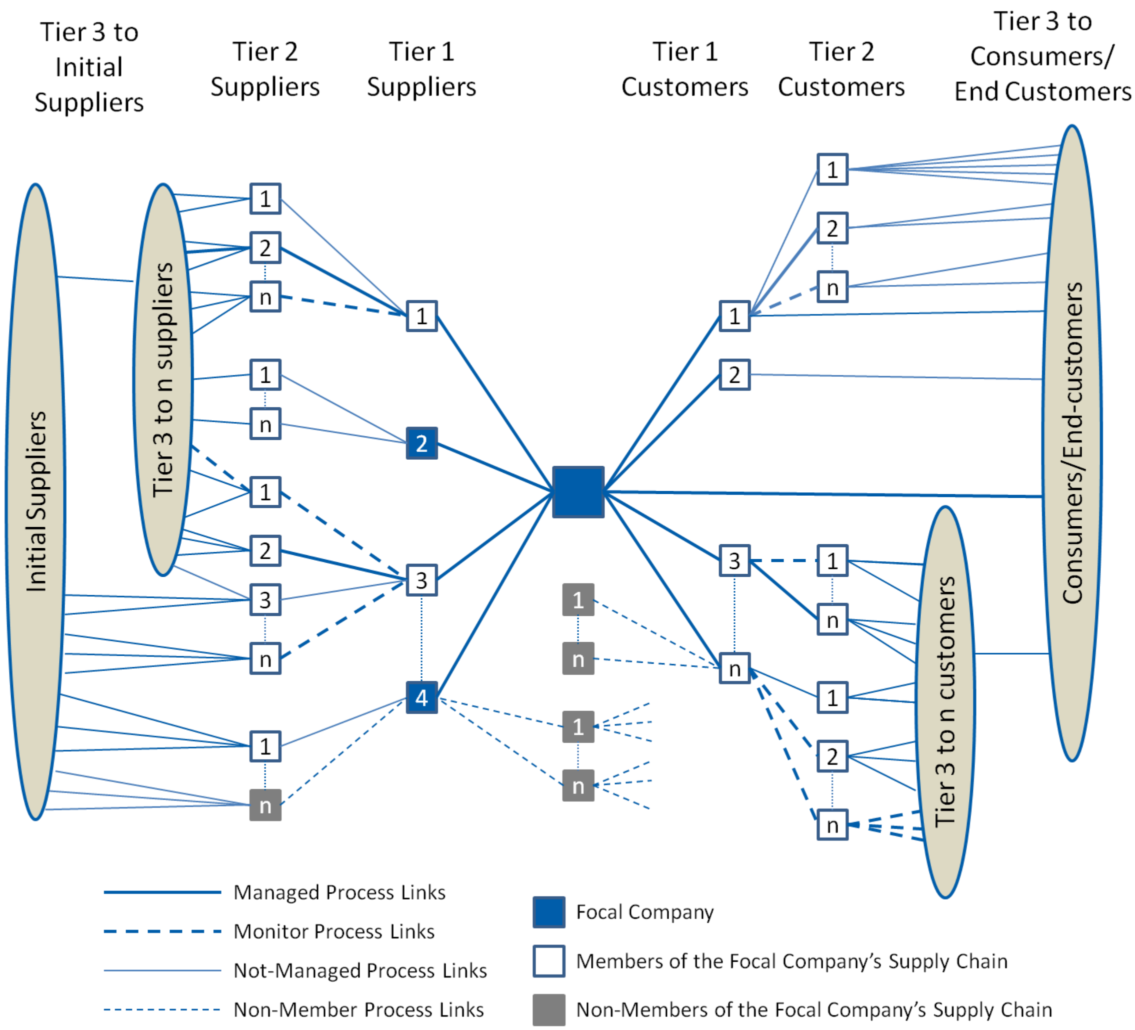

Figure 1.1: Supply chain network, adapted from (Lambert 2006)

Supply chain managers at the focal company must make strategic decisions relating to not only their immediate suppliers, but also their suppliers' suppliers and so on leading back to the procurement of raw materials. It should be determined which suppliers should be actively managed, which ones should be kept at arm's length but monitored regularly, and which are best left to manage themselves. Then, for each managed connection in the network, an appropriate procurement strategy should be specified and put into practice. The procurement strategy defines the rules of buyer-supplier interaction such as when to use dual sourcing, how much inventory should be kept on hand and where it should be held, and how much visibility should be established and maintained. It is important to predetermine for each connection what type of information the focal company is willing to share with the suppliers and how frequently.

Decisions should be made on how and when to consider the potential effects of major disruptions on supply chain performance. How does the choice of the day-to-day procurement strategy affect the focal company's ability to respond to disruption? If one of the actively-managed first-tier suppliers fails due to an unexpected malfunction, it is probable that management would become aware of the issue immediately and could respond promptly. However, if the same failure occurs at a supplier that is not actively managed, then there is a strong likelihood that the focal company's response capability would be less adept.

The questions relating to supply chain disruption management form the primary motivation behind this research. A decision support tool is needed to help supply chain managers to decide what type of relationships to develop with its supply base to best equip itself for effective disruption response. At the same time, the decision support tool should consider that an optimal strategy may not be attainable due to uncontrollable external factors, and that suppliers will be making decisions to act in their own interest.

Supply chains can be described as socio-technical systems, meaning that they are comprised of both a technical network of facilities linked by material and information flow and a social network based on formal and informal exchanges of information (Behdani 2012). Supplier Relationship Management (SRM) is an established sub-process within the realm of supply chain management that has the goal of providing structure and planning to the development and maintenance of supplier relationships (Croxton, Garcia-Dastugue et al. 2001). SRM creates the rules of interaction between buyer and supplier, including the development of Product Service Agreements (PSA's) or other contracts. The buyer-supplier relationship can be as generic or as specialized as is necessary for the success and satisfaction of both entities. The requirements for information exchange and coordination increase rapidly as the complexity of the supply chain increases. Thus, it becomes necessary to prioritize the management of critical suppliers. The identification of these critical suppliers is one of the main outcomes of SRM and it is often achieved through a process known as supplier segmentation. The segmentation process is used to determine appropriate relationships for each supply chain member and can be an important step toward ensuring the success of both the focal company and its partners. Different methods of supplier segmentation are discussed further in Section 2.1.

Adding to the complexity of supply chain management is the fact that supply chain networks must often be designed to meet conflicting objectives. As indicated by the "2010 and Beyond" research initiative which surveyed current and future issues pertinent to supply chains, to be successful supply chains must compete on cost, responsiveness, security, sustainability, resilience, and innovation (Melnyk, Davis et al. 2010). These qualities represent only a subset of many other desirable supply chain characteristics. This work will consider the performance trade-offs that exist between resilience against disruptions and other objectives. The work explores the possibility of expanding the application of supplier segmentation as a tool for increasing supply chain resilience and robustness.

1.2 Key Definitions

Key terminology in risk management for the supply chain has been used with varying consistency. It is important to state formally the foundational definitions as will be used throughout the remainder of the work.

Risk management can be formally defined as "the identification, evaluation, and ranking of the priority of risks followed by synchronized and cost-effective application of resources to lessen, monitor, and control the probability and/or impact of unfortunate events" (ISO 2009). Figure 1.2 shows the framework established by ISO for risk management.

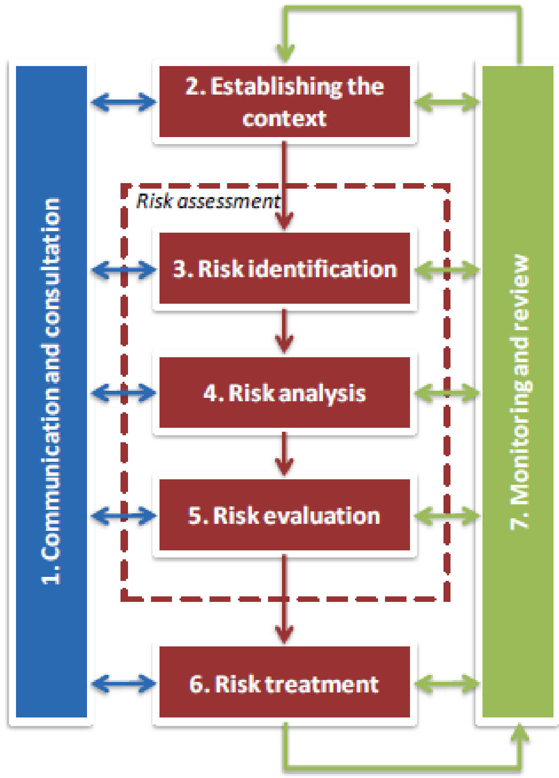

Figure 1.2: Risk management framework (Oehmen and Rebentisch 2010)

The ISO framework contains five core steps which occur sequentially, and two concurrent steps which entail continuous monitoring and communication of the results (Oehmen and Rebentisch 2010). The core steps begin with the establishment of context. This includes selection of the product of interest and drawing of any boundaries for what will and will not be considered. The center of the framework contains the three stages of risk assessment: identification, analysis, and evaluation. Risk identification involves specification of any events of interest which would have a negative impact on the supply chain performance. The identification may attempt to uncover an exhaustive list of potential risk sources or focus on a very specific scenario depending on the goals of the assessment. Next, risk analysis is conducted to increase knowledge about the identified risk scenarios. This may be done by establishing some ranking of likelihood of occurrence and significance of any potential impact. Analysis is a data-intensive process and may rely on historical data or domain expert opinions. Finally, risk evaluation is the stage in which results of analysis are examined and the risks are prioritized. Risks needing immediate attention can be separated from those needing continued monitoring and others which do not pose a significant threat. Risk treatment follows the assessment stages and involves implementation of solutions to reduce the threat level.

Risk can be succinctly defined as the '*likelihood of conversion of a source of danger into actual delivery of loss, injury, or some form of damage*,' (Garrick, 2008). The results of risk identification and analysis can be specified by a set of risk triplets, where the items in the triplet reflect the risk scenario, its estimated likelihood, and the consequence of its occurrence (Abyaneh, Hassanzadeh et al. 2011).

$$R = \{\langle S_i, P_i, X_i \rangle\}, i = 1,2, \ldots N \qquad \textit{Equation 1.1}$$

S_i represents a possible risk scenario, while P_i is the probability that the scenario will occur and X_i is a measure of the consequence should the scenario occur. This approach is especially geared towards high probability events, where the expected duration of the problem can then be estimated based on past occurrences. This work emphasizes a kind of risk scenario known as a disruption, defined as '*an unintended and anomalous event resulting in an exceptional situation that significantly threatens the course of normal business operations*' (Wagner and Bode, 2009). Disruptions occur infrequently and it may not be feasible to characterize them by their likelihood of occurrence. The consequence, or severity, of a disruption is high. Low likelihood, high impact disruptions represent the events for which an organization does not have experience upon which it can rely. Rather than focusing on likelihood, organizations must focus on the recovery period and acting to provide as many options for recovery as possible (Sheffi 2009).

Resilience is an important concept which refers to the ability of a system to recover from a disruption. Resilience has been defined as the '*ability of a system to return to its original state or move to a new, more desirable state after being disturbed*' (Christopher and Peck 2004). Furthermore, it is important to distinguish the property of robustness which is defined as '*a measure of supply chain strength or an ability to remain effective under all* *possible future scenarios*' (Klibi, Martel et al. 2010). The concepts of resilience and robustness can be visually represented on a disruption response profile, such as the one presented in Figure 1.3.

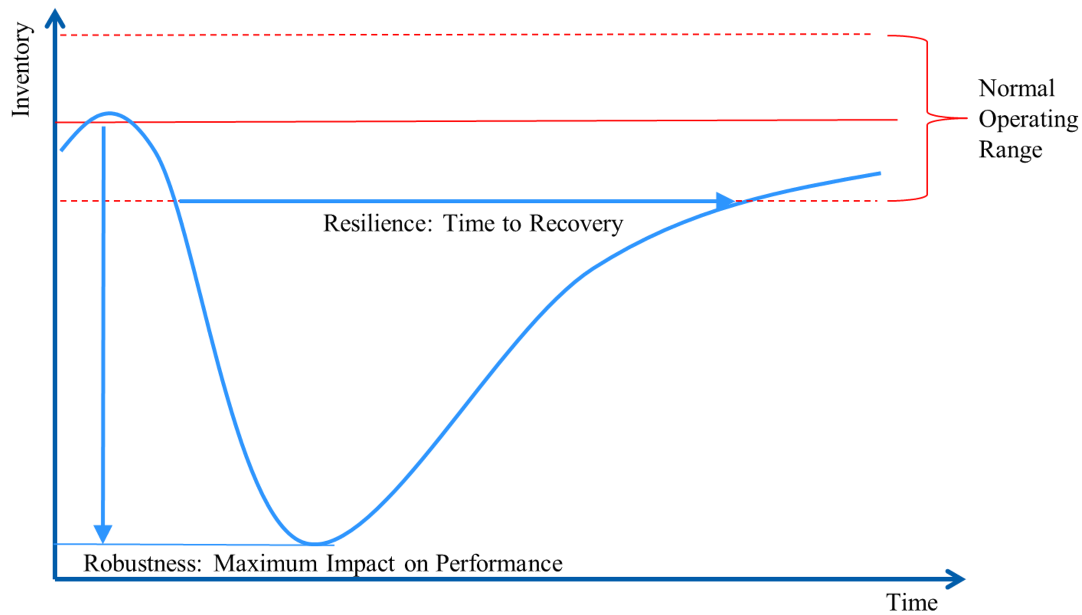

Figure 1.3: Disruption response profile (Brown and Badurdeen, 2015)

In Figure 1.3 the initial normal operating performance range for inventory can be seen represented by the horizontal dashed lines. The inventory serves as a performance measure on the y-axis and could be replaced by profitability, market share, production volume, or perhaps some aggregate score based on many variables. The spread around the normal performance level indicates the possible performance fluctuation due to operational disturbances like machine downtime or demand fluctuations. In contrast, the performance level drops well below the normal range when a disruption occurs. Robustness of the supply chain is a representation of its ability to minimize performance degradation after a disruption. The distance from normal operating performance to the minimum performance level is a measure of robustness. Resilience, on the other hand, is measured along the time axis. A more resilient supply chain will return to and remain in the normal operating range more quickly after the disruption has ended. In general, the inventory level of more resilient supply chain would spend less time below the normal operating range.

1.3 Research Gap

The 2014 Business Continuity Institute (BCI) survey on supply chain resilience indicates 80% of the surveyed organizations (525 respondents from 71 countries) reported at least one disruption incident in 2014 (Alcantara 2014). Full results on frequency of incidents reported are shown in Figure 1.4. Of the reported incidents, 23.6% resulted in cumulative losses more than €1 million compared to 12.4% in the previous 4 years. Of these respondents, 50.1% indicated that the incidents reported arose from below tier 1 suppliers. Reported consequences of disruption include loss of productivity, increased cost of working, impaired service outcome, customer complaints, and loss of revenue. Despite these trends, management commitment to increasing the level of supply chain resilience has declined, with 32% reporting no commitment at all in 2014 compared to 22% in 2013. Although there is an increasing trend of requiring supplier certification and suppliers to have business continuity management plans, these plans are often not fully validated.

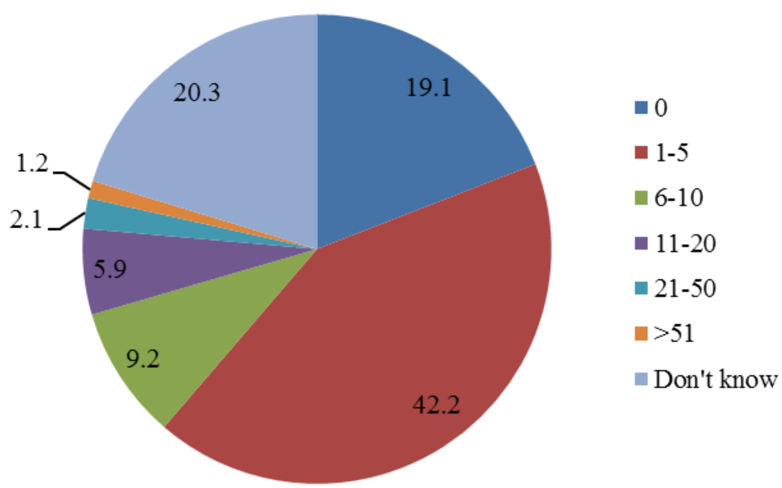

Figure 1.4: Percentage of respondents reporting in each range # of disruption occurrences (Alcantara 2014)

It may be difficult to increase resilience and robustness without trade-offs in other areas. For example, outsourcing initiatives are often implemented to increase revenue and reduce cost (Tang 2006). Though designed to provide economic advantages, these initiatives may come at the expense of increased exposure to potential supply chain disruptions. Incorporating the aspects of supplier relationship structure into a risk assessment remains a difficult problem. With continued pressure for companies to drive down operating costs, investments to increase resilience will need strong justification requiring increased understanding of trade-offs between different management strategies. It becomes pertinent to reveal strategies capable of adding resilience against disruption without increasing the cost of day-to-day operations. Detailed simulation studies can be performed to conduct such trade-off analysis. However, these studies are resource intensive and are difficult to complete when the scope of the supply chain study is very large.

Supplier segmentation is a resource-efficient decision tool that can be used to specify appropriate management strategies by grouping suppliers into segments with similar needs. Similar procurement strategies can be formulated and applied to the suppliers in each segment, thereby removing the need to develop a fully-tailored procurement strategy for each individual supplier. In this way, management resources are efficiently allocated throughout the supply chain. However, one drawback of supplier segmentation is that existing methods have failed to fully consider the potential implication that procurement strategy may have on disruption preparedness (Brown and Badurdeen 2015). The following work aims to develop a revised supplier segmentation method that employs additional consideration of resilience-oriented variables not considered in traditional segmentation approaches. The revised segmentation method should serve as a tool for supply chain managers to approach procurement strategy selection in a systematic way that considers the tradeoffs between day-to-day operational efficiency and disruption preparedness. The specific research question to be addressed is broken into multiple parts.

a) How does supply chain resilience and robustness compare when the baseline and revised segmentation methods are used?
b) How does the choice of supplier's segment and associated procurement strategy affect the severity of impact of a disruption at that supplier?

c) How is the impact of the disruption affected by its coincidence with periods of normal or elevated demand?
d) How does the percent of production capacity lost during the disruption affect the severity of impact?

2 Literature Review

The literature review can be divided into two main sections. First, supplier segmentation is studied for its applicability as a tool for increasing supply chain resilience. The first objective of this review is to identify existing supplier segmentation methods. Next, the variables used to characterize the suppliers are extracted from the different segmentation methods, and the segmentation variables are later examined for any plausible interactions with supply chain resilience. In this way, aspects of resilience which are not effectively assessed by existing segmentation variables can be revealed. Limitations and opportunities for future advancement of the segmentation process are presented.

The second section of the review aims to identify and categorize a comprehensive set of supply chain resilience-enabling factors by conducting a systematic literature review. Developing a comprehensive list of all resilience-enabling factors is important so their consideration in existing segmentation methods can be recognized. Throughout the review, the term *factors* will be used to distinguish the most frequently cited management strategies and supply chain characteristics relating to resilience. Each factor is then further specified by a set of *elements.*

Finally, insights are drawn regarding the possible integration of resilience-enabling factors into existing supplier segmentation methods. The modifications should facilitate selection of the best procurement strategies for resilience. In Figure 2.1, a theoretical framework is proposed linking resilience-enabling factors to supplier segmentation. The steps shown in the framework in solid outline demonstrate a proposed resilience-oriented segmentation process, and the steps shown in dashed outline demonstrate a traditional approach. In the traditional approach, there is some overlap between the set of segmentation variables used and the exhaustive set of resilience-enabling factors and elements. In the revised approach, the set of segmentation variables has been expanded so that all resilience-enabling factors are assessed in some way and included as inputs to the segmentation process. The expected result of the revised method is an improved combination of robustness and resilience.

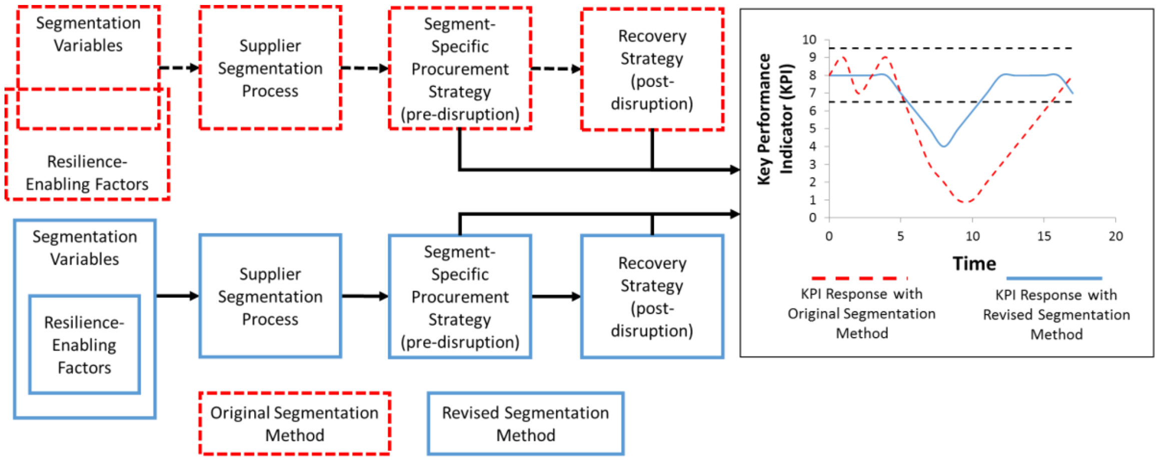

Figure 2.1: Theoretical framework

2.1 Supplier Segmentation

Over the period of about thirty years the role of an organization's purchasing department advanced from a primarily clerical role into a strategically integrated business function from which competitive advantage can be derived (Gelderman and Weele 2005, Day, Magnan et al. 2010, Rezaei and Ortt 2012). Suppliers to an organization can have varied characteristics and can introduce different risks. Therefore, it becomes necessary to differentiate suppliers into groups and to develop similar purchasing strategies based on this characterization (Dyer, Cho et al. 1998, Gelderman and Weele 2005). The practice of grouping suppliers is one of the major sub-processes of SRM and is referred to as supplier segmentation. Supplier segmentation can be defined as "a process that involves dividing suppliers into distinct groups with different needs, characteristics, or behavior, requiring different types of inter-firm relationship structures in order to realize value from exchange" (Day, Magnan et al. 2010). Supplier segmentation is a relatively mature topic and informative literature reviews have been offered describing developments in the field (Turnbull 1990, Carter and Narasimhan 1996, Gelderman and Weele 2005, Rezaei and Ortt 2012). Although the topic is mature, supplier segmentation methods remain subject to various criticisms largely related to the lack of standardization in selection of variables used for grouping suppliers or the lack of consideration for relationship interdependencies (Dubois and Pederson 2002, Gelderman and Weele 2005, Rezaei and Ortt 2012).

Segmentation methods have not focused specifically on the objective of improving supply chain resilience, but rather concentrate around sustained profitability, innovation, and risk reduction primarily with respect to operational risk. This proposal suggests the need to consider the potential impact of disruptions when defining supplier relationships.

Existing methods of supplier segmentation are discussed in the following review and can be differentiated by their classification structures and additionally by their unit of differentiation. Classification structure refers to the number of dimensions used for classification and the underlying objective of classification. Classification structures identified are the portfolio approach, the involvement approach, and the partnership model. The unit of differentiation defines what is being grouped together. Possible units of differentiation are the suppliers themselves, the products to be sourced, or the types of buyer-supplier relationships. Additional details regarding the types of segmentation are provided in following sections.

2.1.1 Portfolio Methods

One of the most popular methods of supplier segmentation, portfolio modeling, is derived from the field of financial investments (Markowitz 1952) and has the objective of either maximizing return at a given level of risk, or minimizing risk for a given return. Likewise, the portfolio method in the context of supplier segmentation focuses on reducing risk exposure that results from supplier transactions (Day, Magnan et al. 2010). Portfolio methods can be distinguished from other supplier segmentation methods because of this focus on risk. Much of the background literature used in the portfolio method is derived from transaction cost economics which focuses on specifying the various costs that are derived from buyer-supplier transactions.

Some of the realized benefits of the portfolio method include an increased coordination of different business functions and improved utilization of limited resources. Furthermore, use of portfolio models was shown to be positively correlated with purchasing sophistication (Gelderman and Weele 2005). Variations of the portfolio method have been introduced, but all use variations of the two-dimensional ranking method. The dimensions are presented on an x-y axis and subdivided into high and low values, resulting in a 2 x 2 characterization matrix. The two dimensions identified are supported by several underlying variables which are assessed based on managerial input and performance data.

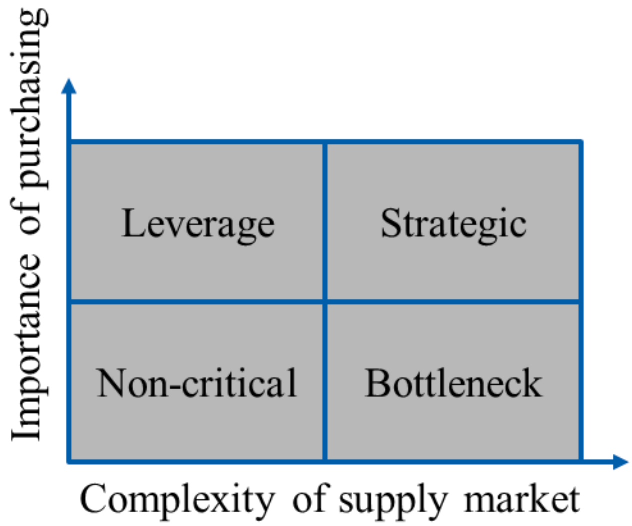

Figure 2.2: Supplier segmentation matrix, adapted from (Kraljic 1983)

The now most commonly cited portfolio model was introduced by Kraljic (1983) and bases supplier segmentation on the two dimensions: complexity of supply market and importance of purchasing. Market complexity can be based on variables such as availability of suppliers, competitive demand, presence of make-or-buy opportunities, storage risks, and material substitution possibilities. Importance of purchasing is described by variables like volume purchased, percentage of total purchase cost, impact on product quality, or business growth (Kraljic 1983). Supplier segments are then associated with management strategies. The suggested strategies associated with the four segments are described by (Rijt and Santerna 2010). The reasoning in support of the strategies for each segment are summarized in Table 2.1: Relationship strategies for supplier segments, adapted from (Rijt and Santerna 2010).

Table 2.1: Relationship strategies for supplier segments, adapted from (Rijt and Santerna 2010)

Supplier Segment	Suggested Strategy	Reasoning
Leverage	Incentivize lower costs; The suppliers are set up against each other	Total purchase cost or volume is high, but many suppliers exist
Strategic	Aim for close relationship with a sole supplier	Products are expensive and only available from a few or sole supplier
Routine/Non-Critical	Reduce administrative costs	Risk is low and admin cost may exceed purchase cost
Bottleneck	Reduce dependency; find substitutes if possible	Buyer is “locked-in” to the supplier resulting in high risk situation

Olsen and Ellram (1997) present a method similar to the one where Kraljic (1983) categorizes the purchase according to its strategic importance and management difficulty. According to these dimensions the purchases or types of products are differentiated and the segments described are the same as those presented in Kraljic (1983). The next phase aims to differentiate supplier relationships by the strength of the relationship and the relative supplier attractiveness. In short, this is a form of supplier performance rating combined with an assessment of the current buyer-supplier relationship. Based on the identified positions of supplier relationships, the manufacturer may decide to strengthen the relationship, try to improve the supplier attractiveness or relationship strength, or reduce the resources allocated to the supplier.

Portfolio-based models can be expanded to study supplier relationships as they evolve over time. Rezaei and Ortt (2012) suggest that segmentation should follow a natural progression where supplier selection is first performed followed by the segmentation procedure based on the dimensions: willingness to form and maintain a relationship with the buyer, and the supplier’s performance capability. After segmentation, supplier relationship management strategies are defined to fit the criteria. After operating according to the defined relationship structure, the buyer may choose to develop supplier capabilities. Regular evaluation of the benefit provided by the relationship can help the buyer to determine if a supplier should be replaced or possibly re-segmented. Finally, the authors demonstrate the importance of considering the full range of business functions when segmenting suppliers. The segmentation of suppliers should be considered not only as it affects purchasing but also the impacts on departments such as production, finance, logistics, etc. Different functions at the suppliers can be segmented differently according to the dimensions of willingness and capability, and therefore individual efforts may be made to strengthen relationships specific to each function.

In large part, Japanese automotive manufacturers have provided the impetus for the shift from transactional supplier relationships to developed partnerships, but it is shown that they do not necessarily rely totally on the partnership approach (Bensaou 1999). In an empirical study of managers in U.S. and Japanese automobile manufacturers, variables were identified to relate to effective supplier relationships. The dimensions were the specific investments made by the suppliers and by the buyers. It was found that a lower percentage of relationships in the Japanese industry relied on strategic relationships than on traditional market exchange, but that both U.S. and Japanese manufacturers rely on a distributed portfolio with different styles of relationships tailored to the given requirements. Interestingly, the type of relationship does not show a direct connection with the relationship performance. More important is the correct alignment of the relationship type with the given environment and effective management of the relationship. Time and resources including purchasing personnel are not sufficient to allow formation of strategic partnerships with every supplier organization with which a company does business (Hadeler and Evans 1994). This position also argues the need for a variety of different types of relationships to be maintained. The dimensions for supplier segmentation can be based on product complexity and value potential with resulting segments describing various strengths of relationship.

Collaboration is both a source of and a remedy for risks. When considering possible collaboration opportunities, Hallikas, Puumalainen et al. (2005) argue that the supplier viewpoint must be taken into consideration, whereas nearly all portfolio methods for segmentation focus on the viewpoint of the buyer. The decision-making structure that is defined for each supplier is highly dependent on the relative power position of the buyer and supplier. Risk is studied mainly from the perspective of the relative dependence of the buyer on the supplier and vice-versa. Depending upon their relative investments in one another, relationships are classified as strategic, non-strategic, or asymmetric. Risk can be managed through collaborative learning with the suppliers, but a side-effect of strong collaboration is an increased entry barrier for new suppliers in the network.

2.1.2 Partnership Model

Lambert, Emmelhainz et al. (1996) describe the partnership model which differs somewhat from the portfolio method. The purpose of the partnership model is to assess suppliers and buyers for compatibility and in so doing to identify potential suppliers for strategic relationships. The authors note that supply chain partnerships can be beneficial but are not appropriate for all situations. Business success is possible through more traditional arms-length relationships. Here the arms-length relationship is defined as a standard product offering for a range of customers with standard terms and conditions. The relationship lasts essentially as long as the exchange takes place, but can be renewed over many exchanges. A partnership, on the other hand is "a tailored business relationship based on mutual trust, openness, shared risk and shared rewards that yields a competitive advantage, resulting in business performance greater than would be achieved by the firms individually." Three levels of partnership are identified which are distinguished by the level of integration of the companies. Drivers for partnership include asset and cost efficiencies, customer service improvements, marketing advantage, and profit stability and growth. Drivers must be sufficient for both buyer and supplier to enter the partnership. In addition to drivers for the partnership, facilitators are needed which are elements of a supportive environment. These include the key elements of corporate compatibility, managerial philosophy and techniques, mutuality, and symmetry. Other facilitators may exist but their absence will not undermine the partnership. Finally, in each partnership components are defined which are activities and processes controlled in the partnership. Some components include planning, joint operating controls, communications, risk and reward sharing, trust and commitment, contract style, scope and financial investment.

Similar to the strategic relationship/partnership described by Kraljic (1983) and Dyer (1998), Kaufman, Wood et al. (2000) identify strategic partnerships as a new type of inter-organizational relationship alternative that can be considered in addition to the traditional make or buy options. Specific methods are used by the buyers to identify potential partners in the supply base. Make or buy decisions are made by weighing the tradeoffs between added cost of monitoring a self-interested supplier and the return expected from collaboration. Suppliers are described based on the dimensions of collaboration and technology. Suppliers that offer low technological capability and low collaborative input should be handled as commodity suppliers (competing on cost, standard catalog-based products). Low technological capability and high collaborative input suppliers can be managed as collaboration specialists (design specifications provided to suppliers, standard technology used). High technological capability and high collaborative input suppliers are managed as problem solvers (process and product continually improved, mutual dependence). Finally, high technological contribution and low collaborative input suppliers are technology specialists (suppliers make proprietary products, should not outsource strategic parts to these suppliers). A survey conducted in the research indicates that partnerships are developed more commonly with technologically sophisticated suppliers.

In practice, supplier evaluation and segmentation is a key step in determining whether to begin a long-term business relationship. Shambro (2010) argues that criteria should be selected so that segmentation determines the nature of value provided by the suppliers. If a bid request is to be sent out for an alternate supplier, then the motivation for doing so should be clear. For example, current suppliers should be clearly underperforming before the relationship structures are changed. Valid motivation for change may exist, and focus should be maintained on the costs of transition. Organizations should understand the requirements from current suppliers in both the short and long term. Although the portfolio method for supplier segmentation has been subject to certain criticisms, it has also been used with demonstrated success. At Kraft, the consumer packaged goods manufacturer, an open innovation strategy was developed in order to better utilize expertise from suppliers and outside the company. Through segmentation, Kraft is able to understand which of its suppliers has the most innovation potential (Jusko 2008).

Partnership models are less focused on risk and cost reduction than portfolio models and tend to be focused more toward the strengthening of key relationships. Each approach is however aimed at streamlining the process of managing suppliers.

2.1.3 Involvement Methods

Another segmentation approach that differs from the portfolio method has been called the involvement method (Rezaei and Ortt 2012) or the continuum approach (Hallikas, Puumalainen et al. 2005). The involvement method is distinguished from portfolio methods due to its more specific focus on determining when and to what degree a supplier should be involved in product development. It has the similar objective to other methods in determining the best role for specific suppliers. In this approach, an organization focuses on separating the products and services it provides into core competencies, relevant core activities and non-core activities. Strategic partnerships should be formed for suppliers offering products closely related to the organization's core competencies. On the other hand, a transactional-based "durable-arm's length" relationship is suggested for suppliers that offer non-core products and services (Dyer, Cho et al. 1998). Arms-length suppliers interface only through purchasing and sales, prices are benchmarked across different suppliers, and inter-firm investments are minimal. In contrast, strategic partnership practices include the interfacing of many organizational functions, benchmarking of different suppliers based on capability, and substantial inter-firm investment. The involvement method has some similarities to the partnership model, but is more closely focused on the nature of the products themselves and their significance to the focal company.

2.1.4 Units of Differentiation

It is useful to establish the unit that is being classified in the various segmentation methods. Although the classification method is strongly connected to the unit of classification, some variation exists. In some cases, the focus of the segmentation is on identifying suppliers with similar characteristics that may be managed similarly. Alternatively, the characterization may focus on the product itself. In this case, products with similar characteristics are managed in similar ways with less emphasis on the suppliers themselves. Finally, the characterization may focus on the type of buyer-supplier relationship. This approach describes existing relationships and identifies opportunities to strengthen or relax the current practice. Some methods may characterize all specified units. For example, it may be possible to first understand the nature of the existing relationship, and then use product and/or supplier characteristics to determine the future course of action.

A summary of supplier segmentation methods is presented in Table A.1 in Appendix A.

2.1.5 Limitations of Existing Segmentation Methods

Most articles on supplier segmentation methods focus on determining the best set of dimensions for classification or the best ways to differentiate the segments. Strategically, each dimension used in segmentation should be an influencing factor to one or more performance metrics. It is common for existing segmentation methods to relate dimensions to traditional performance metrics like cost, quality, and delivery. One desired outcome from the proposed research would be the specification of a set dimensions influential to resiliency-oriented metrics such as time-to-recovery.

Another difficulty related to segmentation relates to the question of incentive. That is, how can the buyer and supplier decide whether the proper incentives exist to move a supplier to a different segment? Up to this point, this question has been answered primarily from the buyer (or focal company) perspective, and has largely only taken into consideration the context of normal operating conditions. To properly examine the incentives, relationship interdependencies need to be better understood from a network perspective.

One of the major criticisms of the existing methods of supplier segmentation is that they result in independent classifications of suppliers, products, or relationships (Ritter 2000). For example, a supplier might be recognized as a good candidate for development as a strategic partner, but the effects of the actions taken in the development of the relationship are not reflected in the portfolio. Developing one supplier relationship may have damaging effects on other relationships, but this does not factor into the segmentation decision. This issue relates to network interdependency, which arrives from the structure of buyer-supplier connections. Network structure interdependency refers to the relationships that exist between supply chain partners. The relationships exist because of the transactions that occur between buyers and suppliers. These transactions can include material, financial, and information flow (Tang and Musa 2011). Most segmentation methods focus on the buyer perspective and often the supplier perspective is ignored (Gelderman and Weele 2005). It can be beneficial to consider an even wider system perspective that includes multiple supply tiers and the position of competitors. The entire set of network connections needs to be considered when making decisions on the allocation of resources.

It is advantageous to consider the network of interdependencies rather than focusing on single relationships (Olsen and Ellram 1997). As quoted from (Coate 1983) “portfolio models have a tendency to result in strategies that are independent of each other.” These models tend to focus on categorizing a product, customer, or a relationship. However, products are often closely related, and this association should be reflected in the segmentation method. For example, image interdependency has to do with the reputation of the buyer at the supplier. Past purchases can help to build a good reputation and allow the buyer to gain leverage at the supplier for later purchases. The history of purchases may in some cases also affect the image of a company to its customers. Thus, it is important to consider the implications of supplier segmentation in the long-term. Dubois and Pedersen (Persson and Hakansson 2007) present an article that focuses on the contrast between the portfolio method, which focuses on the exchange of pre-specified products, and the “industrial network approach”, which focuses on inter-firm relationships. This viewpoint allows consideration of a network of interdependent relationships rather than a simple buyer-supplier product exchange dyad. The article notes that the benefit realized through supplier development is a function of that supplier’s other relationships. The article argues that the dimensions used by portfolio methods are interdependent and that information and opportunities for increased productivity may be lost if they are only considered separately.

Because businesses interact with a supply network, they are dependent upon the resources controlled by other firms. This reality further supports the importance of considering the interconnectedness of business relationships. Ritter (Ritter 2000) notes a lack of analytical tools to study this effect. In addition to the direct relationships between buyers and suppliers, there are indirect relationships that take effect. For example, two suppliers may not interact with one another but are indirectly related in selling to a common customer. This type of indirect connection would be realized if, for example, technological developments were built in collaboration with one supplier but later benefit the other supplier as well. If a shared supplier experiences a reduction in capacity, one customer might find itself in short supply because of preferential treatment for the other customer. These relationships, direct and indirect, can be described as positive, negative, or neutral, as depicted in Figure 2.3. This represents whether the existence of one relationship is beneficial or detrimental to another relationship. Direct relationships between firms are indicated by the solid lines connecting nodes while indirect relationships are shown as + or – arrows between the direct links.

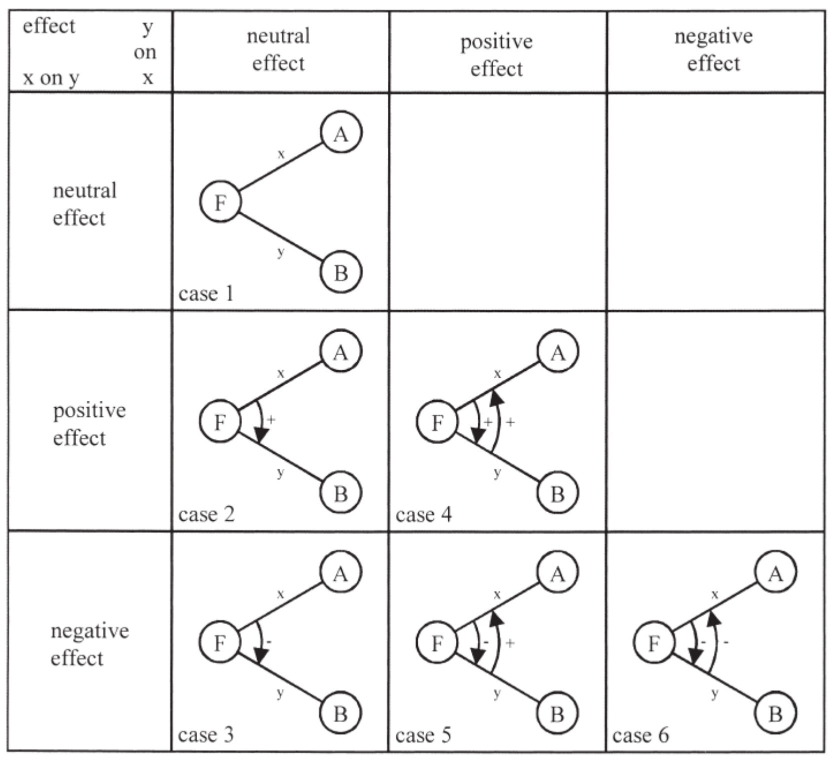

Figure 2.3: Positive, neutral, and negative inter-firm relationships, (Ritter 2000)

The effect of buyer-supplier relationships should be considered in both directions. If a buyer has relationships with two suppliers, the relationship with the first supplier may positively affect the relationship with the second (shown by a + arrow), while the relationship with the second might negatively affect the relationship with the first (shown by a – arrow). Such an example corresponds to case 5 in Figure 2.3. Most portfolio-based supplier relationship strategies focus on a single buyer-suppler dyad. While the direct relationship is important, the network effects need to be studied to fully understand the possible implications of actions taken. Portfolio methods can be improved by incorporating the interconnectedness of the supply network in this way. This requires models that take into consideration the effects of this relationship information.

It is possible to segment suppliers based on the nature of identified relationship interdependencies (Persson and Hakansson 2007). According to the type of interdependencies, classified according to (Thompson 1967), collaborative strategies are suggested to improve purchasing efficiency. Network interdependencies are described as pooled, serial, and reciprocal interdependencies. Pooled interdependence means two entities are related to a third activity such as a shared resource. Serial interdependency refers to a situation where the output of one activity is the input to the next. Reciprocal interdependency refers to mutual exchange between parties, such as projects involving multiple entities. Based on the type of interdependency, an appropriate level of collaboration is suggested, as shown in Figure 2.4.

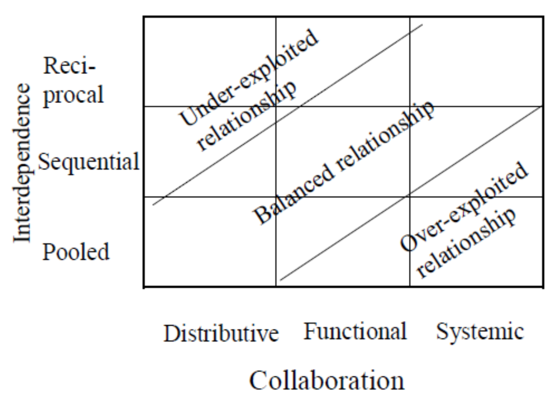

Figure 2.4: Collaboration based on type of relationship interdependency, (Persson and Hakansson 2007)

Distributive collaboration relates to economies of scale. Organizations using the same resource (pooled interdependence) can work together to drive down the cost of that resource. The advantages gained from functional collaboration are describes as economies of function. Functions with sequential dependence can improve efficiency by sharing information such as forecasts and production plans. Finally, systemic collaboration calls upon the economies of innovation and agility. Systemic collaboration is akin to a partnership and is characterized by a culture of mutual problem solving. The article argues that collaboration between buyers and suppliers can be seen as the creation and exploitation of different types of interdependencies. While portfolio segmentation tends to focus on identifying which suppliers to collaborate with, this interdependency-based method identifies collaborative strategies to improve long-term transactional efficiencies.

In summary, there are several actions that can be taken to better-incorporate relationship interdependencies into supplier segmentation methods. The network can be visualized by mapping the supply chain tier by tier, component by component to classify the existing interdependencies. The supplier perspective can be considered, including indirect relationships. Models should consider the process of implementation of mitigation efforts, and examine the effects that indirect relationships may have on these efforts. If multiple transactions and types of components are transferred between organizations, these transactions should be looked at individually, so that the best recovery strategy for each component can be identified. Situations where suppliers have incentive to act in their own best interest can be considered. For example, a supplier may have incentive to favor one customer over another in the case of supply shortage. Manufacturers should consider how this scenario would affect disruption recovery.

2.2 Management Strategies for Increased Resilience

The systematic review is modeled after that by Denyer and Tranfield (2009). The method includes five steps: question formulation, study location, study selection and evaluation, analysis and synthesis, and report and use of results. The merits of the systematic review process have been demonstrated in several recent publications (Hallikas, Puumalainen et al. 2005, Rezaei and Ortt 2012, Hohenstein, Feisel et al. 2015). Among the merits are increased transparencies of paper inclusion and exclusion criteria, which allow replication of information analysis and add a level of control to the comprehensiveness of the review.

The systematic literature review process begins with the development of a primary research question and the definition of search terms. The primary research question can be stated as ‘What management strategies exist to enable supply chain resilience against disruptions?’ The research question is deconstructed to formulate search criteria based on a combination of key words from two groups: the first pertaining to supply chain management and the second to disruptions. A Boolean search criteria was used requiring terms from each group of related terms shown in Figure 2.5.

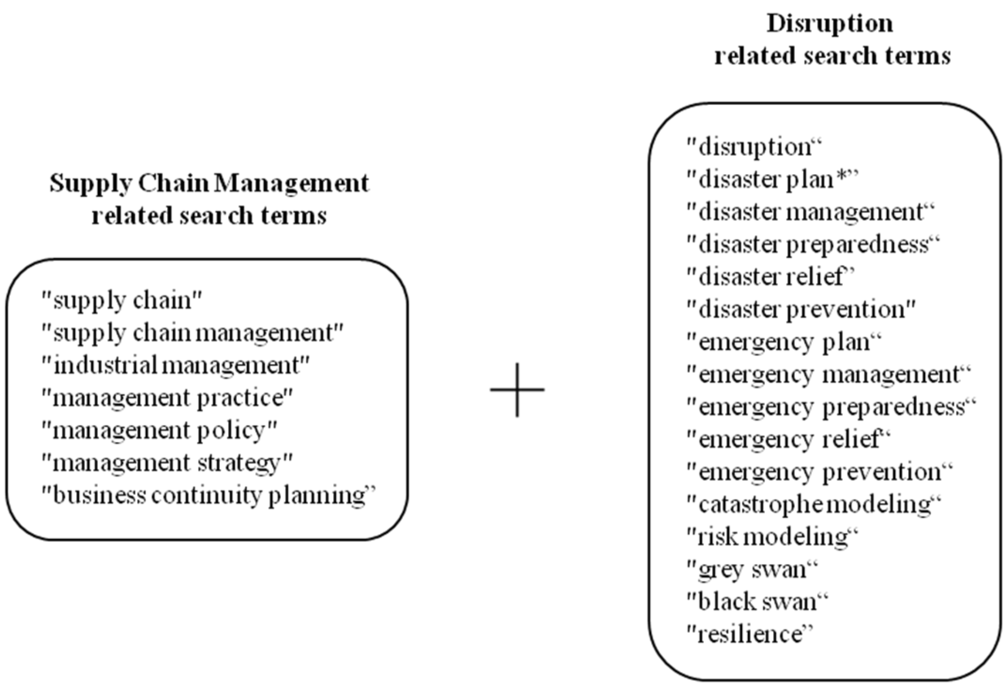

Figure 2.5: Literature review search terms to identify management strategies for increased resilience

The databases Compendex and Business Source Complete were used to find publications in business and engineering. The search results in articles that contain some combination of terms listed above. The initial search returned 938 references between the years 1967 and 2015. From this population of references, a secondary search was conducted to identify the sub-set of empirical studies that focused on identification of factors for increased resilience. The secondary search resulted in 43 articles, which were individually checked for relevancy. An article was deemed to be relevant if it met the following criteria:

(1) Relates directly to the effects of major disruptions
(2) Discusses strategies for managing supplier relationship
(3) Includes supply chain context, pertaining to at least one buyer-supplier exchange

Articles that primarily focused on the effects of operational risk were excluded, since this work is concerned with low-probability, high-impact disruptions. In addition, articles that solely focused on the modeling of technical aspects of supply chain management were excluded, since this work studies factors influencing specification of socio-technical supplier relationship strategies. Finally, articles that do not show a direct connection to supply chains were removed from the study. The final set contained 34 articles and formed the basis of the review.

The goal of the synthesis stage is to provide insight that would not be discernible solely through individual analysis of the collected articles. The synthesis of information from the remaining articles is supported by the development and examination of sub-questions. The sub-questions can be stated as ‘What major resilience-enabling factors can be extracted from the identified management strategies?’ and ‘How are the identified resilience-enabling factors assessed?’

As evidenced by the large number of articles returned by the initial search terms, significant interest surrounds the field of supply chain resilience. Some of the works center around the goal of identifying and classifying key factors influencing supply chain resilience. The article by Hohenstein, Feisel et al. (2015) aggregates several studies to reveal 36 resilience-enabling ‘elements’. Of the elements identified, the most frequently mentioned were flexibility, redundancy, collaboration, visibility, agility, multiple sourcing, capacity, culture, inventory, and information sharing.

Other works demonstrate the importance of supply chain network-related factors such as network density, complexity, and node criticality (Craighead, Blackhurst et al. 2007, Greening and Rutherford 2011), and examine the application of supply chain ‘capabilities’ to the reduction of ‘vulnerabilities’ (Jüttner and Maklan 2011). Capabilities examined by the authors included flexibility, velocity, visibility, and collaboration.

The existing research in the field of supply chain resilience provides an important foundation and guide for the work presented in this article, which has the goal of synthesizing information from the identified sources. The purpose of the following examination is to organize existing information regarding management strategies for resilience, and to combine related strategies into major groups of resilience-enabling factors. Figure 3 presents a summary of the frequency of mention of distinct management strategies and supply chain characteristics. Starting from this list of strategies and characteristics, distinguishable groups of resilience-enabling factors were identified. Details explaining the justification behind grouping of certain strategies and elaboration of the different factor elements are provided in the following sub-sections.

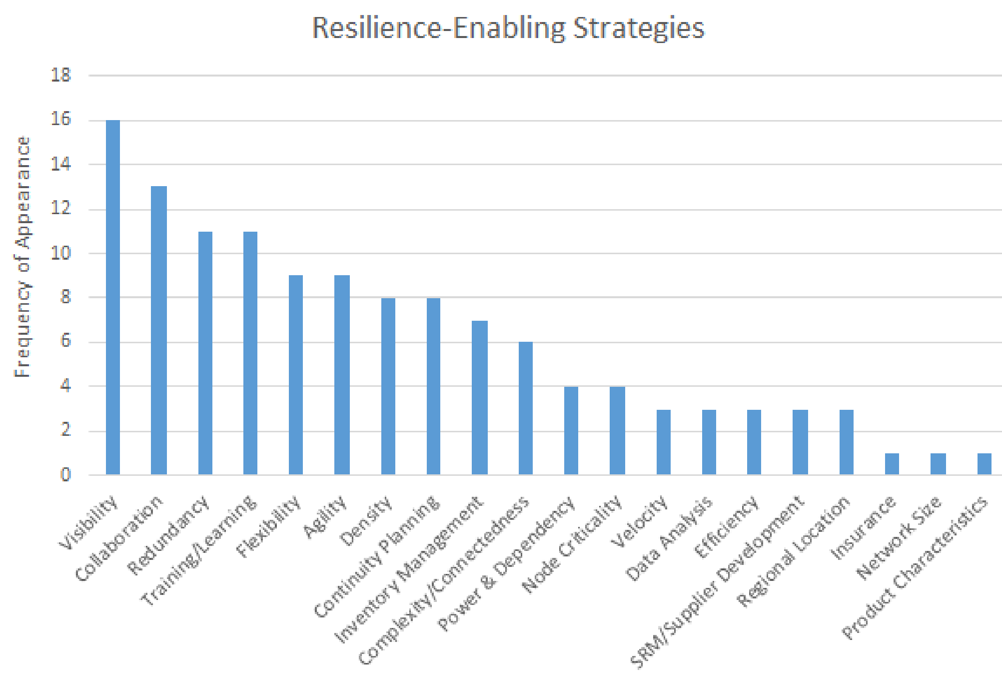

Figure 2.6: Frequently mentioned strategies and characteristics of resilience

2.2.1 **Supply Chain Visibility and Data Analysis**

Based on the reviewed literature it is surmised that visibility is a multi-faceted concept centered on communication with suppliers through sharing of information. The factors of visibility and data analysis act together to allow a company to collect, interpret, and exchange information. The various assessments and descriptions of the concept relate to the type of information collected, the extent or timeliness of information shared, the capability of a company to convert the shared information into useful knowledge, the information uncertainty, and the types of tools used to enable information sharing.

Regarding the type of information collected, knowledge of the status of inventory and material flow throughout the supply chain are of key importance (Shao 2013). Brandon-Jones, Squire et al. (2014) describe visibility as access to information regarding inventory and demand levels throughout the supply chain. Monitoring and detectability create visibility into events occurring in the surrounding environment concerning end-to-end orders, transportation, and distribution (Jüttner and Maklan 2011). Scholten, Scott et al. (2014) indicate relevance of monitoring events that occur within the supply chain and noting any deviation from planned and actual outcomes.

The extent of information that is shared or the timeliness of information sharing can be descried in a number of ways. Blackhurst, Craighead et al. (2005) emphasize real-time information sharing from all supply chain nodes. Hohenstein, Feisel et al. (2015) note the importance of early warning indication achieved through real time monitoring. Relational competencies such as communication and cooperative relationships have been examined for their potential importance to the enabling of resilience (Wieland and Wallenburg 2013). The development of relational competency reflects visibility in that it implies a supplier's openness to regular screening a willingness to take sensitive information regarding disruptions and make it available. Olcott and Oliver (2014) examine the relevance of social capital to disruption recovery, where social capital refers to the goodwill and sense of obligation that exists between organizations, as well as to trust between firms and the development of a common knowledge base. Organizations that share a higher degree of social capital are likely to experience greater degrees of information sharing and reduced monitoring costs.

The presence and exchange of data cannot lead to increased resilience unless it is converted into useful information, such as an improved warning capability. Craighead, Blackhurst et al. (2007) describe warning capability as the interaction and coordination of resources to detect a pending or realized disruption and to disseminate pertinent information about the event throughout the supply chain. In this way, visibility relates directly to data analysis capability. In addition to the collection of information from suppliers, data analysis is needed to process the data through such means as predictive analysis (Blackhurst, Craighead et al. 2005) as well as forecasting and development of early warning signals (Pettit, Croxton et al. 2013). Data analysis capability is important after a disruption for determining accuracy and relevance of the available information. Ojha, Gianiodis et al. (2013) note the importance of developing an awareness of risk levels and improving understanding of optimal operating performance levels. This awareness can improve detection of deviations. Using the term disruption orientation, Ambulkar, Blackhurst et al. (2015) also examine the significance of a firm's focus on developing awareness of pending disruptions.

When assessing strength of visibility it is important to recognize the potential effect of uncertainty in the shared information. Blackhurst, Craighead et al. (2005) stress the importance of information accuracy. Inaccuracies in data may result from changing requirements for quality and price or from forecasting uncertainties (Ellis, Henry et al. 2010).

The collection, analysis, and sharing of information can be streamlined though the use of standard tools, methods, and procedures. Tangible systems to support visibility include connectivity infrastructure, such as Information Technology (IT) systems (Olcott and Oliver 2014), and visualization tools that can be used to communicate information about the status of the supply chain (Basole and Bellamy 2014). For example, in one empirical study of the electronics industry, a network visualization was used to represent collaborations between organizations as well as the risk level and strategic importance of each partner based on network position (Basole and Bellamy 2014). Sheffi and Rice Jr (2005) discuss visibility in terms of disruption detection through use of technical capabilities such as shipment visibility systems. Development and use of formal knowledge management systems may be crucial to the orchestration of effective disruption preparation and recovery (Ponis and Koronis 2012). Kleindorfer and Saad (2005) discuss the practice of sharing of information and best practices through compatible communication and information technologies.

The elements of visibility are summarized in Table B. 1: Elements of visibility and data analysis in Appendix B.

2.2.2 Collaboration and Supplier Development

Many authors cited the importance of collaborating with supply chain partners to ensure resilience. Supplier development is also included in this factor as the efforts to develop supplier capability are dependent upon resources owned and shared by both the buyer and supplier. When examining the various assessments for level of collaboration, the individual elements were found to relate to the types of mutual efforts made, the use of shared information for synchronous decision making, supplier openness to meeting buyer requirements, the presence of shared incentives or risk, the types of efforts made to organize and unify employee efforts, and cultural compatibility.

Collaboration can be conceptualized as the establishment of joint efforts by organizations to achieve a common objective (Hohenstein, Feisel et al. 2015). Integration between organizations can serve to improve warning capability through the interaction and coordination of resources, which in turn positions the firm for faster recovery after a disruption (Shao 2013). Collaboration may exist between organizations not necessarily in direct partnership in the form of contributions to and participation in development of information databases and exchanges, or through development of trade partnerships (Blackhurst, Dunn et al. 2011). Examples of collaborative supply chain activities include development of a business continuity plan (Hohenstein, Feisel et al. 2015), joint training efforts (Kovács 2009), and improvement of supplier performance (Chiang, Kocabasoglu-Hillmer et al. 2012).

Although collaboration relates heavily to information exchange, an aspect already discussed under visibility, a distinction can be made in the context of collaboration in that the information is used mutually in an effort to build new knowledge that is beneficial to each party. The information is used for the enablement of synchronous decision making (Jüttner and Maklan 2011). For example, decisions can be made jointly between buyer and supplier regarding optimal order quantities and timing of promotional events (Mandal 2012). Mutual use of information is needed to perform collaborative planning and forecasting (Kleindorfer and Saad 2005, Peck 2005).

Collaboration often requires an openness of the supplier towards meeting the buyer requirements. The willingness of the supplier to collaborate may be related to relative power position. A dominant organization in a supply network has the opportunity to lead and support 'extended enterprises' wherein information and risk are shared in a way that is beneficial for all the involved parties. However, the dominant organization must possess the willingness and capability to drive this form of collaboration (Peck 2005). Wieland and Wallenburg (2013) also note the need for willingness to support sharing of sensitive information during cooperative efforts.

The strength of collaboration in the supply chain can also be indicated by the alignment of incentives (Jüttner and Maklan 2011, Mandal 2012). The presence of a sense of mutual obligation, or a shared stake in both the success and risk of an endeavor can reflect the nature of cooperative behavior between firms (Olcott and Oliver 2014).

An important pre-requisite to collaboration is the identification of personnel and their roles and responsibilities. It is advantageous to maintain a good understanding of the presence and location of expertise within the collaborate network (Scholten, Scott et al. 2014). Developing a formal specification of roles through planning can be helpful in facilitating efficient collaboration between parties of multiple affiliation. It is important to develop a good understanding of the capabilities and restrictions that may be in place at any potential collaborator (Kovács 2009). Venkateswaran, Simon-Agolory et al. (2014) studied factors influencing business continuity and economic recovery, including the formal assignment of roles and responsibilities during recovery efforts.

Finally, the degree of cultural compatibility between firms can reflect the strength of collaboration. Kleindorfer and Saad (2005) make the point that contractual agreements and incentive schemes can be used to encourage and solidify collaborative efforts, but that a level of trust is needed between the participating parties to reach these agreements. Management of extreme events necessitates an increase from the typical levels of coordination and goodwill between responding agencies (Kapucu and Van Wart 2006). For collaboration to exist, a level of visibility is needed between firms which includes access to sensitive risk-event information (Jüttner and Maklan 2011). However, through a collaborative arrangement involving cultural alignment companies can safeguard themselves against opportunistic behavior (Chiang, Kocabasoglu-Hillmer et al. 2012).

The elements of collaboration and supplier development are included in Table B. 2 in Appendix B.

2.2.3 Training, Learning, and Business Continuity Planning

Many management strategies for increasing resilience relate to the actions taken to increase the experience and skill level of employees in disruption preparedness and recovery. Such actions include training employees in recovery procedure after a disruption using simulations and discussions of previous events. The presence of a risk-oriented culture can also indicate greater disruption preparedness at a supplier. The process of learning from the past and training for future events can be formalized though development of Business Continuity Plans. The effectiveness of such plans can be measured using a pre-established system of metrics and performance indicators. Together these elements help to establish an organized plan of action for suppliers both before and after a disruption.

Study and awareness of previous disruptions can increase the level of preparedness in the pre-disruption phase (Ponis and Koronis 2012). Learning capability is indicated by an openness and receptivity to change. The level of innovation exhibited during and after a disruption may be proportional to the magnitude of the event (Golgeci and Ponomarov 2013). Learning can then result in ideas for process improvement (Revilla and Sáenz 2014). Organizations that learn from disruptions hold post-disruption discussion sessions and commit to implementation of improvements based on the generated ideas (Pettit, Croxton et al. 2013).

In addition to learning from past events, organizations can learn by taking part in simulations and training exercises (Revilla and Sáenz 2014, Scholten, Scott et al. 2014, Venkateswaran, Simon-Agolory et al. 2014). This type of preparation can help employees to practice implementation of their response actions when faced with different disruption scenarios (Hohenstein, Feisel et al. 2015).

Development of employee skills for resilience can be achieved in part by means of effective human resource management (Hohenstein, Feisel et al. 2015). Employee skills that should be developed include their ability to maintain a risk-sensitive mindset and to function in cross-functional teams. Innovation was shown to be a relevant skill in the form of motivation and capability to devise creative business solutions (Golgeci and Ponomarov 2013). The findings indicate that firms with greater levels of innovation were more likely to establish desired levels of resilience.

By fostering a culture that encourages learning, organizations can increase resilience (Sheffi and Rice Jr 2005). This includes making risk assessment a formal part of regular decision making (Scholten, Scott et al. 2014). A cultural commitment is required for effective continuity planning to take place, and this commitment can be realized through the provision and maintenance of the necessary infrastructure such as a dedicated risk or disruption department and information system (Ambulkar, Blackhurst et al. 2015).

Through development of business continuity plans, organizations can improve communication by reducing the focus on managerial hierarchy and allowing the most knowledgeable employees to act in positions of responsibility (Ojha, Gianiodis et al. 2013). The reduction of decision hierarchy reduces reliance on centralized authority which may not be immediately available (Kapucu and Van Wart 2006). The planning process equips decision makers with information regarding potential challenges that may arise during the stages of disruption recovery (Kovács 2009). Planning programs can help in the establishment of trust with key suppliers, and can increase a firm's understanding of its supplier's capacity and alternative options (Blackhurst, Dunn et al. 2011). Requiring suppliers to create formal business continuity plans can be an important step in supplier development, as the plan outlines in detail the steps the supplier will take, including schedules for periodic testing, to ensure survival of the business (Venkateswaran, Simon-Agolory et al. 2014).

Finally, commitment to training and learning can be exhibited though the use of a consistent set of performance indicators to manage risk (Kleindorfer and Saad 2005). Periodic review of the performance metrics can help to establish a baseline and facilitate benchmark comparisons (Pettit, Croxton et al. 2013).

Table B. 3: Elements of Training, Learning, and Business Continuity Planning in Appendix B summarizes the elements of training, learning, and business continuity planning.

2.2.4 Redundancy and Inventory Management

Adding redundancy of resources in the supply chain is a straightforward means of increasing disruption preparedness. The level of redundancy can be indicated by the amount of buffer inventory kept on hand, the amount of unused production capacity, the number of suppliers used, and the availability of surplus labor. However, redundancy can lead the supply chain to incur excess cost and it is important in the design process to balance cost and vulnerability (Sheffi and Rice Jr 2005). The effectiveness of buffer stock in adding resilience is often dependent on a larger strategy of inventory management. Inventory management is characterized by strategic placement of inventory and careful placement of controls on inventory levels and reordering practices.

Redundancy can be achieved through the practices of keeping excess resources in reserve, often referred to as safety stock, buffer inventory, or insurance inventory (Klibi, Martel et al. 2010, Zsidisin and Wagner 2010, Blackhurst, Dunn et al. 2011). The inventory may be held by the focal company, or in some cases by its suppliers who are required to hold a certain number of days' worth of material (Zsidisin and Wagner 2010, Blackhurst, Dunn et al. 2011). An important insight is made by Suzuki (2012) that consumable products, particularly fuel for transportation, should also be considered as an important resource when conducting material management after a disruption.

Keeping extra production capacity is another element of redundancy (Zsidisin and Wagner 2010). Similarly, Klibi, Martel et al. (2010) discuss insurance capacity as an enabler of resilience. Decisions regarding specification of capacity and inventory planning are a large component of supply chain design (Mandal 2012). Capacity considerations can also be extended beyond production to include transportation requirements (Hohenstein, Feisel et al. 2015).

The practice of employing more than one supplier for a given component is another frequently-cited form of redundancy (Sheffi and Rice Jr 2005, Zsidisin and Wagner 2010, Hohenstein, Feisel et al. 2015). While multiple suppliers can increase redundancy, it can also be shown that the number of nodes in a network is inversely related to resilience (Blackhurst, Dunn et al. 2011). When designing in redundancy to increase resiliency, diversification in facility locations is an important consideration, as this may affect the likelihood of multiple sites being affected simultaneously (Kleindorfer and Saad 2005, Hohenstein, Feisel et al. 2015).

The choice of positioning of buffer inventory throughout the supply chain can be an important factor in determining its benefit. The location of inventory relative to the location of the disruption, as well as the number of routing options available for the existing buffer each affect the realized level of redundancy (Klibi, Martel et al. 2010, Blackhurst, Dunn et al. 2011).

Boone, Craighead et al. (2013) examine different approaches to inventory management, including the item approach and the system approach. The item approach seeks to maintain pre-specified service levels for each item, while the system approach considers all items in the system simultaneously with the goal of attaining system-level objectives. The choice of inventory management system should be aligned with the operating environment, and can be important to enabling improved continuity and resiliency. Furthermore, inventory management systems can implement controls on the process of ordering materials, such as requiring a special authority to release inventory (Sheffi and Rice Jr 2005). The re-ordering rules can be used to add redundancy by allowing for a safety factor in the expected order lead time (Peck 2005), or planning for operational delays (Kleindorfer and Saad 2005).

Finally, redundancy can be developed by maintaining plentiful human resources and expertise (Peck 2005). Labor availability can be a key factor in ensuring sufficient levels of operating capacity (Blackhurst, Dunn et al. 2011).

Table B. *4: Elements of Redundancy and Inventory Management* in Appendix B includes the identified elements of redundancy and inventory management.

2.2.5 Flexibility, Velocity, and Agility

The terms flexibility, agility, and velocity have been used in the literature to describe a related set of capabilities for enabling resilience, all of which relate to the supply chain's ability and speed in reaction to changing conditions. Agility as a concept has varying interpretations in literature, so it is important to be clear when establishing the context and use of the term. Different authors may use varying levels of specificity when using the term. Agility has been defined simply as the ability to respond rapidly to change through adaptation of an initial stable configuration (Wieland and Wallenburg 2013). In the context of supply chain reconfiguration, agility can imply a combination of the related capabilities flexibility, velocity, and visibility. A supply chain that has good visibility into upcoming supply and demand fluctuations, and is able to quickly reconfigure to accommodate these fluctuations would thus be referred to as agile. The different elements that emerge describing this concept include the ability to adjust production rate according to demand, to reroute logistics, to reconfigure the supply chain, to perform rapid reconfiguration, to interchange labor and processes, and to replace or redesign components.

The term velocity can be used in the supply chain context to refer to the time it takes between order placement at the first stage of production and receipt of the final product by the customer (Christopher and Peck 2004). To respond quickly to changes in demand, the supply chain should be able to adjust its velocity up and down, an ability that Christopher and Peck (2004) call acceleration. Acceleration may depend on the speed with which reconfiguration can take place (Shao 2013, Scholten, Scott et al. 2014). The change in production rate should be responsive to sudden changes in supply and demand. In many cases this capability is achieved by maintaining extra production capacity with flexible utilization (Jüttner and Maklan 2011, Shao 2013).

Jüttner and Maklan (2011) refer to flexibility in terms of re-configurability, or the number of possible states a supply chain can take. The number of configurations possible is directly related to the number of sourcing options available, which is increased by the use of dual or multi-sourcing strategies (Sheffi and Rice Jr 2005, Pettit, Croxton et al. 2013). Although many suppliers may be available, re-configuration requires a contract flexibility or otherwise-enabled ease of switching between different sourcing options (Hohenstein, Feisel et al. 2015). The presence of highly-dependent relationships and rigid formalization of management processes may be indicative of a lack of flexibility for reconfiguration (Wieland and Wallenburg 2013, Ambulkar, Blackhurst et al. 2015).

In addition to the number of possible supply chain configurations, the speed with which reconfiguration can occur is also of relevance to resilience (Mandal 2012). Being in a position of strong social capital and having strong supplier relationships can facilitate collaboration and have a positive effect on the rapid mobilization of resources (Zsidisin and Wagner 2010, Olcott and Oliver 2014). The overall speed of reconfiguration depends on the ability to quickly identify changes in the marketplace (Shao 2013) and to respond to them with quick ramp-up of alternative manufacturing plants (Hohenstein, Feisel et al. 2015). Use of supplier certification programs can be associated with resilience (Zsidisin and Wagner 2010), due to the increase in efficiency in ramping up certified versus uncertified alternative suppliers.

Logistical rerouting can be seen as an independent issue from supply chain reconfiguration. The rerouting capability refers to the flexibility of distribution of materials, and it is often reflected by the usage of multiple supply channels (Mandal 2012, Hohenstein, Feisel et al. 2015). This element of flexibility also pertains to the ability to adjust delivery quantities (Yusuf, Musa et al. 2014).

Flexibility involves the ability to respond to disruptions by developing interoperable processes and systems (Sheffi and Rice Jr 2005). This interoperability allows a disrupted process to be moved to another location quickly with little requirement for modification and validation (Shao 2013). In a similar way, employing a cross-trained workforce can be useful in preventing disruption due to unavailability of labor. Clustering, or geographic co-location was shown to have a positive influence on agility in the oil and gas industry because of the increased skilled-labor pool in the industrial cluster (Yusuf, Musa et al. 2014).

Kleindorfer and Saad (2005) note that modular product design can be a key aspect in achieving flexibility. If a component becomes temporarily or permanently unavailable, the modular design may allow it to be easily replaced with a similar replacement component, or to simply shift to production of parts with a slightly different end configuration. Agility may be developed by use of postponement, a production strategy which delays final customization of a product to the finishing processes, thereby affording the manufacturer the ability to respond quickly to changes in demand for specific configurations (Pettit, Croxton et al. 2013, Durach, Wieland et al. 2015). Similarly, the concept of product design flexibility entails the use of new product introduction, slight design changes, and product mix adjustment to meet the changing needs of the customer (Chiang, Kocabasoglu-Hillmer et al. 2012).

Table B. 5: Elements of Flexibility, Velocity, and Agility in Appendix B summarizes elements of flexibility, velocity, and agility.

2.2.6 Network Structure

The physical layout and characteristics of a supply chain network can have significant effects on its resilience against disruptions. The descriptive elements of network structure are closely tied to aspects of redundancy and flexibility, but are unique in their consideration of the specific configuration of the nodes in the network. Elements that can be used to differentiate different network structures include size, density, connectedness, stability, and the criticality of individual nodes.

The element of network size generally refers to the number of suppliers or the supply chain length (Blackhurst, Dunn et al. 2011). The number of nodes in the network has also been referred to as node complexity (Adenso-Diaz, Mena et al. 2012) or network scale (Brandon-Jones, Squire et al. 2014). Increasing numbers of suppliers can increase risk exposure if not mitigated by other resilience-enabling factors.

Other network-related measures include density, or the number of connections that exist in the network compared to the maximum number of connections it could possibly sustain (Greening and Rutherford 2011). The geographic dispersion of the network represents the spread of the network across different geographical regions. This spread can be useful in terms of offering decentralization of key assets (Pettit, Croxton et al. 2013). However, certain advantages may be available to organizations operating in geographical clusters such as ease of communication, reduced transportation delay, and co-location of skilled labor (Blackhurst, Dunn et al. 2011, Shao 2013, Yusuf, Musa et al. 2014).

The network can be described in terms of its flow complexity, measured by the number of interconnections between nodes (Adenso-Diaz, Mena et al. 2012). Connectivity distribution, a concept from complex network theory, describes the average number of connections possessed by each node in a network and can be used to represent supply chain connectedness (Hearnshaw and Wilson 2013). For example, a 'scale free' network implies a system in which a small number of hub firms possess many connections while a much larger number of peripheral firms possess few connections. An increase in connectedness has a positive effect on resilience as this implies greater flexibility and collaboration among firms.

Node criticality is an important measure which takes into account a variety of information, and can be described as the importance of the node within a supply chain due to what it does and what its relative contribution is to the overall realized value of the end product (Craighead, Blackhurst et al. 2007). The replicability of the affected product, and the degree of connectedness of the affected node all influence node criticality. Furthermore, if a supplier with a high-power position is affected by disruption, the realized effects may be greater implying greater criticality. Although the criticality of the node may be derived mainly from non-network related variables, the position of a critical node within the network can be of great significance if and when it is affected. The importance of a node based on its network position can also be reflected by the metric 'betweenness centrality' which represents the node's use as an intermediate connection (Basole and Bellamy 2014).

Geographic location of a node can also affect its strategic nature and therefore it can be an important factor in supply chain resilience (Kovács 2009, Revilla and Sáenz 2014). Revilla and Sáenz (2014) found though survey analysis that risk sources from natural hazards, market, and socio-economic sources vary by region/country. For instance, the sub-Saharan Africa region suffered more political and economic instability than other regions, and natural hazard exposure varied by region depending on the type of hazard considered. In contrast, the survey showed that the level of implementation of supply chain disruption management practices was not dependent upon the region considered.

The overall network stability relates directly to the amount of time over which the network has been established. As time progresses the supply chain network tends to evolve and become more stable as buyer-supplier relationships are established and verified (Greening and Rutherford 2011). The less volatile network is generally favorable for enabling resilience.

Table B. 6: Elements of Network Structure in Appendix B includes the elements of network structure extracted from literature.

2.2.7 Power and Dependency

Being in a low power position or a position of dependency can present difficulties for an organization in the event of a disruption. Whatever the reason, this positioning inhibits the ability of the supply chain to respond effectively after a disruption because of the reliance on the affected node (Adenso-Diaz, Mena et al. 2012). A buyer may depend on its supplier because the supplier controls an important resource that the buyer needs, because the supplier is simply in a superior market position, or because the component being supplied is strategically important.

In some cases, a supply chain member can exhibit high levels of control over a desirable resource. The resource may be a highly specialized component, requiring significant investment of time and resources for development of any alternate source (Ellis, Henry et al. 2010, Pettit, Croxton et al. 2013). There may be few options for switching suppliers, diminishing the negotiating power of the buyer (Greening and Rutherford 2011). In such cases, it is common for a buyer to be forced to rely on a single-sourcing strategy (Adenso-

Diaz, Mena et al. 2012). Resource constraints should be identified through examination of the supply chain network, including areas of typically low visibility such as 2nd and 3rd tier suppliers.

If one company has a significantly higher market share or organizational strength, the less powerful firm may be subject to the other's demands (Peck 2005, Sheffi and Rice Jr 2005). Determining the presence of such power dependencies requires examination of the relative strengths of the buyer and supplier. Examples of ways in which these strengths may be exhibited include customer loyalty, market share, and brand recognition.

In some cases, a buyer may be dependent upon a specific resource, simply because of its strategic importance (Ellis, Henry et al. 2010). For example, the resource may represent a large portion of the value realized in the end product. In this situation, a dependency may result regardless of market conditions or the level of supplier control over the resource supply.

Table B. 7: Elements of Power and Dependenc in Appendix B summarizes the elements of power and dependency.

2.3 Incorporating Resilience-Enabling Factors in Segmentation

From the systematic literature review a variety of resilience-enabling factors that influence supply chain performance were identified. The commonly used segmentation methods were also reviewed to identify variables that are frequently used to group suppliers. A closer review of the findings from these two studies reveals that many individual segmentation methods may neglect resilience-enabling factors when assessing dimensions used to group suppliers. For example, the portfolio method presented by Kraljic (1983) uses two dimensions: complexity of supply market and importance of purchasing. It can be argued that Kraljic's two dimensions would also be influenced by a number of resilience-enabling factors as shown in Figure 5.

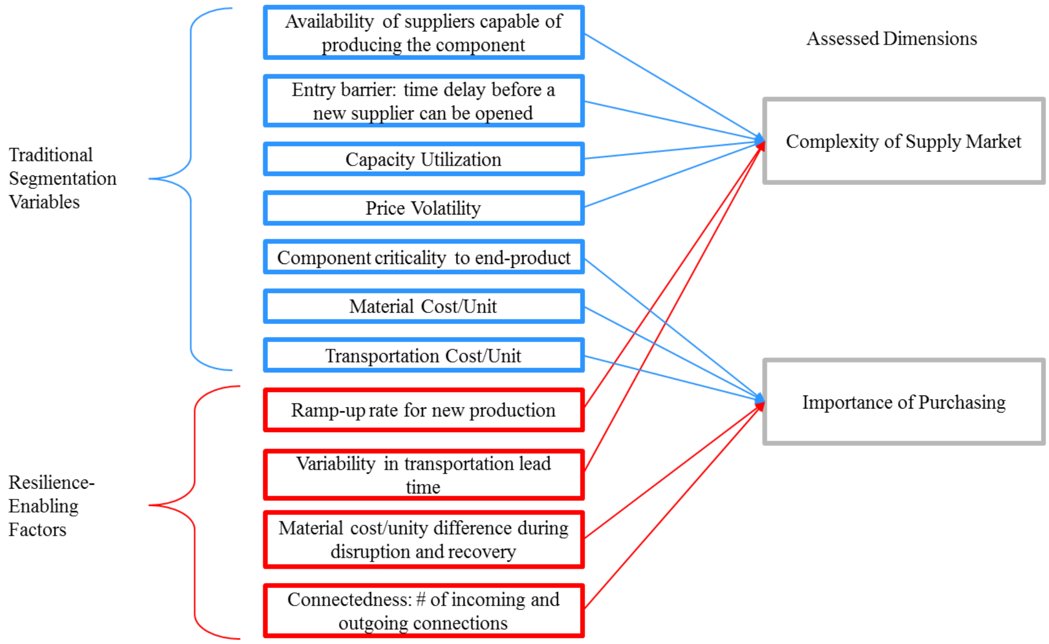

Figure 2.7: Integration of traditional segmentation variables and resilience-enabling factors

Thus, we postulate that by including a new set of resilience-oriented information, a different perception of supply market complexity and purchasing importance may arise. For example, the suggested factor 'network connectedness' may shed light on a dependency in the network that exists with a certain supplier. Because this dependence is made evident by the inclusion of the variable, the overall assessment of purchasing importance may be higher than if the dependency had not been considered. Any of the resilience-enabling factors could be potentially influential in the overall characterization of the supply base. It is thus proposed that any resilience-oriented segmentation method should consider some descriptive element of each of these main factors.

For further insight, the 161 segmentation variables from the studied segmentation methods were examined in terms of their ability to reflect the resilience-enabling factors. Any variables that could be used as an assessment of one of the resilience-enabling factors were noted along with their category. In this way, it was possible to demonstrate which resilience-enabling factors were best represented by the studied segmentation methods and by which segmentation variable categories.

From this examination, it is shown that the resilience-enabling factors ‘visibility and data analysis’ are fairly-well represented and are assessed primarily by the segmentation variables for ‘supplier capability’. Visibility depends largely on the capability of the supplier to collect data and convert it into usable information. The variables in the category of ‘current relationship’ also relate to visibility, indicating a need for developing a relationship with suppliers that fosters exchange of information.

Understandably, collaboration is reflected primarily by the ‘current relationship’ variables. Although the segmentation literature reviewed does not represent an exhaustive list, it is interesting to note that of the 161 examined variables there is no representation for the specific collaboration elements ‘decision synchronization’ or ‘planning of employee efforts.’ These elements of collaboration may be overlooked in existing segmentation methods.

The resilience-enabling factor ‘training, learning, and business continuity planning’ is overall poorly measured by the 161 segmentation variables. The variables that did represent this factor centered on technical know-how at the supplier. Specific elements relating to skills for recognizing risk, learning from past events and training simulations, and developing and testing continuity plans are largely overlooked by segmentation variables. The observations for this factor highlight the need for buyers to develop and include variables for self-assessment regarding these skills.

The resilience factors for redundancy and flexibility have greater implications on day-to-day operations, and thus are better represented by segmentation variables than other factors. These factors are dependent on segmentation variables from all categories, with redundancy being slightly more dependent on variables in the category ‘supplier capabilities.’

Network structure is unique in that it appears as both a resilience-enabling factor and a category of segmentation variables. The network represents the system in which all other capabilities must be developed. Although both resilience and segmentation literature focus on the size and dispersion of the network, the resilience literature introduces an additional concept in the connectedness of the network. The number of connections in the network may be more relevant after a disruption occurs and alternate production routes must be established. A resilience-oriented segmentation should therefor include some assessment for network connectedness.

The final resilience-enabling factor, power and dependency, is determined mainly by the relative market strengths of the buyer and supplier. Notably, the nature of the product is more relevant to power and dependency than any other resilience-enabling factor because it is the importance and value of the product that gives significance to the control of its production.

Development of a resilience-oriented supplier segmentation method will require a resilience-assessment of buyer and supplier capabilities, buyer-supplier relationship, product, and network. Current segmentation methods do not consider all factors of resilience, but the examination of existing methods provides insight into the development of a more exhaustive approach.

3 Methodology for Comparison of Segmentation Methods

The steps needed to assess the effectiveness of a supplier segmentation method for enabling resilience and robustness are summarized in Figure 3.1.

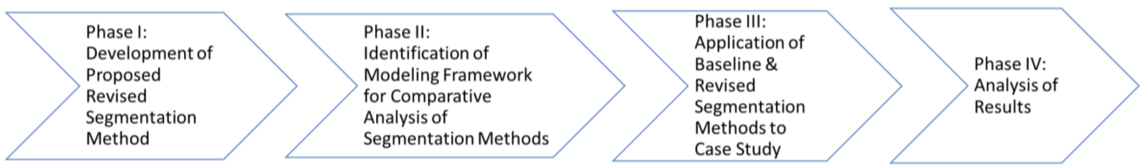

Figure 3.1: Steps for assessing segmentation method

3.1 Phase I: Develop Revised Segmentation Method

For the purposes of this study, two dimensions and the resulting four supplier segments described by Kraljic (1983) will be used in two supplier segmentation methods which are to be compared. First, in the baseline method, only traditional variables are used to characterize the suppliers on the two dimensions: complexity of supply market and importance of purchasing. In the revised method, additional variables are used which are not typically used in segmentation but have been identified in literature as having an importance to supply chain resilience. The variables used to assess suppliers on the two dimensions are shown in Table 3.1 and Table 3.2.

Descriptions are provided for each variable to guide the user in assigning values from 1 – 3. The number listed in the description are case specific, and should be modified to suit the context in which they are applied. For example, in Table 3.1, ramp-up rate is subdivided into categories of one month, one to three months, and more than three months. These ramp-up lengths may or may not be appropriate depending on the product being manufactured and their suppliers. The values 1 – 3 can be more generally interpreted as low, medium, and high levels. A discussion and approval process should be undergone in which these levels are defined. However, a clear distinction between levels is necessary so that the users can answer consistently in case the assessment is repeated later or if multiple respondents are consulted. The discussions held to define the categories for each variable should focus on identifying the points at which the overall contribution to market complexity changes significantly.

Scoring of each dimension is completed by summing the ratings for each variable. The dimension is divided into low and high regions by dividing the range of the scores for each dimension in half. If a supplier's dimensional rating falls exactly at the midpoint, the supplier is shifted into the segment corresponding to the higher value.

Table 3.1: Assessment variables for complexity of supply market

	Baseline Variables				**Additional Resilience-Oriented Variables to be used in Revised Method**	
Rating Scale	**Availability of suppliers for the component**	**Entry Barrier: time delay before a new supplier can be opened**	**Capacity Utilization**	**Price Volatility**	**Ramp up rate**	**Variability in transportation delay**
1	Many suppliers available in the market	Short time delay before opening new supplier (month)	Extra capacity is readily available	0-5%	1 month	Less than 8 hours
2	Limited number of suppliers are available in the market	Medium time delay before opening new supplier (quarters)	Extra capacity can be made available	5-10%	1-3 month	More than 8 less than 2 days
3	Single supplier available that can produce the component	Long time delay before opening new supplier (over 1 year)	Capacity is very limited; difficult or expensive to expand	10-15%	More than 3 months	over 2 days

Table 3.2: Assessment variables for importance of purchasing

Rating Scale	Baseline Variables: Component criticality to end-product quality/performance/distinguishability	Baseline Variables: Cost/Unit	Baseline Variables: Transport Cost/Unit	Additional Resilience-Oriented Variables to be used in Revised Method: Cost per unit difference during disruption and recovery	Additional Resilience-Oriented Variables to be used in Revised Method: Connectedness: # of incoming and outgoing connections
1	Could be replaced or substituted without significant change	Lower 1/3 of all purchases	Proportional to distance, lower 1/3	The same or less than standard cost	Low # of Connections (1-2)
2	Customer may notice some change in if component is replaced or substituted)	Middle 1/3 of all purchases	Proportional to distance, middle 1/3	slightly more than standard cost (1 - 2X)	Medium # of connections (2-3)
3	Replacing or substituting component will cause an obvious change	Upper 1/3 of all purchases	Proportional to distance, upper 1/3	significantly more than standard cost (> 2X)	High # of connections (>3)

Suppliers are classified as strategic, leverage, non-critical, or bottleneck. Once each supplier has been associated with one of the four segments, an appropriate procurement strategy should be assigned. Suppliers that fall in the range of higher market complexity, strategic and bottleneck, are typically managed with frequent collaboration and information sharing. Fast-response mechanisms should be put into place in the event of a disruption at one of these suppliers. The level of strategic importance also affects such decisions as how much buffer inventory to hold for each component, and whether to use a dual or multi-sourcing strategy. Although the procurement strategies for each segment can be described with detail, the study is limited by the requirement that such strategies must be operationalized and assigned to many suppliers in the simulation. The aspects of strategy that could be included in the simulation for each segment are summarized in Table 3.3.

Table 3.3: Procurement strategies for each supplier segment

Importance of Purchasing

Leverage • **Dual source** • **Keep inventory low to reduce cost** • **Less emphasis on developing visibility**	**Strategic** • **Single source (limited supplier availability)** • **Keep inventory low to reduce cost** • **Strong focus on developing visibility**
Non-Critical • Dual source • Keep inventory low to reduce cost • Less emphasis on developing visibility	Bottleneck • Single source (limited supplier availability) • Willing to hold more inventory • Strong focus on developing visibility

Complexity of Supply Market

3.2 Phase II: Framework for Comparative Analysis

In practice, the segmentation process should act to reduce the requirement for complex systems modeling and analysis. In the ideal case, the assessment should indicate an appropriate strategy for each supplier without need for further confirmation. However, for the purposes of this research a modeling and simulation paradigm is needed to assess the supply chain performance after being segmented with the baseline and revised strategies. A discussion of various modeling and simulation paradigms available and their usefulness in different contexts is presented in chapter 4.

In this work, the Agent-Based Modeling and Simulation (ABMS) paradigm is used to test the supply chain's resilience and robustness to different disruption scenarios. The justification for using the ABMS paradigm is also outlined in chapter 4. Once the disruptions have been implemented, the resulting resilience and robustness can be observed, in addition to the normal operating range for KPIs.

3.3 Phase III: Application to Case Study

The segmentation method must be assessed in the context of a supply chain, which requires the specification of an end-product and its bill of materials. A subset of the entire bill of materials can be used as required for complexity reduction. Furthermore, the network of suppliers from which the raw materials and sub-assemblies are procured must be defined and organized into a network structure. Data is then collected regarding the different suppliers' characteristics. The data needed is defined by the user and is to be used in the segmentation process. Based on the available data, the suppliers are then characterized according to the predefined segmentation process. A complete description of the case study employed in this work is presented in chapter 5.

3.4 Phase IV: Analysis of Results

Output data is to be collected from the ABMS for KPI after segmenting the supply chain with each method. For each method, different disruption scenarios are studied that are differentiated by their points of origin within the network. Furthermore, the disruptions are implemented with two different start times and two different severities. The disruption start time occurs either in the second or fourth quarter of the year. The severity is either a 50% or 100% loss of production capacity. The combination of two levels for severity and start time requires four disruption scenarios to be analyzed for each point of origin and each segmentation method.

The robustness and resilience are assessed by first observing the supply chain during its normal operating conditions. The normal operating range for inventory levels at the distribution centers (DCs) is determined for each quarter of the simulation runtime. The types of inventory that are observed include final assembly, photoconductor, and cartridge assembly. The total supply chain cost is also determined for each quarter. Robustness can then be measured as the maximum deviation that occurs from the normal operating range. Resilience is assessed as the total amount of time the metric falls outside the normal operating range.

A set of hypotheses is developed regarding the expected behavior of the KPI during the various simulation scenarios.

a) The revised segmentation method will increase resilience of the supply chain compared to baseline method.

   The revised segmentation method incorporates additional information that is shown by literature to have a direct connection to resilience. The incorporation of the new variables does not necessarily indicate that more or fewer suppliers will fall into any one segment. Rather, the new information creates a tendency for suppliers with a strong potential to create significant disruption impact to be separated and segmented differently from suppliers with a weaker potential for creating a large impact. Making use of information pertinent to supply chain resilience increases the likelihood that suppliers with similar needs for resilience and robustness will be grouped together.

b) A disruption at a strategic supplier is likely to have a more severe impact on the supply chain than a disruption at a non-critical supplier. The impact after a disruption at bottleneck or leverage suppliers is likely to fall into a middle range of severity.

   This hypothesis is based on the idea that a supplier with higher strategic importance and a more complexity in the market will be more likely to create a high-impact disruption. Non-critical suppliers have the lowest market complexity and importance of purchasing. Bottleneck and leverage suppliers have a mix of high and low market complexity and importance of purchasing.

c) Disruptions that start during a period of high demand are likely to have a stronger impact than those that occur during normal demand periods.

   Most of the KPI used to assess resilience and robustness are related to inventory and material flow. Production capacity is more constrained during periods of elevated demand. If the production capability is diminished at a time when it is under high demand, there is a greater likelihood that the need for production will exceed available resources.

d) Disruptions that cause a greater reduction in production capacity will have a greater impact on the supply chain.

   As with the previous hypothesis, the production capacity is necessary to maintain the desired inventory levels. If the capacity is 100% depleted in a disruption, it will take longer for the resources to return to their original state than if the capacity were only reduced to 50%.

4 Analysis and Selection of Modeling and Simulation Paradigm

The modeling and simulation paradigm used to assess the behavior of the supply chain should be chosen carefully according to the needs of the study. The objective of this section is to examine the primary modeling and simulation paradigms that have been used to represent supply chains. These methods are discussed regarding their convenience toward answering different types of questions. The paradigms that will be discussed include Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Modeling and Simulation (ABMS). A survey of different modeling approaches is described by North and Macal (2007). A representation of the Beer Game is constructed using each modeling approach in the attempt to highlight the differences in model structure which can all be used to represent a similar phenomenon. In the work, it is noted that each modeling paradigm can be differentiated according to its primary element of focus. For example, when constructing a DES representation of a system, the primary focus is on describing the individual processes and variability associated with those processes. In an SD model, the focus is on high level system behavior as defined by a set of stock variables and their change over time. ABMS focuses on representing the decision-making rules that exist within the system. The methods can also be differentiated by their representation of time, as each is able to capture the dynamic evolution of the system in a unique way. Finally, some questions which are particularly well-suited for each paradigm are described. These descriptions are collected in Table 4.1.

Table 4.1: Modeling Paradigms

	Discrete Event Simulation (DES)	System Dynamics (SD)	Agent-Based Modeling and Simulation (ABMS)
Primary Elements	Process and Variability	Stock and Flow Variables	Decision-Making Units (Agents)
Time Representation	Discrete points at which events occur	Constant increments	Constant increments
Appropriate Questions	What are the effects of increasing/decreasing process variability? Estimate flow times, wait times, etc.	What are the long-term trends given a range on external conditions? How to avoid unintended system behavior?	What is the emergent behavior of a group of autonomous decision makers?

ABMS appears to offer the most promising capability because the objective of the proposed research is to study the effect of individual behaviors at suppliers, manufacturer, and distributor. In chapter 5 of Managing Business Complexity, North and Macal (2007) list a number of characteristics of problems suited for ABMS. From the list of characteristics, the ones aligned most with the requirements of the supply chain problem are the following.

1. When it is important that agents adapt, and change their behavior.
2. When it is important that agents have dynamic relationships with other agents, and agent relationships form and dissolve.
3. When it is important that agents have a spatial component to their behaviors and interactions.
4. When process structural change needs to be a result of the model, rather than an input to the model.

Together these features justify the use of ABMS for the purpose in the proposed context of modeling disruption impact under different procurement strategies. Given the choice of ABMS as a modeling and simulation paradigm to be used in the remainder of the work, it is pertinent to provide a review of ABMS and its uses with a focus on supply chain applications.

4.1 Agent-Based Modeling and Simulation

The origins of Agent-Based Modeling and Simulation (ABMS) are in the field of complex adaptive systems (CAS), which is primarily focused on examining the adaptive mechanisms of biological systems (North and Macal 2007). In CAS, individual elements of the biological system respond to a changing environment to increase their chances of survival. Over time the field of CAS expanded from its early focus on biology into other areas such as network, social, and systems science, leading to the current field of ABMS. Since its development many types of problems have been studied using ABMS, including the flow of crowds during evacuations, predator-prey population dynamics, and cellular systems (North and Macal 2007). ABMS is related to but should not be confused with Multi-Agent Systems (MAS) which is based on solving problems related to the interaction of machines and designing agents to solve specific problems. An MAS tends to be normative, where the machines are designed to complete an objective, whereas ABMS is typically descriptive, and used to examine patterns of behavior that emerge in a complex system of autonomous agents (North and Macal 2007). In large part, ABMS is distinguished from MAS because of its background and relation to social systems and use for behavioral observations.

A simple example which demonstrates emergent behavior of agents is known as the Boids simulation, which imitates the flocking behavior of birds using agents with a set of only three rules (Zsidisin, Melnyk et al. 2005, Reynolds). First, the rule of cohesion dictates that each agent (or bird) should move towards the average position of its surrounding "flock-mates." Next, a separation rule is applied so that the birds will avoid overcrowding. Finally, an alignment rule dictates that each agent should orient itself toward the average direction of those in a specified surrounding area. Based on these simple rules applied only at the individual agent level, a systematic flocking behavior emerges wherein it appears that the birds share a common objective, or heading.

ABMS is an object-oriented technique which can be used to study the behavior of complex systems by focusing on the individual decision making units, or agents, upon which the system is built (North and Macal 2007). Each agent-based model consists of a set of agents, which are described by Lee and Kim (2007) as problem-solving entities that act through autonomous rule-based reasoning. Agents respond to environmental conditions, and send and receive messages to other agents regarding their current situations. Each agent contains a set of attributes and behaviors, and can relate to other agents and the surrounding environment (North and Macal 2007). Agents can conduct interactions in either a co-operative or self-interested manner. Unlike in a traditional optimization model, there is no centralized objective. Rather, ABMS is used to reveal emergent trends based on the specified behavior of the individual agents.

Agents can be classified into three types of architecture: reactive, deliberative, and hybrid (Forget, D'Amours et al. 2008). Reactive agents link specific inputs to specific outputs, meaning that if the agent observes an environmental condition, then it has a pre-specified action. This is the simplest of the three architectures and is characterized by a lack of adaptability. Deliberative agents use the knowledge gained from environmental observations combined with internal goals to execute their actions. This allows the agents to make decisions suited for the approach of long-term goals. In dynamic environments, the time needed for the agents to process the information and act on it can be important. Agents need to be able to make informed decisions before the environmental conditions change. Hybrid architecture uses a layering technique to gain some of the advantages of both reactive and deliberative agents. First, the agent will observe the environment and determine if there is an existing behavioral response for the situation. If there is no known response, the agent deliberates to try to find an action that will solve the problem. If the agent cannot find a solution to the problem, it will collaborate with the other agents to find a feasible solution.

Collaboration between agents is relevant to the study of SRM, and it is important to understand the various modes of inter-agent collaboration if the strategies of SRM are to be represented in a supply chain simulation. Methods used to facilitate cooperation among supply chain agents have been categorized by de Santa Eulalia (2009). These methods are summarized in the following paragraphs.

Communication - describes the conveyance of information between agents. Communication can be direct or indirect, such as through a universal access point. Other questions include whether the information exchange is synchronous or asynchronous, how many agents will receive information, whether there is human participation, and what the sending and receiving rights of the agents should be. There may be security mechanisms in place such as required authentication to prevent leaking of confidential information.

Grouping and multiplication - relates to the forming of agent coalitions to solve problems. One example is agent cloning to allow parallel computation. The agents group together for concurrent information processing.

Coordination - mechanisms used to manage dependencies in activities. This facilitates agent interaction in a way that leads to an overall solution and prevents chaos. Different coordination frameworks include direct supervision during activity execution, mediation during activity execution, mutual adjustment during activity execution, direct supervision with plan, mediation with plan, joint plan establishment, coordination by standardization, coordination by reactive behavior, synchronization, and coordination by regulation.

Collaboration - a group of agents work together on a common task by sharing tasks and resources. Tasks are decomposed into subtasks and then resources are allocated to the subtasks. The decision can be centralized or distributed.

Conflict resolution through negotiation and arbitration - mechanisms used to resolve conflicts of resource allocation. Negotiations can be bi-lateral or multi-lateral. Arbitration can be used which requires an impartial third party referee, agreed to by all agents involved in the dispute. Arbitration is suited for reactive agents, while negotiation is mainly associated with deliberative agents.

ABMS has been demonstrated in the context of supply chains, and may prove to be especially beneficial when different entities in the supply chain act in their own self-interest. A representation of the existing work in applying ABMS techniques to supply chain problems is provided in Section 4.2. As demonstrated in the examples, the ability to allow agents to make autonomous decisions based on their internal objectives is a key feature of ABMS that makes it well-suited for modeling the complexity of supply chain interactions.

4.2 Supply Chain Applications of ABMS

One of the earliest uses of intelligent agents to represent the supply chain was presented by (Fox, Chionglo et al. 1993). The work was in response to the company's desire to rely less on rigid planning and to allow faster responses to changes in the system such as demand variation and late deliveries. The authors divide supply chain management activities into three levels: strategic, tactical, and operational. The article highlights the important issues of determining how to distribute supply chain activities among agents, establishing how the agents interact to arrive at mutually acceptable solutions, the time required for an algorithm to come up with a response to a given situation, and knowledge availability. The agent architecture used consists of functional agents, which plan and control activities, and information agents, which assist the functional agents by providing communication. The six functional agents used are logistics, transportation management, order acquisition, resource management, scheduling, and dispatching. A graphical depiction of the agent interactions is shown in Figure 4.1.

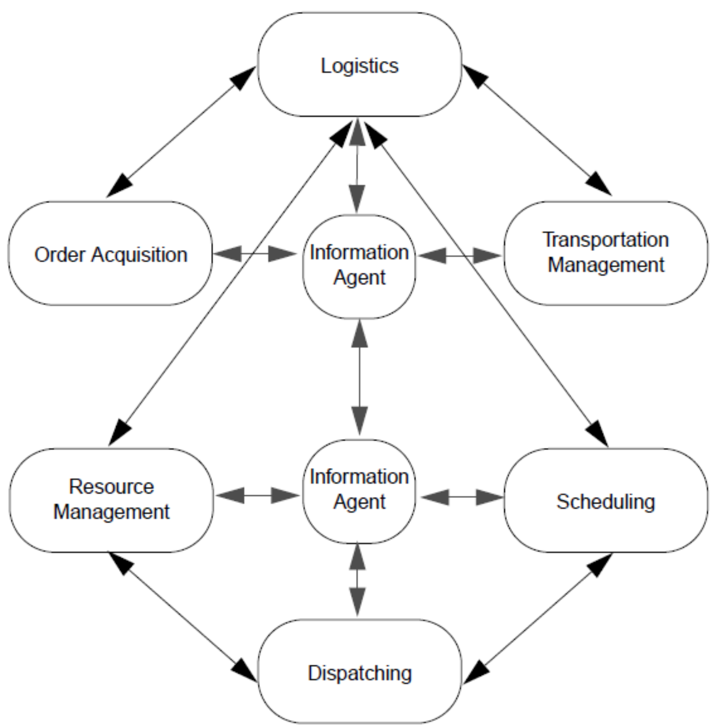

Figure 4.1: Supply chain agent interactions, (Fox, Chionglo et al. 1993)

The logistics agent tries to ensure on-time delivery at minimum cost. As input, it receives orders from the order acquisition agent, and outputs production and transportation requirements. The transportation management agent assigns and schedules transportation resources taking into consideration different assets and routes. The order acquisition agent negotiates price and due date with the customer, and forwards order information to the logistics agent. The resource management agent generates purchase orders and manages inventory. The scheduling agent schedules activity in the factory based on order information received from logistics, resource problems from resource management, and schedule deviations from dispatching. Finally, the dispatching agent performs real time order release and floor control.

The model presented by Fox, Chionglo et al. (1993) provides a good foundation for understanding the capabilities of ABMS in the supply chain context. To better reveal additional capabilities, a literature review was conducted specifically to uncover examples of ABMS for supply chain with a special emphasis on understanding and categorizing the methods of representing the relationships between supply chain entities. A search was conducted using the Compendex and Business Source Complete databases. Search terms included are shown in Figure 4.2.

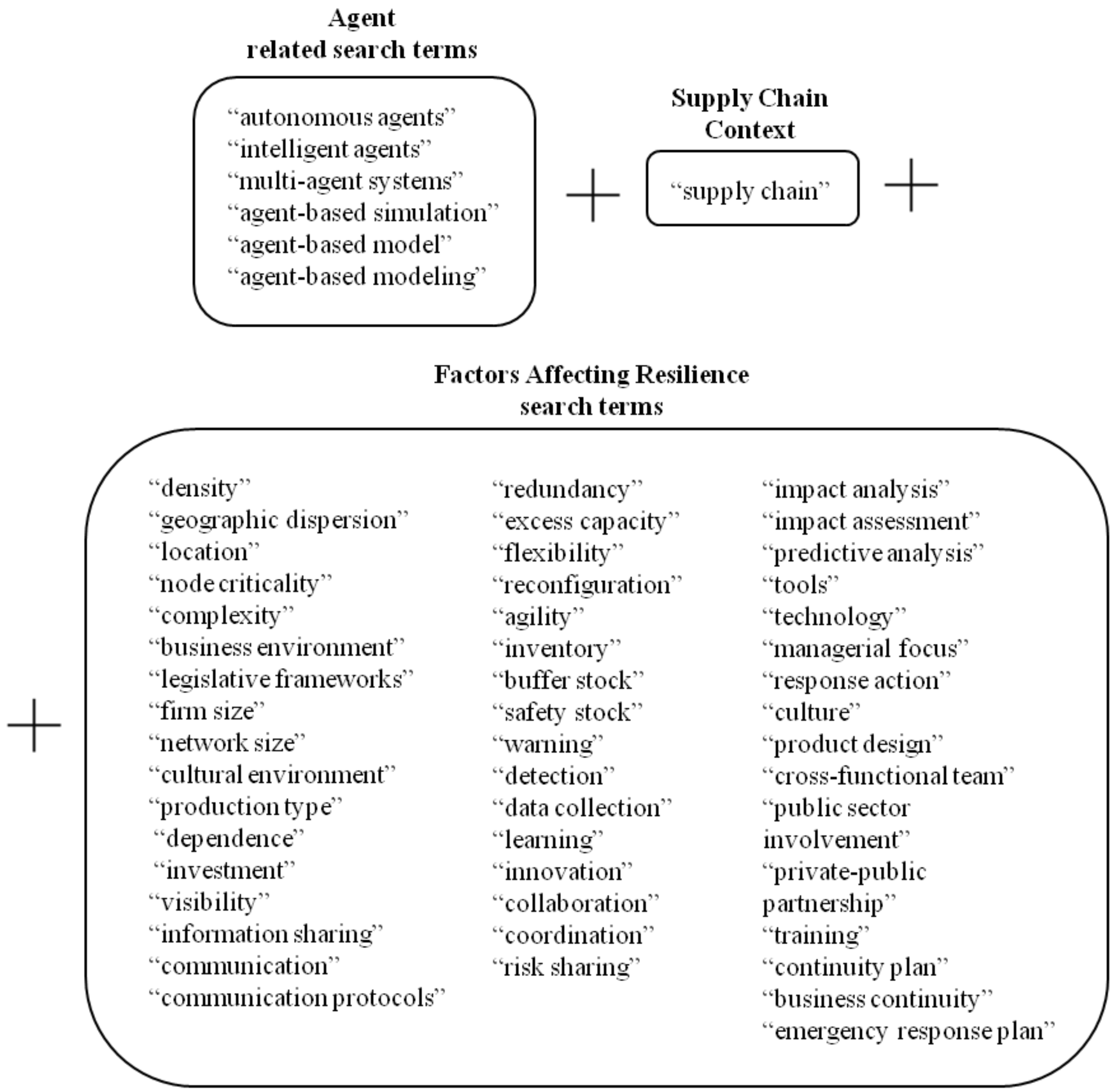

Figure 4.2: Supply chain ABMS search terms

Related terms are shown within the boxes. To conduct the search "or" statements were used between related terms and "and" statements were used between categories. This approach should result in articles concerning supply chain applications of ABMS. Furthermore, the results should include one or more of the terms in the third category which includes resilience-enabling (or disenabling) factors which were identified in the previously conducted literature review described in Section 2.2.

Examination of the resulting articles will begin with a look at a small subset of the articles which consider modeling of disruptions. The purpose of this initial focus is to highlight the ways in which resilience or robustness has been measured. The review should examine how the disruptions themselves are represented and identify any variables that might mediate the effects of disruption.

One study examined the effect of the network characteristics on the robustness against disruptions (Nair and Vidal 2011). Network characteristics included were average path length (the average distance between any pair of nodes in the network), clustering coefficient (relates the probability that the two nearest nodes are connected), and largest connected component (the size or number of components in an isolated sub-cluster of the network and the maximum distance between nodes in the sub-cluster). The performance measures examined as an indication of robustness are inventory level, backorders, and total cost. Two network topologies are considered. Scale-free topology indicates that nodes exhibit preferential attachment logic while random topology indicates random attachment of nodes with no specific preference. Findings indicate that long average paths between nodes in the network are detrimental to robustness. Clustering of the nodes within the supply chain network can increase the efficiency of operation, but these advantages should be balanced with the adverse effects to disruption response. The authors warn that various performance metrics need to be considered to fully understand the effects of the network topology on robustness. A limitation of the study is that it does not allow for re-configuration or adaptation in the network after a disruption occurs. Also, the potential benefits of building up and maintaining a buffer inventory at certain potentially vulnerable facilities is not considered. In the model, the disruptions occur at random based on a given probability, with three levels of likelihood examined. The model also considers targeted attacks. The severity of the disruption is measured in terms of the length, 1-3 weeks. All the facilities are considered agents as well as the customers modeled by a random demand function. Decisions made follow a similar format to the beer distribution game (Sterman 1989), with each entity deciding what orders to place in each iteration.

Another ABMS studies a disruption at the retailer (Wu, Huang et al. 2013). Input variables include the stockout length at the retailer for different products and the initial market share of the retailers and products. The response variable considered is the market share after the stockout. The purpose of the model is to study the impact of the stockout at the manufacturer and retailer. Agents are defined as retailers, manufacturers, and consumers, where consumers are classified as brand-loyal, habitual, or not loyal. Consumer decisions allowed in the model include purchasing products at another store when the preferred store is stocked out, delaying purchase to a later time, substituting with the same brand, substituting with a different brand, or not purchasing at all. The strength of this model is its allowance for different consumer response profiles based on market research. The agents can make autonomous decisions much like in a real system, and the agents' decision making rules can adapt over time. Different stockout lengths are considered. Resilience is measured in terms of the change in market share for both manufacturer and retailer. Different product types are considered having different customer response profiles. Also, different initial market shares are considered for the retailers. It is shown that the manufacturer and retailer may find mutual benefit in directing their attention to satisfying the right kinds of customers who have the most impact on market share and by focusing on products that have a high level of loyalty associated with them.

There is a need to integrate modern IT systems into a framework for developing agent-based decision support systems for handling disruptions in the supply chain (Giannakis and Louis 2011). A literature review was conducted to support the development of a framework for a disruption management system. The article focuses on the disruption management part of the framework, which is designed to initiate collaboration between agents when a potential problem is detected. Separate agents are proposed for communication, coordination (operating within the individual organizations/facilities), monitoring (watching the production schedule and triggering warnings), wrapper (facilitating information exchange from legacy systems like ERP and other agents), and disruption manager (proposing solutions to the problem at hand, considering past approaches for similar problems). The agents cooperate to detect the problems and convey the information to the disruption manager. Risk identification comes from regular monitoring of KPI's, such as inventory, throughput, utilization, and delivery lead time. Aberrations from normal level indicate a disruption is present. This result provides a good follow up to a survey paper published in 2006 on the use of ABMS in manufacturing (Shen, Hao et al. 2006). A key takeaway from the work is the suggestion that future work in the area should focus on integrating agent-based planning and scheduling systems with existing systems, such as real-time data collection systems, Enterprise Resource Planning and Material Requirements Planning.

Li and Chan (2012) examine collaborative transportation management (CTM) in handling demand disruptions. The aim of the research study was to find out what possible side-effects CTM might have on risk, as it is originally designed to increase efficiency. In the model, demand has a normal distribution and in the disrupted state is represented with a shift in the original distribution. The manufacturer gets demand data from the retailer and uses that to establish a re-order point, rather than relying on the retailer to place orders. In this way, CTM changes the information sharing and cooperation relationships of the involved parties. The CTM system is shown to improve response to demand disruptions specifically by reducing cost and adding flexibility. CTM has the intended purpose of making transport planning and execution more efficient. Each company in the model is simulated by an agent. The model includes stochastic demand, one retailer, one transporter, and one manufacturer. Performance is measured in terms of supply chain profit and cost, retailer’s inventory, and transporter’s delivery ability. Limitations noted in the paper are the inability to handle other types of risk including financial, supply, and information risks. Only the total profit of the supply chain is considered. Ultimately, it was concluded that supply chains implementing CTM could handle demand disruptions better than those without CTM.

Also focused on the area of demand disruption, but still providing insight into ABMS applications for supply chain disruption is the article by Upton and Nuttall (2014) that relates to fuel panic buying. The work offers a model to inform policy makers during such periods of demand disruption. The value of this work is the demonstration of the methods of information sharing to control the panic response. The model tries to reproduce transient behavior observed in past fuel panics. The closing of refineries and subsequent cut off supply resulted in panic buying and accelerated depletion of existing inventory. Twelve years after the initial panic event, the possibility of a strike was rumored, and panic buying again began, this time fueled by political statements. Even though no strike ever occurred, panic buying did ensue. In this instance the effect of the initial panic was different partly because of the prevalence of information about the event via the internet. Agents in the model represent vehicles with a stated fuel tank capacity. They must travel to pre-stated destinations, consuming fuel in the process. A social network overlays the physical system and the agents communicate with each other regarding their state of panic or lack thereof. The decision to panic or not is also related to the size of queue at each filling station. The system is tested by putting all the agents into a state of panic for 300 time units. An agent in the panic state chooses to top off the fuel after any trip. This ultimately leads to an oscillatory behavior as cars maintain close to full capacity until the period of panic ends, and then essentially synchronize their demand cycles. The consensus from the work is that the spread of information is important in modeling the effect of disruption. How the agents interact will largely dictate the result. Many metrics can be used to provide an indication of the system's resilience.

The next article is highlighted for its discussion of performance assessment in the supply chain (Behdani, Lukszo et al. 2010). As noted in the article, the entities in the supply chain form a socio-technical system wherein physical and social networks act together. Achieving the optimal system level goal for the supply chain does not necessarily mean that each local goal can be achieved. Incentives may be provided to persuade individual entities to pursue system-level objectives. Specifically, the paper provides an illustrative example using the model to study the effects of a plant shut down. Recovery policies involve changing the re-order points at the other two remaining facilities, or rejecting some orders if they are not from important customers. These policies have different effects on the number of late orders, total tardiness, and total profit. The model can also be used to process negotiations, such as when the order cannot be delivered on time. Instead of just notifying the customer that the order cannot be fulfilled, the customer and facility agents negotiate on a new due date and possible price reduction.

Figure 4.3 demonstrates a summary of topics synthesized from the initial literature search.

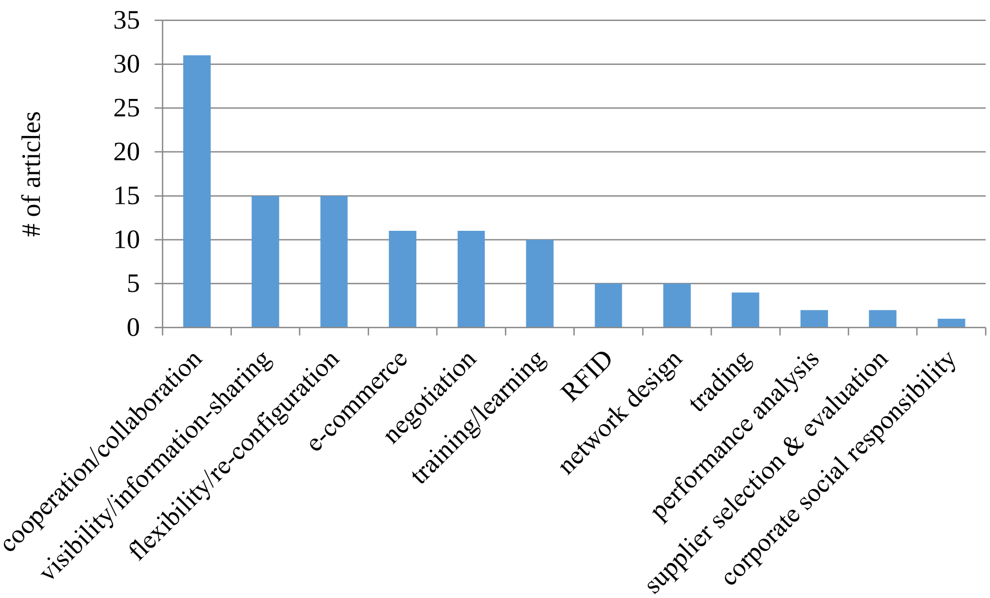

Figure 4.3: Focus areas within literature on ABMS supply chain applications

Of these results, methods of collaboration between entities in the supply chain are of relevance to the proposed work, and many articles were retrieved in this subject. Other topics of prominence which arose include visibility and flexibility which relates to the use of alternative supply configurations. Because collaboration is particularly well-suited for modeling by interacting agents, and has a direct connection to supplier relationship management, the remainder of the review will focus on a subset of articles published in this area.

Hou, Sheng et al. (2008) study the benefits realizable from the formation of alliances between buyers and suppliers. Some potential benefits include shared financial risk and reduced costs, innovative product development, and resolution of competitive conflicts. The authors argue that the de-centralized control of agents offer better representations of supply chains than traditional operations research methods. The agent-based model studies the effect of myopic behavior at a retailer on the supply chain alliance by allowing the retailers to base purchasing decisions on either long or short-term revenues and by allowing retailers to vary supplier switching probabilities. The model also considers the number of retailers in the market and length of order lead time. Results indicate that myopic decision making by the retailer reduces the overall profitability. In the competitive environment with more retailers, this effect is even stronger. The comparative benefit of long-term decision making diminishes but remains favorable as order lead time increases.

Mohebbi and Li (2012) examine long-term partnerships in e-supply networks (e-SNs). Qualified partners are selected. Both buyer and supplier should benefit from long-term multi-period exchanges. The development of e-supply networks facilitates real time decision making. Membership in the supply chain exhibits flexibility. The e-SN system takes an ebay-like approach in that the suppliers pay a fee to exist on a site and buyers can leave ratings based on their experiences with suppliers. Agents can facilitate the sharing of information vertically while preventing access to intellectual property.

Distributed operations planning was examined for the softwood lumber supply chain (Gaudreault, Forget et al. 2010). The agent model is used to plan and schedule the operations within the supply chain. The plans of the different agents are then coordinated. Coordination in this context means that the individual entities should plan with consideration of dependencies on other operations. Within a single plant, coordination across the function of production and supply, production and distribution, and inventory and distribution. This is inter-functional coordination. Coordination also occurs across plants for the same function.

Albino, Carbonara et al. (2007) note most work that has been conducted in studying cooperation in supply chain has been qualitative and has adopted the perspective of large companies as buyers cooperating with their suppliers. The paper focuses on cooperation within Industrial Districts (ID) which are collections of small and medium sized firms acting in a network of buyer-supplier relationships in both competitive and cooperative nature. The type of cooperation examined in the study has the aim of balancing production capacity utilization while minimizing unsatisfied customer demand. The benefits of cooperation are studied under different demand uncertainties and organizational structures (presence of one or more leader firms in the ID). Results indicate that the benefits of cooperation increase when the demand variability is high because of the balance of flexibility and efficiency. The existence of leader firms can result in a reduction of overall flexibility in the ID, especially if the leader firms utilize their extra bargaining power. This is an interesting study that focuses on a single type of cooperation.

ABMS is used to evaluate the value of cooperation (Janssen 2005). A semi-cooperative structure is examined wherein the agents optimize the supply chain while at the same time trying to maximize their own goals. Production agents try to optimize their resource utilization. DC agents try to balance supply and demand, minimize the amount of inventory and reduce stockouts throughout the entire supply chain. Dealer agents try to minimize their individual number of stockouts. The study showed that using the multi-agent approach to determine the amount of inventory to deliver during specific periods from the DCs increased the ability of the supply chain to respond to high volatility of demand.

Autonomous Cooperation and Control (ACC) is assumed to create strategic flexibility (Hulsmann, Grapp et al. 2008). This paper is not about agents per se but focuses on explaining why ACC can provide competitive advantage to the global supply chain. It notes that logistics systems using ACC handle complexity and dynamics more effectively than those that do not. Strategic adaption is the primary mechanism by which the paper suggests competitive advantage can be gained. The systems should be able to take in new information and adjust based on this, but not compromise stability by changing too much with every slight change in input. ACC is a system of decentralized decision making. Compared to a system working toward a centralized objective, ACC has the advantage in terms of flexibility.

Collaborative planning forecasting and replenishment (CPFR) is a process in which trading partners exchange sales information and forecasts (Caridi, Cigolini et al. 2005). The study examines the ability of intelligent agents to improve the negotiation process involved. Three negotiation models are studied: the original CPFR method, an advanced model using agents, and a learning model using agents. Metrics used to measure the improvement are cost, inventory level, stockout level, and sales. CPFR is a 9-step framework for buyer-seller exchange of sales and forecast data on a web-based platform. The negotiations are designed to handle situations where the sales forecast at the buyer and seller differ, or when the order forecast at the buyer differs from the seller's ability to supply. When an exception to the forecast happens, the agreement must be re-negotiated. This effectiveness of negotiations from the different models controls the reduction of bullwhip affect when something unexpected happens and can reduce lost sales.

Articles presenting collaboration-oriented ABMS models can be differentiated by the cooperation goal, the method in which cooperation between agents is represented, the external factors that are considered, and the metrics used to measure the effectiveness of cooperation. Cooperation goals include minimization of unsatisfied customer demand or stockouts (Janssen 2005, Albino, Carbonara et al. 2007), reduction of forecast discrepancies (Caridi, Cigolini et al. 2005), and cost minimization (Gaudreault, Forget et al. 2010). Methods of collaboration include enhanced communication both horizontally between suppliers and vertically up and down the supply chain. External factors considered include demand uncertainty, forecast uncertainty, and available production capacity and utilization. Effectiveness of collaboration can be measured in terms of flexibility or efficiency of operations, lead times, stock levels and number of stockouts, total cost, and on-time delivery percentage.

5 Case Study

An illustrative case study presented in this section will be used to demonstrate the application of ABMS to model disruption behavior. The context of the case study is a laser printer supply chain, based on a combination of information provided by an industry partner and public information about the components of a laser printer. Many of the components to be considered in the supply chain case study are demonstrated in Figure 5.1.

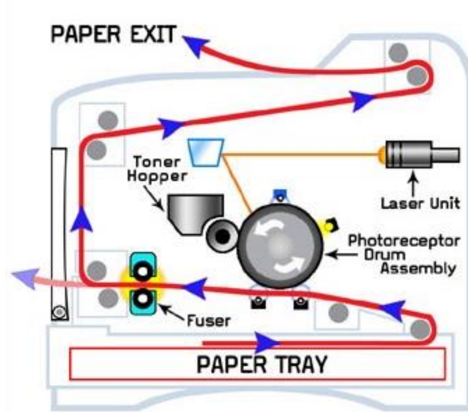

Figure 5.1: Laser printer components (Oki Data Systems 2007)

5.1 Laser Printer Bill of Materials

The case study need not consider a comprehensive list of components for the laser printer. Rather, components are selected to demonstrate a multi-tier supply chain with enough complexity to warrant the need for segmentation. The example will include one facility for final assembly and several regional DCs. Component suppliers are included through the second tier, and both internal facilities and contract manufacturers are included. Figure 5.2 demonstrates the simplified bill of materials for a laser printer to be used in the case study.

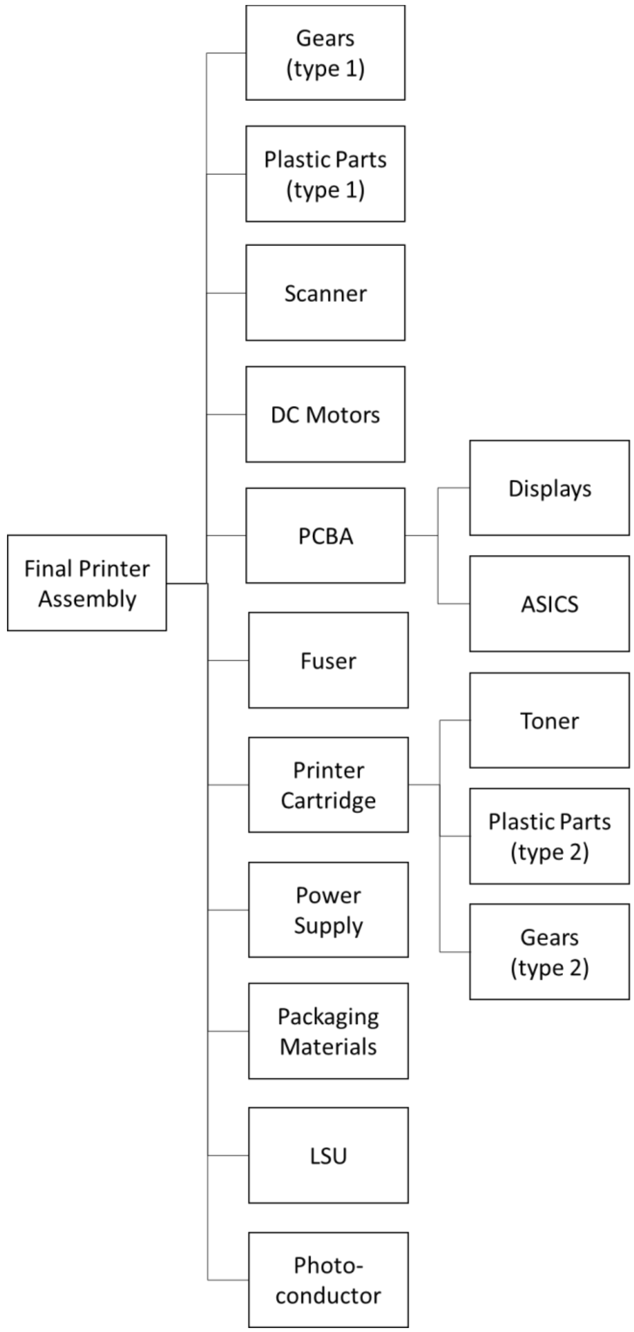

Figure 5.2: Laser printer tiered bill of materials

The printer cartridge assembly consists of the toner itself, plastic parts which make up the structure of the cartridge, and gears. Plastic parts and gears are separated into type one which goes into the final printer assembly and type two which goes into the cartridge assembly. The Printed Circuit Board Assembly (PCBA) includes as subcomponents the display panel and Application Specific Integrated Circuit (ASICS). The Laser Scanning Unit (LSU) consists of the laser, a lens, and movable mirror used to maneuver the beam to write the electrostatic image onto the photoconductor. For simplicity purposes the subcomponents of the LSU are not included. Components which are commonly purchased aftermarket by the end user are the toner cartridge and photoconductor. These components are placed near their demand centers to improve customer responsiveness and each is manufactured in two locations. Other components included in the study are the fuser, which is used to heat and melt the plastic component of the toner, causing the image to be permanently fixed on the page. DC motors are used to power the rollers for paper transport, and the power supply converts electricity to DC for the electronic components. The scanner refers to the document scanner that sits on top of the main printer assembly. The above components represent a simplified version of a laser printer broken down into some of its key components.

5.2 Data Collection

Data for the printer supply chain was collected through a combination of meetings with supply chain professionals at a consumer electronics manufacturer producing laser printers and toner cartridges and research of publicly available information.

A presentation was provided by the company in which the general structure of the global supply chain network was outlined as seen in Figure 5.3. The printer case study that forms the context for the ABMS is based on the initial presentation and follow-up interviews with the company.

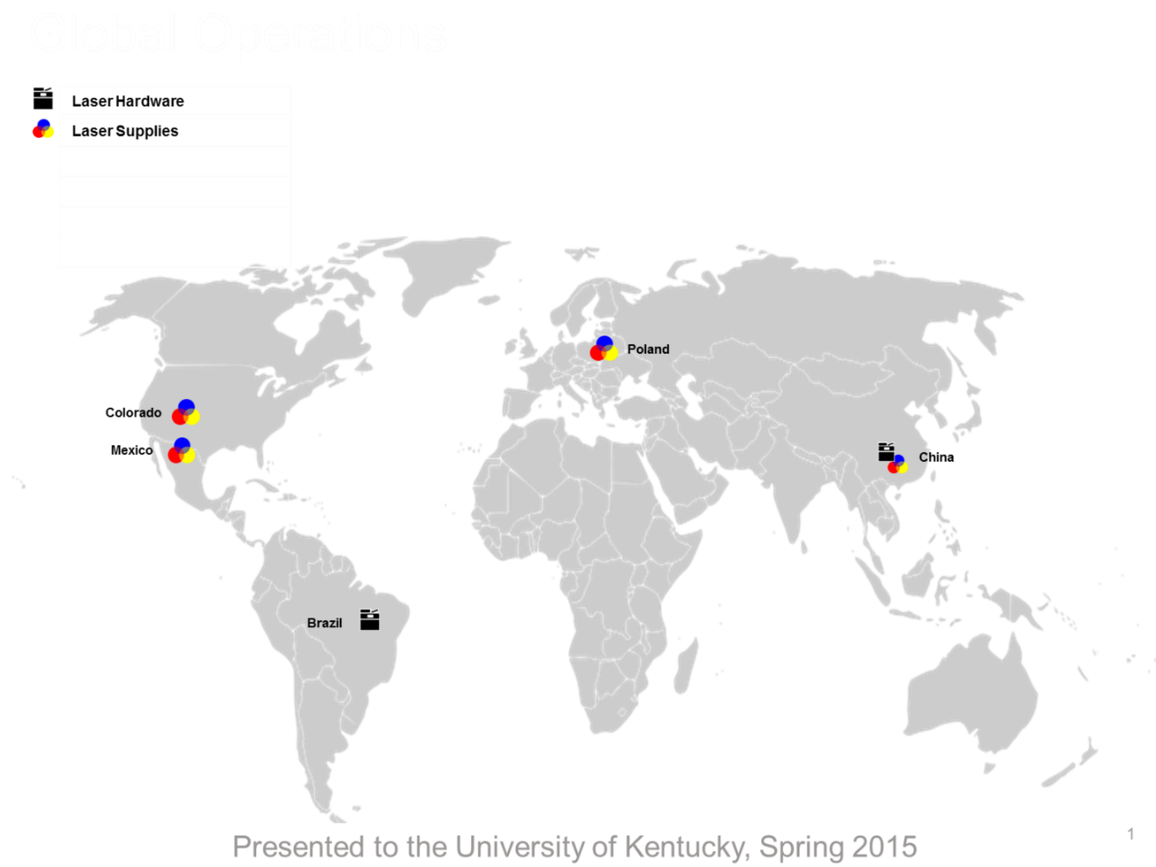

Figure 5.3: Global operations for laser printer supply chain

Basic understanding of the laser printer components was developed and from this a potential BOM and supply chain configuration were presented to the industry partner. After a few iterations, the simplified BOM presented in section 5.1 was agreed upon along with the network structure and spatial representation demonstrated in

Figure 5.4. The arrows connecting the suppliers in the figure are scaled in proportion to the transportation delay between nodes. In the ABMS paradigm, each complete iteration of the simulation procedure is counted as a tick. The simulation is designed such that each tick corresponds to a simulated hour. The longest transportation delay of 16 ticks, or 16 simulated hours, is shown with the red arrow, and so on with the blue and green arrows.

The industry partner was presented with a set of tables (Table 3.1 and 3 from chapter 3) containing a list of assessment variables and a suggested 1 – 3 rating scale with verbal descriptions of the meaning behind each rated value. The supplier for each component in the BOM was assessed based on prior experience from the supply chain managers.

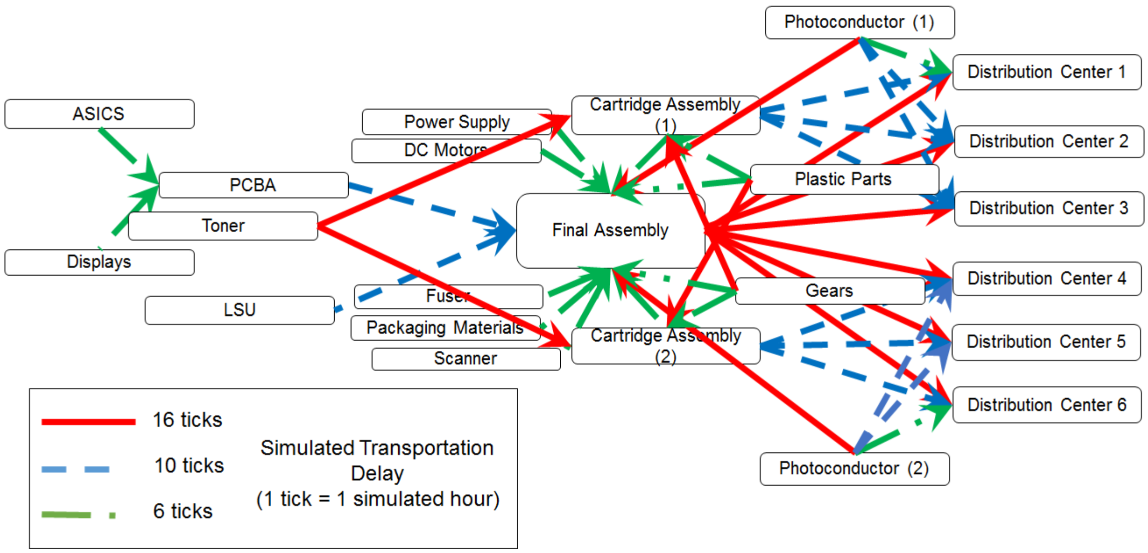

Figure 5.4: Spatial representation of laser printer supply chain

Cost data for each component was first estimated based on publicly available information and then presented to the industry partner to check validity. The information collected was then used to rank each supplier on the two dimensions: complexity of supply market and importance of purchasing (Kraljic 1983). This data would also be included in the simulation as defining characteristics for each supplier. Response data for market complexity for the ranked assessment of each segmentation variable is presented in Table 5.1. The summed scores for market complexity are provided for the baseline method and the revised method which incorporates two new variables. Similarly, the response data for purchasing importance is presented in Table 5.2.

Table 5.1: Variable assessment for market complexity

	Baseline Assessment Variables					Additional Resilience-Oriented Variables		
Supplier	**Availability of suppliers for the component**	**Entry Barrier: time delay before a new supplier can be opened**	**Capacity Utilization**	**Price Volatility**	**Baseline Total**	**Ramp up rate (after opening, how fast does an alternate ramp up to full capacity, and how fast does a disrupted supplier ramp up in recovery)**	**Logistics variability (variability in transportation delay)**	**Revised Total**
Plastic parts	1	2	1	1	5	1	1	7
Packaging materials	1	1	1	1	4	1	1	6
Displays	1	2	1	1	5	2	3	10
ASICS	2	3	2	1	8	3	3	14
LSU	2	3	1	1	7	3	2	12
Gears	2	2	1	1	6	1	1	8
Toner	3	3	1	1	8	3	3	14
Power Supply	2	3	1	1	7	2	1	10
DC motors	1	2	1	1	5	2	1	8
Fuser	2	3	2	1	8	3	1	12
PCBA	1	2	1	1	5	2	2	9
Cartridge Assembly	2	2	1	1	6	1	1	8
Scanner	2	3	1	1	7	2	1	10
Photoconductor	3	3	1	1	8	3	3	14

Table 5.2: Variable assessment for purchasing importance

	Baseline Assessment Variables					Additional Resilience-Oriented Variables			
Supplier	**Component criticality to end-product quality/performance/distinguishability**	**Cost/ Unit**	**Normalized Cost/Unit**	**Transportation Cost/Unit**	**Baseline Total**	**Cost per unit difference during disruption and recovery**	**Connectedness: # of incoming and outgoing connections**	**Normalized Connectedness**	**Revised Total**
Plastic parts	1	12	1	1	3	1	3	2	6
Packaging materials	1	10	1	1	3	1	1	1	5
Displays	1	30	1	1	3	2	1	1	6
ASICS	1	30	1	1	3	2	1	1	6
LSU	1	25	1	2	4	2	1	1	7
Gears	1	3	1	1	3	2	3	2	7
Toner	1	50	2	3	6	2	2	1	9
Power Supply	1	30	1	1	3	2	1	1	6
DC motors	1	5	1	1	3	2	1	1	6
Fuser	1	50	2	1	4	2	1	1	7
PCBA	1	100	3	2	6	2	3	2	10
Cartridge Assembly	1	60	2	1	4	2	7	3	9
Scanner	1	120	3	1	5	2	1	1	8
Photoconductor	1	50	2	3	6	2	4	2	10

Scoring of purchasing importance required normalization on the 1-3 scale for cost/unit, which was estimated in dollars, and connectedness, which was counted as the number of incoming and outgoing connections at a node. Scaling was performed by simply dividing each reported value by the highest reported value for the variable, multiplying the ratio by three, and rounding to the highest integer, as exemplified in Equation 2.

$$Normalized\ Metric = ceiling\left(\frac{Node\ Value}{Max\ Node\ Value} \times 3\right) \qquad \textit{Equation 5.1}$$

In addition to the variable assessment, data was gathered for demand seasonality. The percentage of yearly demand expected to be accrued in each quarter was provided and a constant amount of random variation in demand was applied based on the standard normal distribution. Furthermore, truckload capacity was estimated based on a fixed carrying capacity in terms of weight and volume. Each component's weight and volume per unit was estimated to determine the number of units that could be carried in a single truck. Travel cost was then calculated based on fixed cost per transportation hour.

To divide the suppliers into segments, they are plotted with market complexity on the x-axis and purchasing importance on the y-axis. The range of resulting values for each dimension is divided in half to delineate the separation between 'high' and 'low' values on each dimension. For example, in the baseline case for market complexity supplier scores vary from four to eight, so the line dividing 'high' and 'low' market complexity falls at six. If a supplier scored six for market complexity it is shifted to the segment associated with the higher score. The result of dividing the suppliers in this way is a relative categorization. No fixed level of market complexity is defined for separating suppliers into the low or high end of the scale.

The relative approach to grouping suppliers requires an assumption that the suppliers will be well-distributed in levels of market complexity and purchasing importance, and this was true for the laser printer supply chain. In some situations, however, a different approach may be needed for differentiating suppliers. For example, if all suppliers were assessed in range of one to two, it would be more appropriate to group them all into the low end of the scale than to divide the small range into low and high. Ultimately, the important take-away from the segmentation process is the specification of the quadrant for each supplier, rather than the raw score on each dimension. The ranking and grouping process should be consistent for all suppliers, and should be agreed upon in advance by the user of the segmentation tool and any domain experts providing assessments. The purpose of this study is to determine the effect of different ranking and grouping methods on resilience and robustness, and to demonstrate that they have an impact. The relative grouping method used is appropriate for this purpose. In future work the approach to establishing a fixed division point between low and high dimensional levels should be explored, and should be studied in terms of its dependence on the supply chain context.

5.3 Segmentation Results

The segmentation results are shown in Figure 5.5 for the baseline method and in Figure 5.6 for the revised method. In each case, the suppliers are plotted on an axis according to their dimensional rating. After plotting all suppliers in the grid, the range and domain are divided in half to create the four supplier segments.

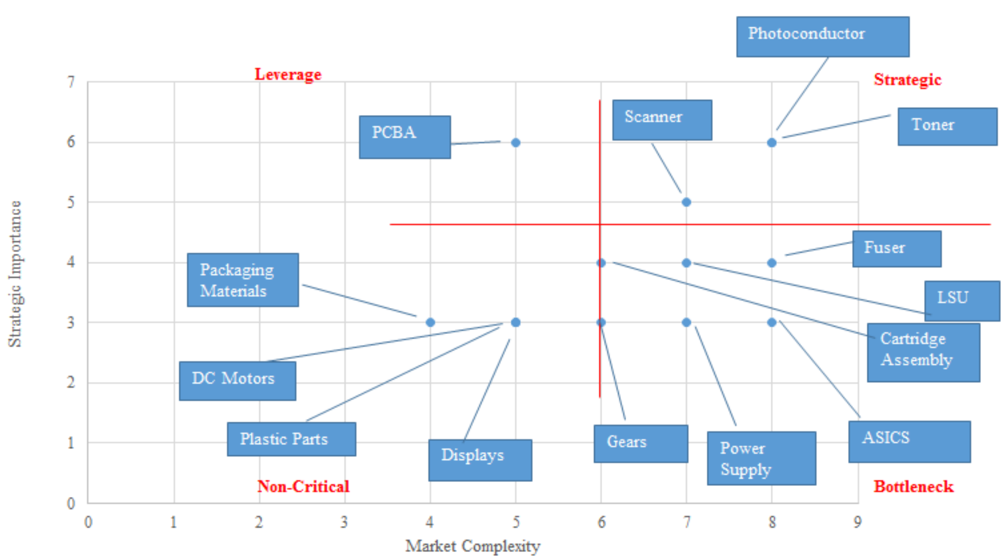

Figure 5.5: Results of baseline segmentation method

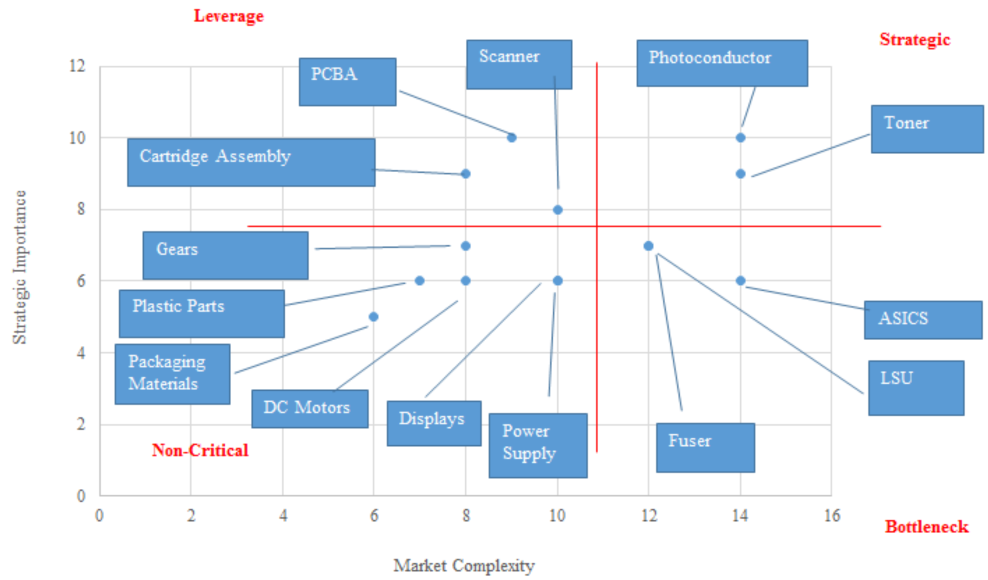

Figure 5.6: Results of revised segmentation method

Table 5.3 further summarizes the segmentation results and provides a good indication of which suppliers were segmented differently in the baseline and revised methods. In the table, the segments are represented by the first letter: B = bottleneck, N = non-critical, L = leverage, and S = strategic.

Table 5.3: Summary of segmentation results for each supplier

Supplier	Baseline	Revised
Plastic parts	N	N
Packaging materials	N	N
Displays	N	N
ASICS	B	B
LSU	B	B
Gears	B	N
Toner	S	S
Power Supply	B	N
DC motors	N	N
Fuser	B	B
PCBA	L	L
Cartridge Assembly	B	L
Scanner	S	L
Photoconductor	S	S

Suppliers that make change their intended segment between the two methods include gears, power supply, cartridge assembly, and scanner. Looking at Figure 5.5 and Figure 5.6 side by side gives a clear indication that when the revised segmentation method was used, a greater number of suppliers were segmented on the left-hand side of the axis than were in the case for the baseline method. When the revised method was employed, every supplier was shown to have higher raw ratings in both market complexity and strategic importance (as observable in Table 5.1 and Table 5.2. Despite the overall translation of all the nodes, a few nodes shifted more dramatically than the others, namely photoconductor and toner. The relative change in the rankings leads to a shift in segmentation to the left-hand side.

It is also interesting to note the specific strategic changes that will result from each segmentation process. The strategies associated with each segment are applied based on the indications provided in Table 3.3. Table 5.4 indicates if dual sourcing is used, whether the desired on-hand inventory is set at a higher or lower level, and finally whether a supplier has visibility into its supplier's production for each supplier in the baseline and revised cases. As indicated in Table 3.3, single sourcing is used for suppliers on the higher division of market complexity, which is a reflection of the difficulty associated with opening and interacting with multiple suppliers in a complex market. Strategic suppliers typically represent high-cost and specialty components, so a low inventory strategy is used to reduce cost. Bottleneck suppliers typically supply less-costly products than strategic suppliers, so a higher-inventory strategy is used. For both segments in the high market complexity side, visibility is developed as a measure to protect against expected uncertainties. Dual-sourcing is employed for leverage and non-critical suppliers since this option is more feasible in the lower market complexity case. Also, dual sourcing is a strategy for encouraging primary and dual suppliers to compete and drive down cost. Inventory is kept low to reduce cost, and visibility is not developed as it is less crucial than in the bottleneck and strategic nodes.

Table 5.4: Strategic sourcing options for each supplier

	Use Dual Sourcing?		Desired On-hand Inventory		Visibility into Buyer Production Rate	
Supplier	**Baseline**	**Revised**	**Baseline**	**Revised**	**Baseline**	**Revised**
Plastic parts	YES	YES	L	L	NO	NO
Packaging materials	YES	YES	L	L	NO	NO
Displays	YES	YES	L	L	NO	NO
ASICS	NO	NO	H	H	YES	YES
LSU	NO	NO	H	H	YES	YES
Gears	NO	YES	H	L	YES	NO
Toner	NO	NO	L	L	YES	YES
Power Supply	NO	YES	H	L	YES	NO
DC motors	YES	YES	L	L	NO	NO
Fuser	NO	NO	H	H	YES	YES
PCBA	YES	YES	L	L	NO	NO
Cartridge Assembly	NO	YES	H	L	YES	NO
Scanner	NO	YES	L	L	YES	NO
Photoconductor	NO	NO	L	L	YES	YES

6 Model Development and Specifications

6.1 ABMS Requirements Determination and Specification

The FORAC Architecture for Modeling Agent-Based Simulations for Supply chain planning (FAMASS) (de Santa-Eulalia, D'Amours et al. 2010) demonstrates a systematic procedure for conducting the analysis phase for advanced supply chain planning. The different pathways that could be followed are shown in Figure 6.1. According to the procedure, different levels of analysis can be performed. For the study presented in this research, the autonomous behavior patterns of agents need to be considered as these reflect the supplier relationship management strategy. At the same time, uncertainties and KPIs must be analyzed at the supply chain level. This description indicates the need to follow Path C as depicted in Figure 6.1. In this section the description of a complete analysis, which requires equal focus on the supply chain and agent levels, will be described.

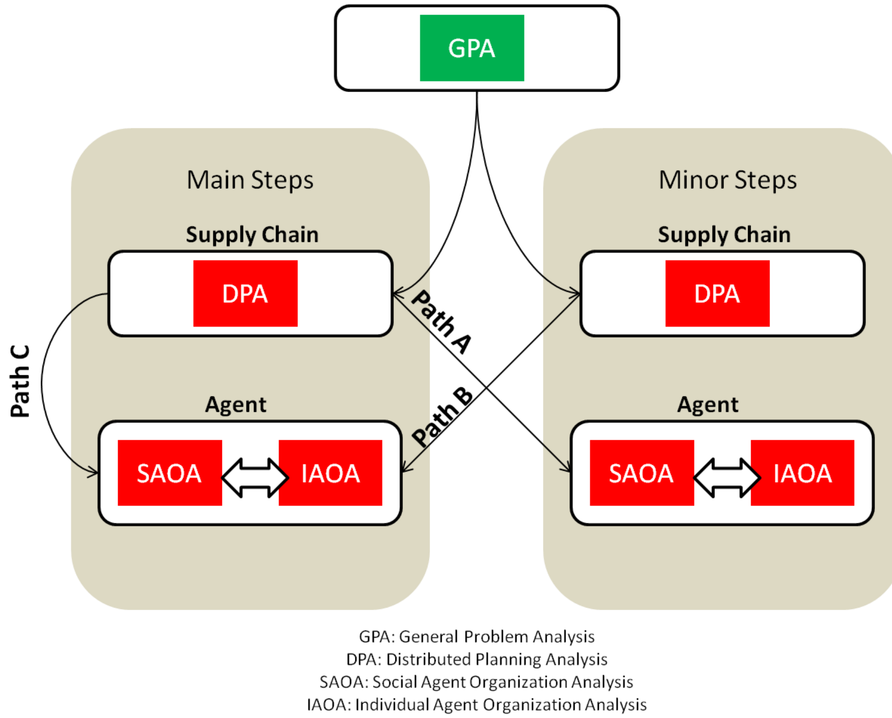

Figure 6.1: Analysis pathways, adapted from (de Santa Eulalia 2009)

For each step in the process, requirements determination and requirements structuring must be performed. In requirements determination, it may be found that different simulation stakeholders will have different requirements. This may necessitate such procedures as observation and interviewing of the intended user. The requirements are then structured using a combination of tables, use case diagrams, and fishbone diagrams. Each analysis path shown in Figure 6.1 begins with General Problem Analysis (GPA). GPA focuses on discussing and providing a good description of the problem. There are six key topics or steps that must be addressed as part of GPA. These are outlined in Table 6.1, with descriptions pertaining to the proposed case study.

Table 6.1: GPA descriptions for the proposed case study

Steps	Description
Objective	The objective of the case study can best be described as a ***trade-off analysis***. Trade-off analysis is defined as "investigating the balance of factors which are not all achievable at the same time" (de Santa Eulalia 2009). The trade-offs exist between inventory and cost robustness and resilience for each supply chain member.
Scope	The simulation will be performed for academic/research purposes. ***A virtual supply chain is to be created as inspired from a real-world example***. Only the amount of detail needed to test the hypothesis will be included in the model.
Object, Environment and Hypothesis	The object of study is the ***supply chain network from tier 2 component suppliers to regional distributors***. Within this context, the supplier segmentation process will be studied. The object is subject to the surrounding environment, which will consist of several ***disruption scenarios***. Each disruption will vary in location of origin, severity, and start time. The over-arching hypothesis is that the supply chain network performance, as measured in terms of both ***robustness and resilience, will be improved*** through implementation of the revised supplier segmentation process.
Virtualization	Both object and environment are virtualized.
Supply Chain Subsystems	***Operating system***: tracks flow of inventory, orders, and cost ***Information system***: incorporated to reflect variables related to disruption detection and communication ***Decision system***: strategic choices made based on segmentation and disruption planning; tactical choices made
Anticipation	Strategic decisions regarding segmentation of suppliers and pre-disruption planning influence the tactical decisions regarding choice of mitigation strategy after a disruption occurs. The choice of mitigation strategy then affects the operational order placement and distribution decisions. Each higher-level decision anticipates the effect of the chosen strategy on lower levels. Assume perfect anticipation, meaning that each higher-level decision making agent has complete knowledge of the logic used by lower-level decision making agents. Agents at the same level, ***different suppliers, may not be equipped with complete visibility into the decision logic of each supplier.***

The next phase of analysis in the FAMASS procedure is Distributed Planning Analysis (DPA). The DPA process centers largely around the process of identifying planning entities called Supply Chain Blocks (SCB). This phase also focuses on identifying required simulation inputs, namely factors and levels, uncertainties, and key performance indicators (KPI).

A three-dimensional supply chain cube is used to frame the various distributed planning entities involved in supply chain. The three axes are described as functional, spatial, and intertemporal dimensions. First, the intertemporal dimension is placed on the vertical axis and represents the hierarchical levels of decision making. Strategic planning considers the longest time horizon and is placed farthest from the origin. This is followed by tactical, operational, and execution levels. Secondly, the spatial dimension is placed on the horizontal axis. The spatial dimension recognizes the fact that planning occurs in the supply chain at geographically distributed entities. In the case of the proposed case study, each facility considered is a different cube in the spatial dimension. These are represented in aggregate from in Figure 6.2 to increase readability.

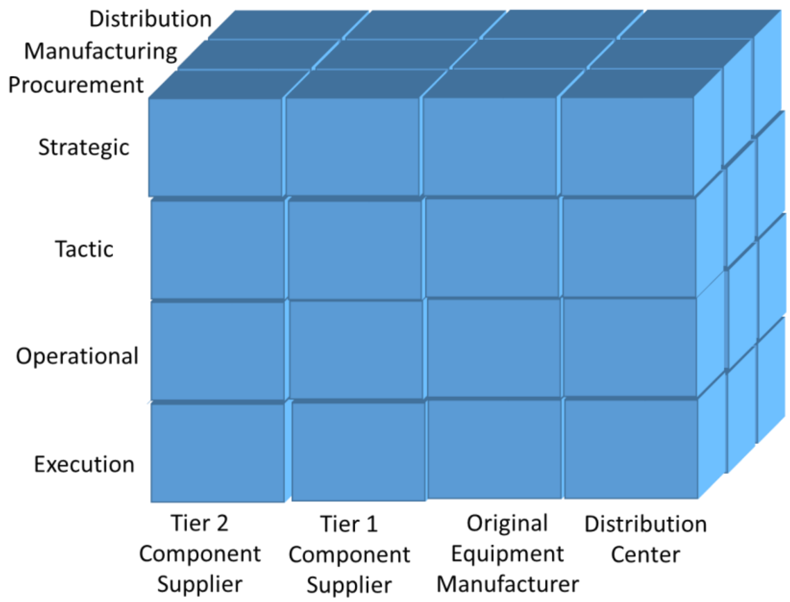

Figure 6.2: Supply chain cube, adapted from (de Santa Eulalia 2009)

That is, component suppliers at the same tier level are consolidated into a single category. Finally, on the z-axis, the functional dimension represents the different planning functions in the supply chain. For the case study, the functional roles are based on the Supply Chain Operations Reference (SCOR) model (Supply Chain Council 2006), which delineates the functions as plan, source, make, deliver, and return. The case study example will draw its scope around the functions from sourcing through delivery, while leaving the complexity of sales and returns, which would entail customer relationship management, for future research.

After specifying the SCB, the next step in DPA is to define the factors and levels, uncertainties, and KPI. Factors at the DPA level can relate to either the parameters or the logic of planning, control, and execution (de Santa Eulalia 2009). Parameters refer to the input data used by the supply chain system. Examples of parameters include lot size, re-planning frequency, desired on-hand inventory, etc.

Uncertainties represent uncontrollable factors that affect the operation of the supply chain. KPI should be identified and associated with a unit of measurement, such as time to recovery, profitability, etc. The KPI must also be associated with a source, referring to the location within the simulation where the data is to be collected. The source relates to the issue of global vs. local KPI. For example, profitability might be measured at each facility or for the entire supply chain network. It is important to note that at these levels the KPI may be in conflict. Choosing the strategy to maximize performance on the global level may not lead to the best result for each supply chain entity. Table 6.2 indicates the factors and levels, uncertainties and KPI's of interest in the proposed research.

Table 6.2: Factors and levels for case study

Factors and Levels	Description	Impact on the DPA model
Desired On-Hand Inventory (2 levels: 24 hrs and 8 hrs)	The amount of finished goods inventory kept on hand at each facility in terms of the number of days of supply	The inventory level will influence the execution of disruption recovery and affects decision on when to open alternate supplier.
Dual Sourcing (2 levels: Yes/No)	Buyer uses one preferred supplier or splits orders evenly between a primary and dual.	Affects operating cost and speed of recovery after a disruption
Inventory Visibility (2 levels)	For strong relationships, supplier will have complete visibility of production rate at the buyer. For arms-length relationships, information is communicated through order receipt and monitoring of internal inventory levels.	Knowledge of inventory and capacity of the system can improve the efficiency of response after a disruption.

The primary trade-off analysis to be conducted through the ABMS is with respect to measures of resilience and robustness. The KPI which the proposed simulation will incorporate are summarized in Table 6.3. The research objective is to increase the resilience of the supply chain by improving the supplier segmentation process. Robustness is measured by the maximum deviation in inventory levels below the lower bound established during normal operating conditions. Lower bounds are established for final assembly, cartridge, and photoconductor inventory at the DCs. Robustness can also be measured by the maximum cost deviation above the upper bound established during normal conditions. The ABMS aggregates total supply chain cost as the sum of material, holding, and travel cost incurred at each node in the supply chain. Although it is possible to account for additional cost elements, such as production cost or a late-delivery penalty cost, the stated cost elements provide a satisfactory indication of trade-offs that can occur between cost and robustness and resilience. Resilience is also measured as the total time any KPI spends above or below its bound established during normal conditions. In some cases, the KPI does not show a definite period of disruption and recovery. Rather, the KPI may fluctuate above and below the normal operating bound due to the complexity of the supply chain's response. For this reason, the measure used for resilience is not strictly a time-to-recovery, but is more accurately described as a total disrupted time.

Table 6.3: KPI for case study

Responses	Robustness Measure	Resilience Measure
Final printer assembly inventory at DCs	The maximum deviation in final printer assembly inventory below the lower bound established during normal operation	The total time final printer assembly inventory level is below the lower bound established during normal operation
Cartridge assembly inventory at DCs	The maximum deviation in toner cartridge assembly inventory below the lower bound established during normal operation	The total time toner cartridge assembly inventory level is below the lower bound established during normal operation
Photoconductor inventory at DCs	The maximum deviation in photoconductor inventory below the lower bound established during normal operation	The total time toner cartridge assembly inventory level is below the lower bound established during normal operation
Total supply chain cost	The maximum deviation in cost above the upper bound established during normal operation	The total time cost is above the upper bound established during normal operation

Finally, section 6.2 will cover the last phase of analysis, Individual Agent Organization Analysis (IAOA), which extends the previous specification with added focus on the specific actions of agents.

6.2 Agent Class and Activity Diagrams

Figure 6.3 gives a high-level overview of the different types of agents included in the printer supply chain ABMS. Agent types include nodes, links, and trucks. The most important variables associated with each agent are shown in the class diagram. Node agents include suppliers, the final printer assembly, and the DCs. All agents of a similar type own the same set of variables, although not all variables will be actively used. The link agents are used only to indicate the supply routes in the supply chain network and will hide with any connected node that either shuts down or opens. Truck agents carry inventory from the supplier to the buyer. Inventory in the simulation is not treated as an agent type, but rather exists as a variable that can be updated by the node or truck agents. Some of the information exchanges that take place in the simulation are also indicated in Figure 6.3. Agents of different types cannot update variables that belong to another agent type, but they can request at any time for the correct agent type to make the adjustment, and can ask another agent type to share the value of one of its variables if it is needed to make a decision. For example, it is common in delivery for a truck agent to ask a node agent its inventory of a certain type.

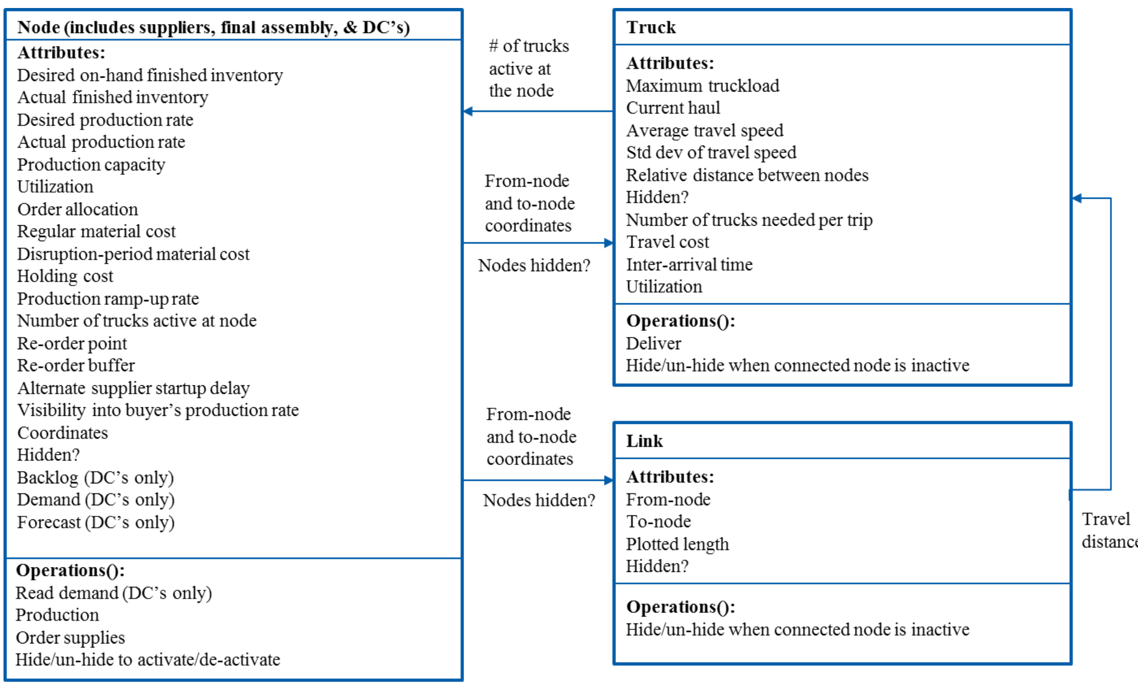

Figure 6.3: Agent class diagram

The main sequence of actions that take place in the simulation is depicted in Table 6.4. A brief description of each step is provided in addition to the frequency with which each step occurs. Most actions in the sequence are relatively simple excepting disruption, read-demand, production, and the deliver steps. Activity diagrams are provided in Figure 6.4

through Figure 6.9. The activity diagrams are organized as flow diagrams with 'swim lanes.' Each swim lane represents a type of agent, and that agent performs all the activities and decisions shown in its lane.

Table 6.4: Primary simulation actions

Primary Actions	Description	Frequency of Occurrence
setup-nodes	read facility names and locations from file, place facilities at coordinates	once per simulation run
setup-trucks	generate one truck agent for each supply route, assign initial truck variables	once per simulation run
setup-initials	assign initial variables for all nodes	once per simulation run
setup-links	generate links along each active supply route	once per simulation run
count-cycle	counts simulated hours and notes the start of new days	every tick
disruption	reduces capacity of disrupted node during disruption and triggers ramp up during recovery, adjust order-allocations, increases material cost during disruption	every tick (active only during disruption and recovery)
read-demand	DCs read customer demand from file, all nodes calculate desired production rate	every cycle (8 ticks)
production	nodes convert raw material into finished goods, coordinates ramp up and switching between dual, alt supplies during and after disruption	every tick
refresh-randoms	refresh current value of stochastic variables	every tick
deliver-to-customer	DCs use inventory to satisfy customer demand, attempt to fill any backorders before new demand	every tick
deliver-to-DC	trucks transport finished printer assemblies, cartridges, and photoconductors to DCs	every tick
deliver-to-FIN	trucks transport raw materials from tier 1 suppliers to final assembly	every tick
deliver-to-T1	trucks transport raw materials from tier 2 suppliers to tier 1 suppliers	every tick
total-costs	calculate current supply chain cost, sum of material, travel, and holding costs	every tick
reset-cycle	if simulated day is complete, reset day counter	every cycle (8 ticks)

The disruption implementation logic, demonstrated in Figure 6.4, will check each node to determine if it is scheduled to undergo a disruption. If the disruption is scheduled, then the disrupted node will increase its material cost and reduce the capacity of the affected node when the time of disruption arises. A disrupted node changes from yellow to red to indicate that it is operating with reduced capacity. If the node runs low on finished goods inventory, it will hide and stop accepting orders until the capacity is regained. If the alternate node has been triggered for ramp up, which occurs in the production action, it will check if the delay before production has been completed, and then ramp up production at the alternate supplier.

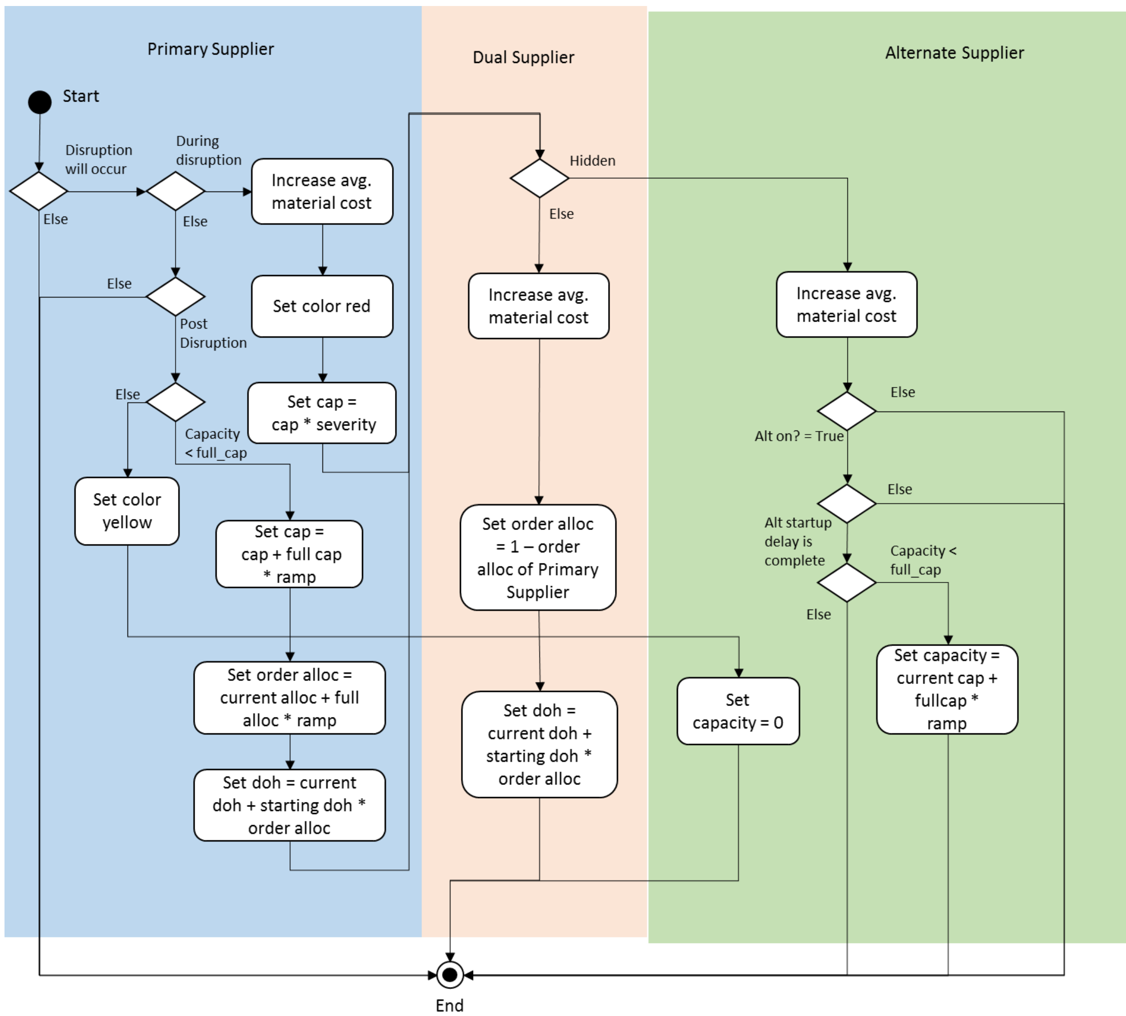

Figure 6.4: Activity diagram for disruption implementation

Figure 6.5 shows the logic behind the read-demand action. Read-demand occurs at the beginning of every 8 tick (representing the 8-hour work day) cycle. Once the cycle counter indicates a new 8-hour period has started, the read-demand logic is triggered to read the demand from the current cycle and the forecast demand for the next cycle. The demand read from the file is taken as normal distribution average. The action also calculates the standard deviation as a percentage of the demand. The DCs store the demand information and attempt to fill the demand in the deliver-to-customer action. The forecast information is used by the DCs to plan the orders placed to final assembly, photoconductor, and cartridge assembly.

The final assembly node uses its current on hand inventory of finished goods, knowledge of the forecast demand at the DCs, and the DOH to determine what its production rate per hour should be for the upcoming cycle. Supplier nodes follow a similar procedure to determine the desired production rate. However, suppliers do not use the forecast demand but only the production rate of the immediate buyer. In some cases, when the supplier has no visibility it must base its production decisions on its current inventory and DOH alone

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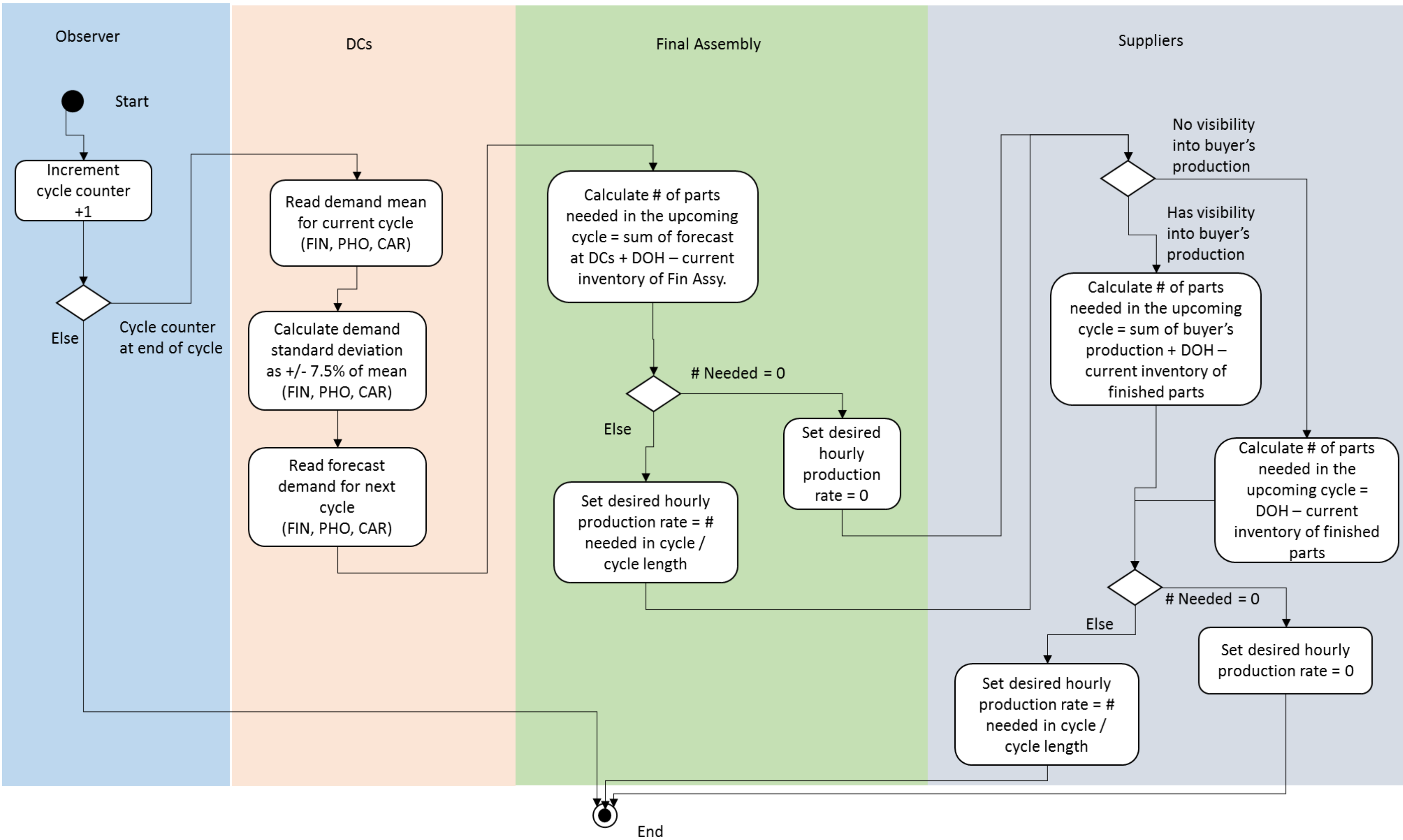

Figure 6.5: Activity diagram for read-demand

The production action is divided into three activity diagrams. First, Figure 6.6 demonstrates the logic for production during normal conditions. The number of parts a node can produce is limited by its current raw material, its maximum production capacity, and the desired production rate determine in the read-demand section. The node should not produce more than the desired production rate. In many cases, the node may produce less than the desired rate due to material or capacity shortage. When raw material is converted to finished goods, the node updates its inventory levels. The production logic also keeps track of node utilization as the current production rate divided by the maximum capacity.

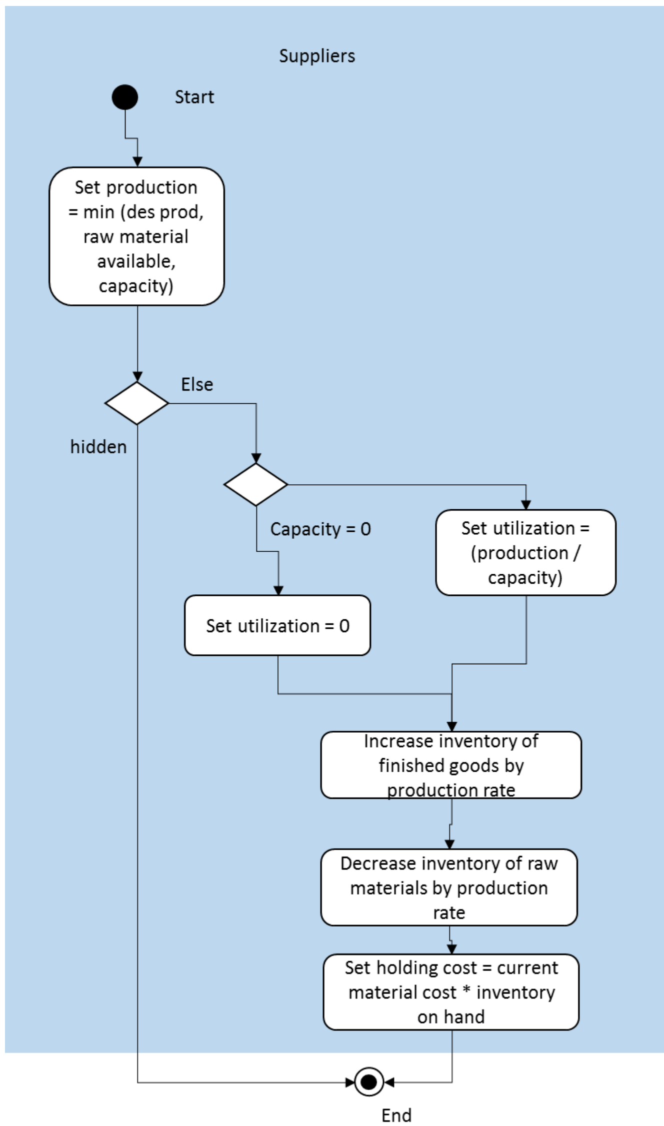

Figure 6.6: Activity diagram for production (normal operation)

Figure 6.7 is quite complex, but represents only how the production logic changes during a disruption and recovery in the case that a dual supplier is open. If single sourcing strategy is used, the logic described by Figure 6.8 is applied. For the case with dual sourcing, the first step is for the primary supplier to check if a disruption is set to occur, by checking a true/false node variable ‘disruption?’ If the disruption variable is set as true, then it will determine if the disruption is ongoing by comparing the scheduled disruption start with the current time, and how assessing how much inventory it has left at the primary supplier. If a disruption has occurred and the inventory has been depleted to below 10 finished goods units, the primary supplier sets it order allocation (OA) equal to 0, indicating it will no longer receive orders. If the primary supplier is disrupted but still has inventory remaining it will continue to receive orders in proportion to its remaining capacity.

Having confirmed that the dual supplier is open, the logic checks if the alternate supplier is hidden. If the alternate has opened, which may have occurred previously, the alternate supplier sets its OA to handle half the orders not fulfilled by the primary supplier. The dual supplier will take care of the remaining half of the orders.

Next, a counter at the dual supplier keeps track of any ticks (simulated hours) during which the inventory at the dual supplier is below its DOH. If the inventory is consistently below DOH, the counter indicates this and it is clear that the dual supplier cannot handle the amount of orders it is receiving. When the counter has shown the dual supplier’s inventory is below DOH for an entire consecutive 8 hours, it will trigger the alternate supplier to start its initialization. Each alternate supplier has an alternate startup delay, which represents the delay for setting up a new supplier. After this delay is exhausted, production at the alternate can start to ramp up.

In Figure 6.8, a similar production logic applies for cases where there is no dual supplier. The main differentiation is that the primary supplier has a counter to keep track of how often its inventory is below DOH, instead of the dual. As the primary supplier is recovering its capacity, or perhaps operating at 50% capacity due to disruption, it is likely that it will not be able to fully satisfy the orders it receives. If this occurs, the alternate supplier should be triggered to initialize, and will do so after meeting the required startup delay.

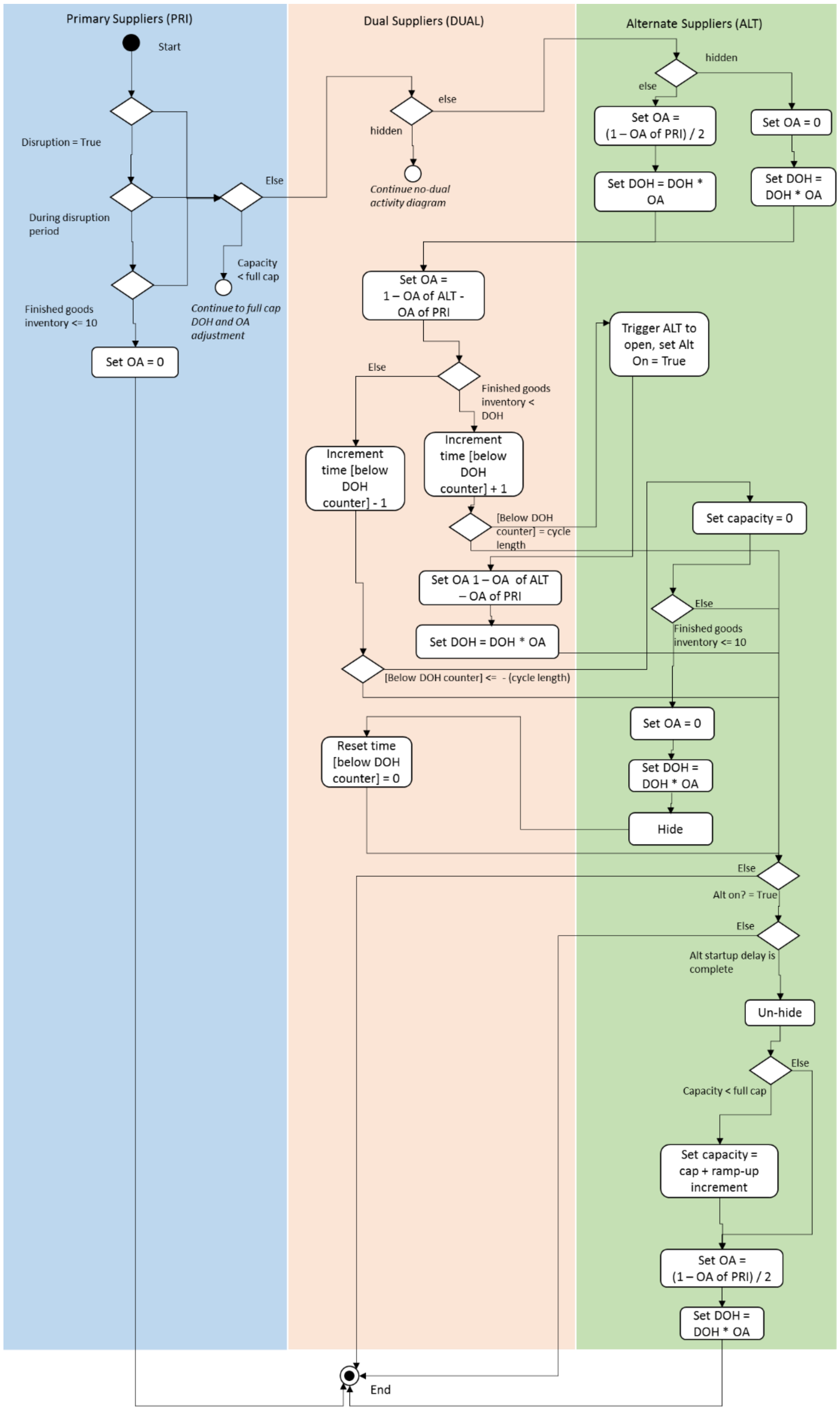

Figure 6.7: Activity diagram for production with disruption (with dual supplier)

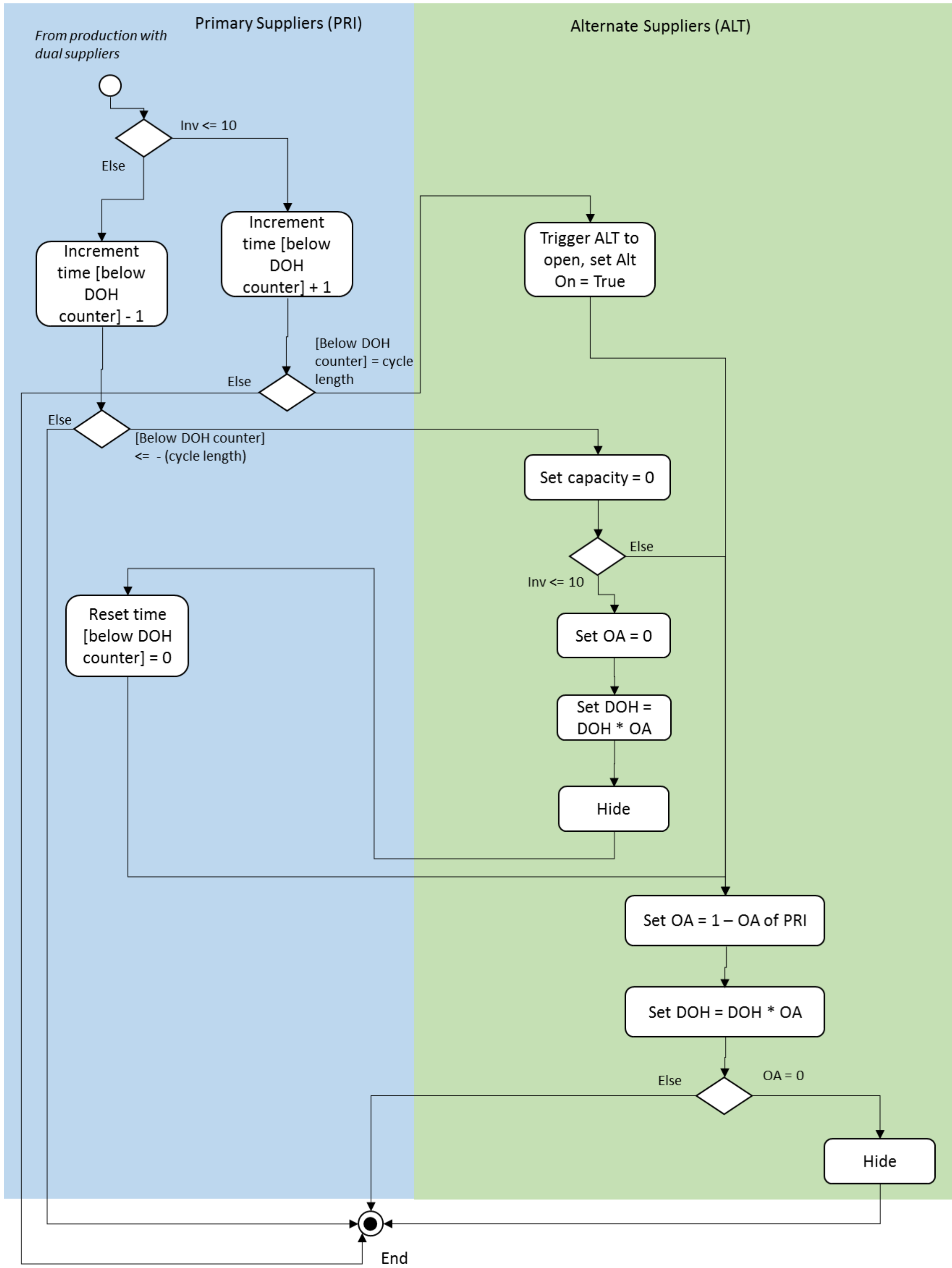

Figure 6.8: Activity diagram for production with disruption (without dual supplier)

The final section of the production activity diagram is shown in Figure 6.9. The logic shown in this diagram takes place after the disruption recovery has ended and the disrupted node has regained its full capacity. The logic checks for key information and adjusts the OA of each node accordingly. First, the logic checks if any inventory remains at the alternate supplier. If so, the alternate supplier should continue to receive orders until it is depleted of all or most of its inventory. Next, if the dual supplier is open as well as the alternate, then both will take 25% of the orders while the primary takes 50%, having regained its capacity. If the dual supplier is not open, then the alternate supplier keeps 50% of the orders until its inventory is depleted.

In case where the alternate supplier does not have remaining inventory, then it should stop receiving orders completely. Orders are then either divided among the primary and dual supplier, or given entirely back to the primary supplier.

The final two activity diagrams, Figure 6.10 and Figure 6.11, depict the logic for delivery. First, Figure 6.10 demonstrates the procedure for the truck to update its haul information. Secondly, the logic shown in Figure 6.11 is responsible for the actual delivery of the haul to the buyer. Each truck starts at the supplier location. Before it can collect its haul from the supplier, the primary supplier must calculate the amount of inventory it can send to any one supply route. The current inventory is divided by the number of outgoing routes to prevent any one route from claiming too large a percentage of the available material. Based on the truck transit time and the production rate at the buyer, the buyer determines when it should place an order to avoid a stockout while waiting for the truck to arrive. The reorder point is calculated by the buyer as just the amount of inventory needed to prevent stockouts. A buffer is then placed above the minimal reorder point. The truck then collects its haul form the supplier, attempting to take the full order quantity but not taking more than its fair share of the available inventory. The truck speed is updated as a stochastic variable, and the truck color is changed as an indication that the haul is loaded and it is ready to go.

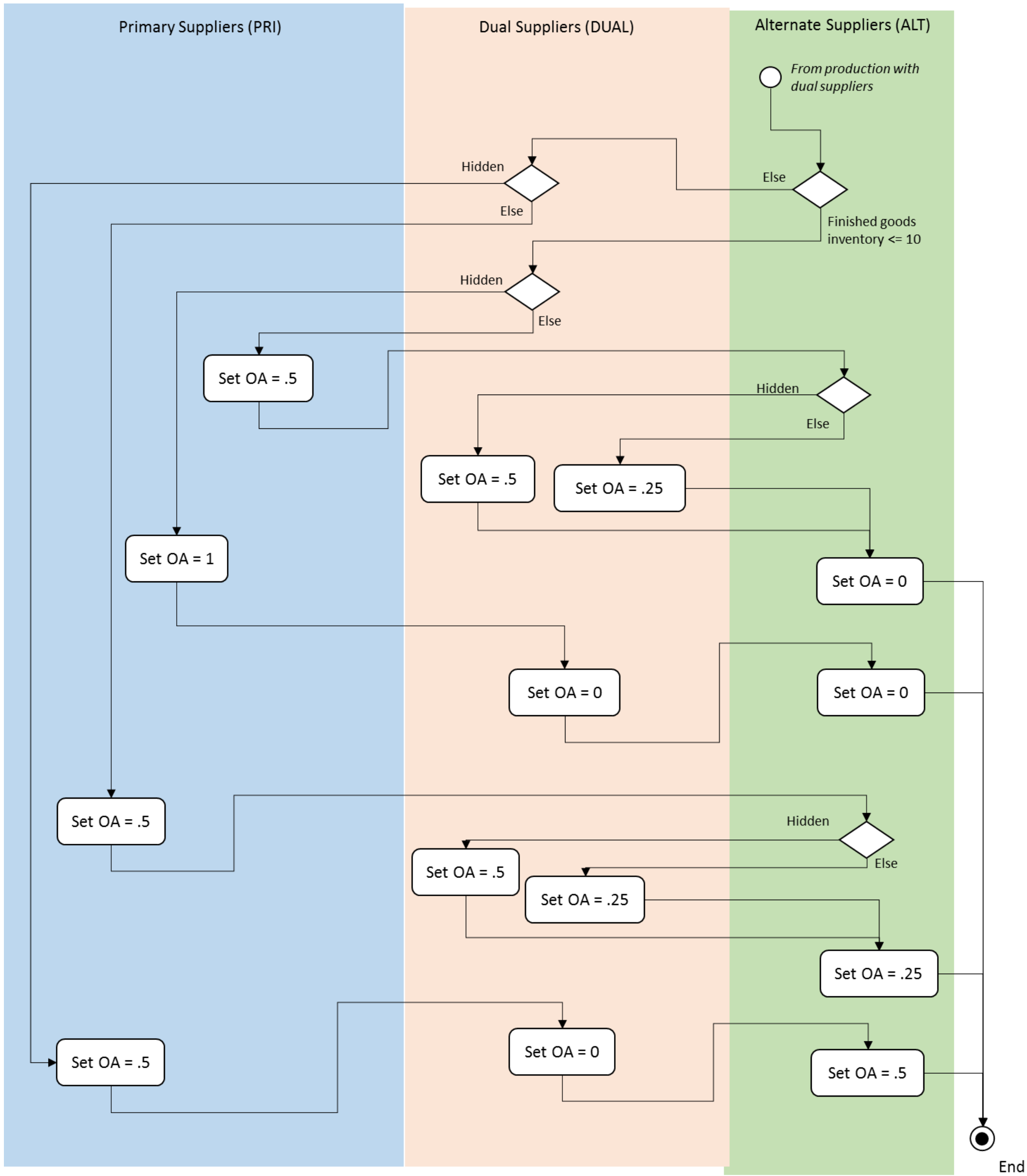

Figure 6.9: Activity diagram for production, setting order allocation levels after disruption recovery

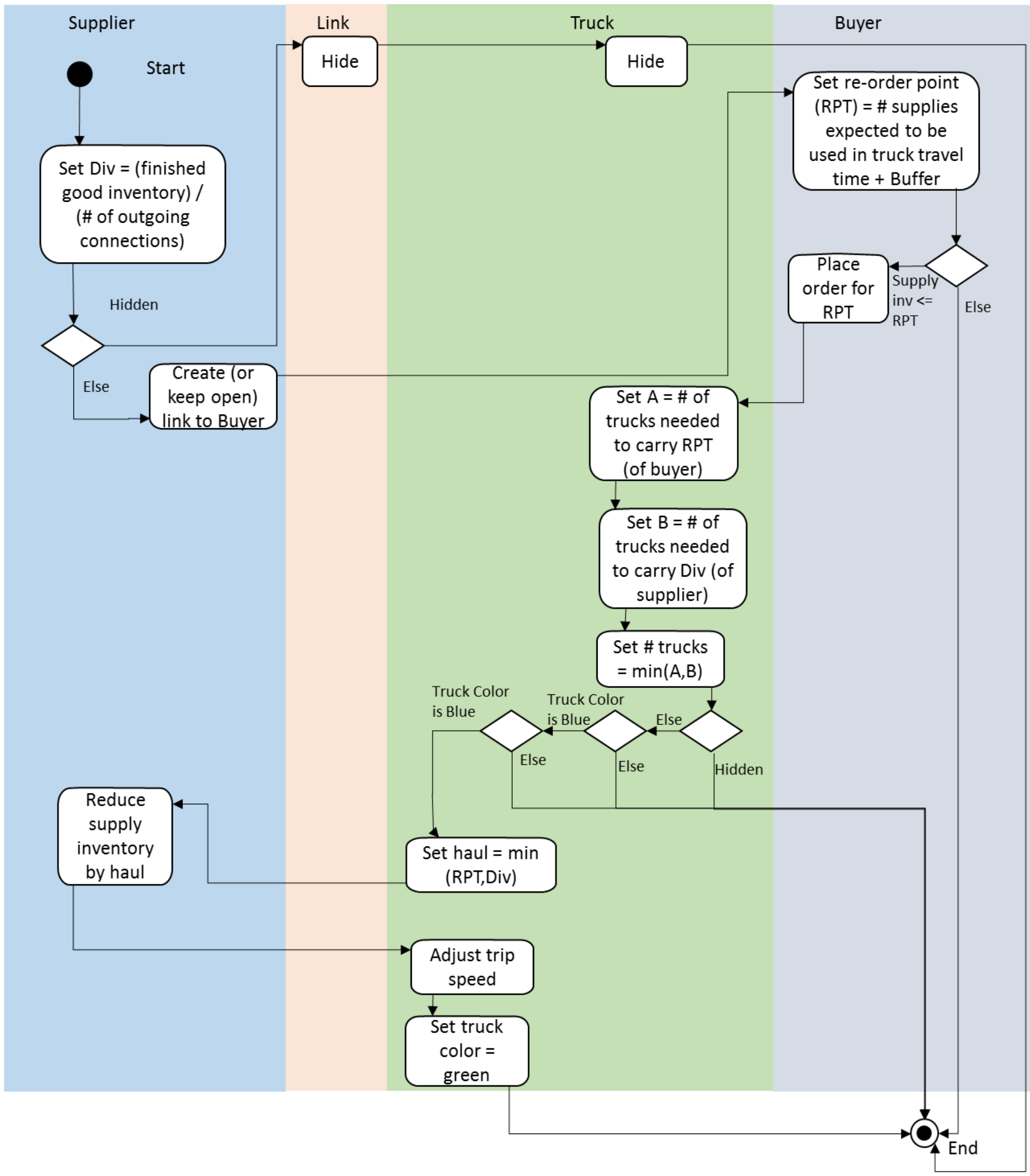

Figure 6.10: Activity diagram for delivery (truck picks up haul)

In Figure 6.11, the truck makes its delivery to the buyer. Assuming the truck's haul is not empty and its color has been set to green, it should move forward to the buyer node at its current speed in terms of coordinate distance / tick. If the truck has not arrived at the buyer, the delivery activity ends until the next simulation iteration. If the distance to the buyer node becomes less than the distance the truck covers per tick, then the truck simply jumps to the buyer. Upon arrival, the trip cost is calculated based on the cost per mile.

The buyer node adds the truck haul to its appropriate stock of raw material, and the material cost for the delivery is calculated.

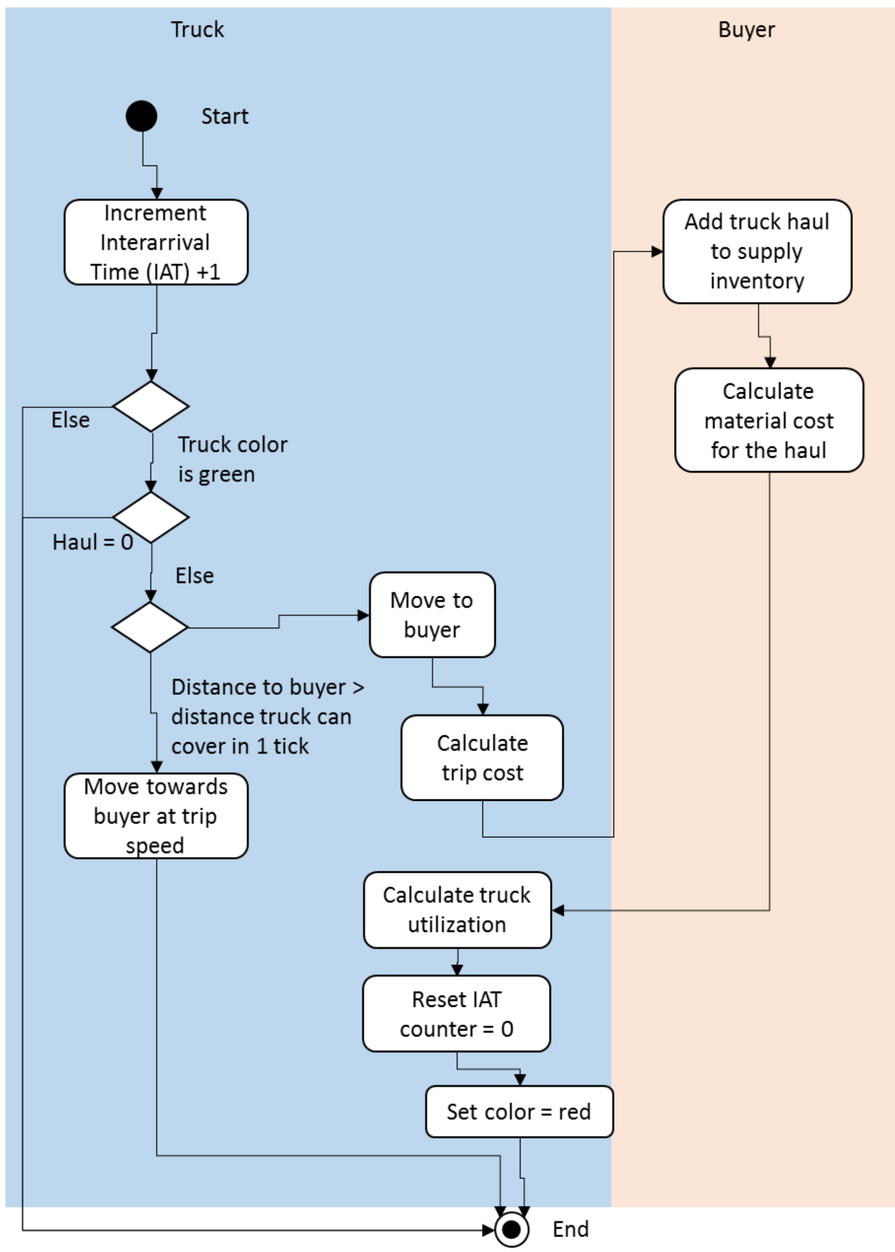

Figure 6.11: Activity diagram for delivery (deliver haul to buyer)

6.3 ABMS Platform

Before building the simulation model, it was necessary to explore the options for development tool. Several of the available toolkits are described by North and Macal (2007) including several packages such as Repast, Swarm, and NetLogo. Development in spreadsheet software such as Excel with VBA was also discussed. The licensed software AnyLogic was also considered. Ultimately, the software NetLogo was selected due to its open source availability, approachable interface for new developers, extensive and clear help menu and example models, and large user community. NetLogo was developed for the original purpose of assisting in teaching of complex adaptive systems, and is a good environment for learning how to implement the principles of ABMS. Given that the laser printer supply chain model has a moderate and fixed number of agents, the NetLogo environment offers sufficient capability to fulfill the necessary computational requirements. A user guide is provided in Appendix D that explains in detail the input files and setup procedure needed to run the laser printer ABMS in NetLogo. The user guide includes screen shots of the model interface and a step by step guide for two use cases. In the first use case, a one-time simulation run with no supply chain disruptions is described. The second use case describes a multi-replication experiment with a disruption and KPI output from each replication.

7 Results

The presentation of results begins with a comparison of normal cost and inventory levels when the supply chain is segmented using the baseline and revised methods. This analysis presents benefits that each segmentation method can have with respect to the day-to-day supply chain behavior. Next, the inventory and cost response is demonstrated for the disruption scenarios. The propagation of impact on the inventory levels is examined starting with the node of disruption origin and ending with the DCs. Finally, the impact's dependence on disruption start time and severity is examined. The effect of disruption start time is analyzed to demonstrate how the concurrence of a disruption with periods of high or low demand might affect the extensiveness of the disruption impact. Disruption severity is studied in terms of the percentage of production capacity that is lost during the disruption.

7.1 Establishment of Normal Operating Levels

The behavior of the simulation with no disruption implemented is observed for the entirety of its two-year runtime to establish the normal operating range for the key performance indicators (KPI). The KPI include total supply chain cost and average inventory at the DCs for final assembly, cartridge assembly, and photoconductor. Observations for the average final assembly inventory are shown in Figure 7.1.

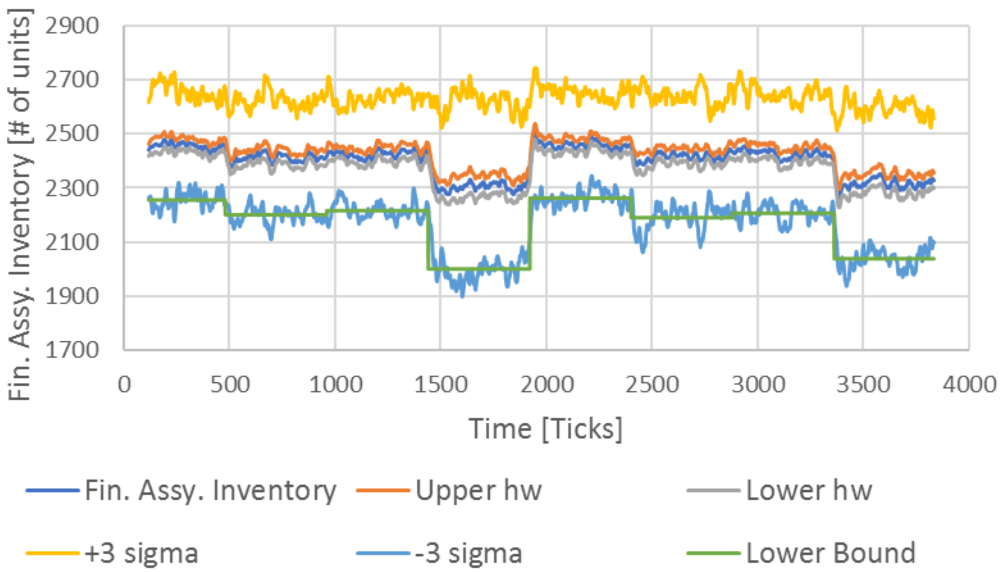

Figure 7.1: Final assembly inventory at DCs (Baseline)

The simulation is repeated for 30 replications to ensure repeatability in the outcome. Figure 7.1 portrays the average inventory over time along with the upper and lower half-width at the 95% confidence level. The true value of average inventory of final assemblies is most likely to fall in the range between the upper and lower half-width. The spread in the sample data for average inventory is indicated by the calculated plus or minus three standard deviation range. Assuming the sampled data approximately fits the normal distribution, 99.7% of all sampled observations should fall in this range. The minus three standard deviation level is used as a lower bound for the expected inventory, and is averaged over each simulation quarter. Quarterly averages are used to account for the demand seasonality and to prevent quarters with higher demand, namely quarters four and eight, from having too much influence on the calculated bounds.

The same procedure used to plot the final assembly inventory data in Figure 7.1 is repeated for the remaining KPI (cartridge and photoconductor inventory at DCs, and total supply chain cost). The comprehensive presentation of this information is provided in Appendix B. Since the main point of interest in this section is the comparison of the respective bounds for the baseline and revised segmentation methods, the complete inventory data is withheld from the remaining plots in this section to improve clarity. Figure 7.2 shows the lower bounds for final assembly inventory at the DCs.

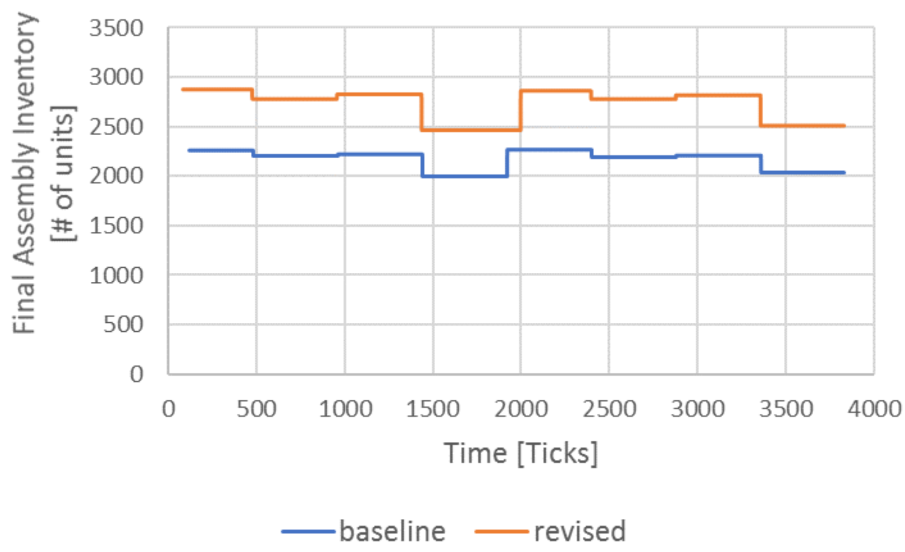

Figure 7.2: Comparison of lower bounds for final assembly inventory at DCs

The final assembly inventory levels follow the same pattern for baseline and revised segmentation methods. The difference between the two lower bounds is constant during each quarter and varies slightly between quarters. Over the entire simulation runtime, the DCs hold on average 557 more units when the revised segmentation method is used. This difference in the bounds can be primarily attributed to the difference in the set points for the desired inventory buffer at the DCs. The buffer levels are set in terms of the number of units the final assembly node would produce if running at full capacity in hour increments. The initial buffer is set at the amount of inventory that final assembly can produce in one hour, and then increased incrementally until minimal backlog is observed during the simulation run with no disruption. With the baseline segmentation method, minimal backlog was achieved with a buffer corresponding to two hours of final assembly production. For the revised segmentation method, it was necessary to increase the buffer to three hours of production to ensure minimal backlog during normal operation. A similar pattern is observed for the lower bound of photoconductor inventory, shown in Figure 7.3.

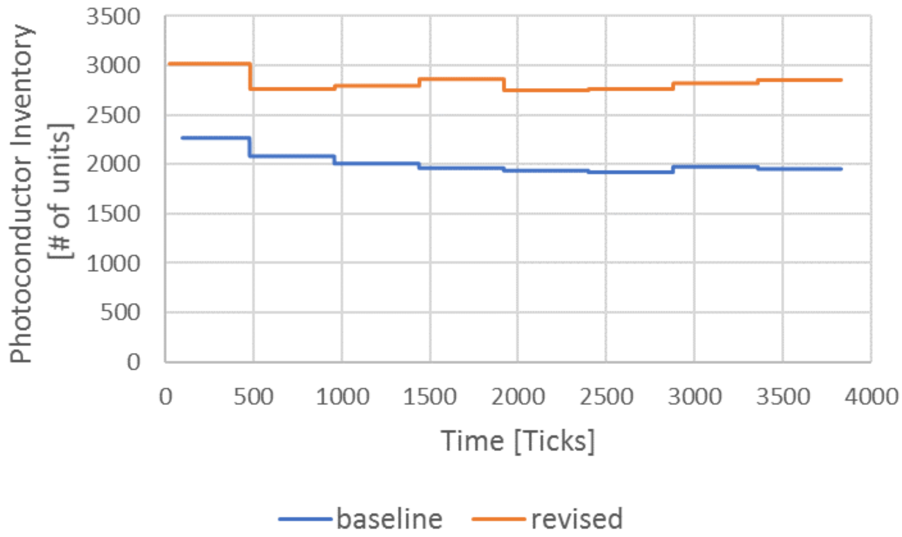

Figure 7.3: Comparison of lower bound for photoconductor inventory at DCs

The inventory of photoconductors at the DCs is, on average for the entire simulation runtime, 816 units more when the revised segmentation method is used. The photoconductor inventory goal used in the baseline method corresponds to one hour of full production at final assembly. When the revised method is used, the photoconductor inventory is increased to two hours of production to ensure minimal backlog during normal operations. The comparison of lower bounds for cartridge inventory at DCs is shown in Figure 7.4.

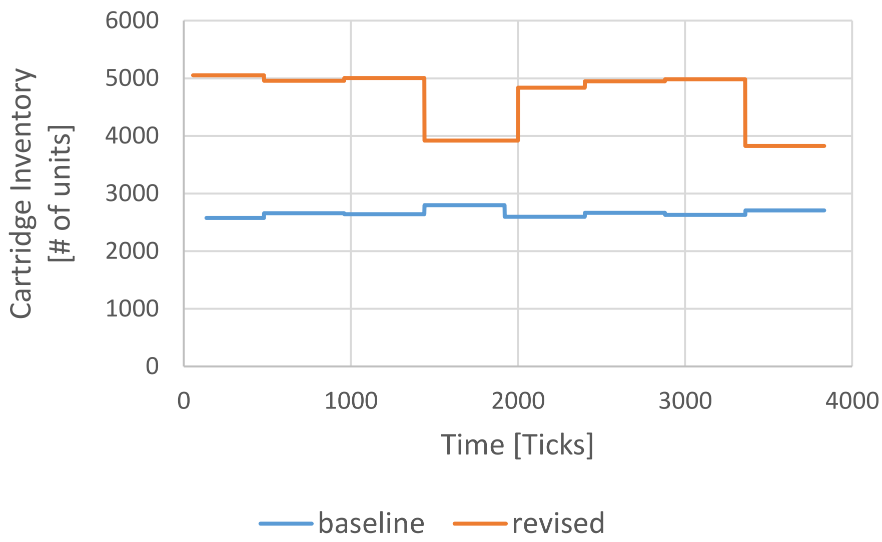

Figure 7.4: Comparison of lower bound for cartridge inventory at DCs

A cartridge inventory goal corresponding to two hours of full production at final assembly is used in the baseline case. The buffer is increased to four hours in the revised case. The lower bound for cartridge inventory shows a noticeable decrease in quarters four and eight when the revised segmentation method is used. This pattern can be attributable to the increase in demand for both final printer assemblies and aftermarket cartridges that occurs at the end of years one and two. The fact that the decrease is observed in both quarters four and eight is a good indication that the increased demand is in fact the cause of the inventory decrease. It is interesting to note the lack of such a decrease when the baseline segmentation method is used. The lack of noticeable response to the demand change in the baseline case is because the cartridge supplier has visibility into its buyers' production, but does not have this visibility in the revised case. With visibility, the cartridge supplier can determine that production has increased at final assembly to account for increased demand, and then increase its own production rate in turn. Without visibility, the cartridge supplier can only base its production rate on its own inventory levels, which results in a delay in reaction time.

It is also pertinent to discuss the normal operating cost for the supply chain in both the baseline and revised segmentation cases. A comparison of the upper bound on supply chain cost is presented in Figure 7.5.

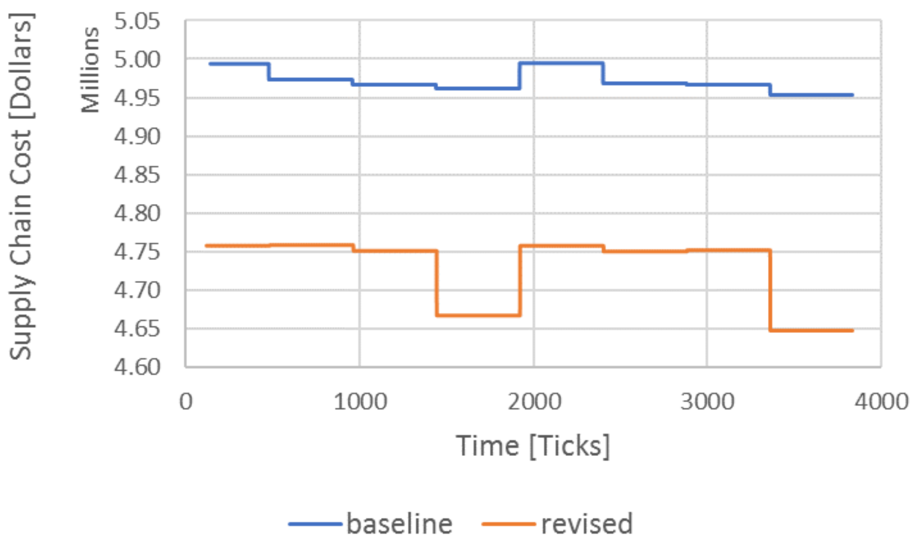

Figure 7.5: Comparison of upper bound for total supply chain cost

The total supply chain cost consists of inventory holding cost, transportation cost, and material cost. However, it is determined that the inventory holding cost is the most significant cost contributor, which explains the decrease in cost for the revised case in quarters four and eight. This decrease in cost corresponds to the decrease in cartridge inventory during the same quarters. Even though the cartridge, photoconductor, and final assembly inventory levels are all lower at the DCs in the baseline case, the revised case still has a lower total supply chain cost. It is necessary to ascertain the source of extra cost that appears to be present in the baseline case. Figure 7.6 was created to compare the inventory holding cost at each node for both baseline and revised cases.

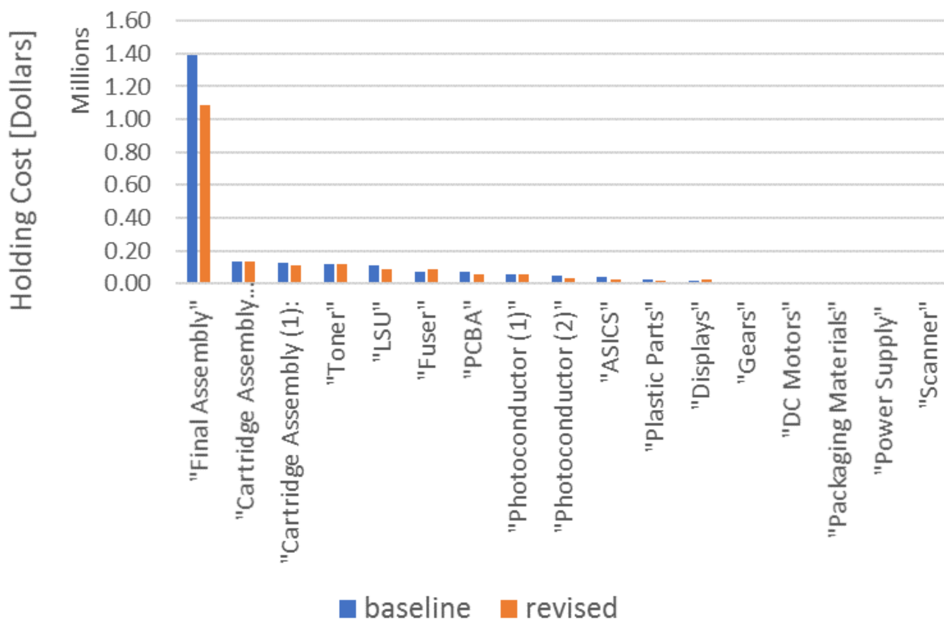

Figure 7.6: Comparison of holding cost at each node

It can be observed from Figure 7.6 that the largest portion of holding cost, and the largest difference in holding cost between the baseline and revised cases, is accrued at the final assembly node. The revised segmentation method appears to offer an advantage in terms of reduced holding cost at the final assembly node when compared to the baseline case. In fact, the holding cost is less for the revised case at all nodes other than the DCs. During normal operating conditions, the revised segmentation method offers and advantage in terms of total supply chain cost. At all nodes except for the toner supplier, the DOH is equivalent or higher in the baseline method. The greatest differences in DOH exist at the power supply, gears, and cartridge suppliers which each have significantly higher DOH in the baseline method. However, it is necessary to test the levels of robustness and resilience offered by each segmentation method.

7.2 Disruption Response Analysis for Baseline and Revised Cases

The comparison of disruption response profiles for baseline and revised segmentation methods are presented in the following subsections. The primary objective of the analysis is to demonstrate how the inventory of both finished goods and incoming raw material is affected by the loss of capacity at the disrupted node. The detailed response data is studied for a disruption that begins at simulated hour 720, midway through the second quarter of the simulated runtime. During the disruption, full loss of production capacity is experienced by the disrupted node. After a duration of 480 hours, or sixty 8-hour “work days”, the production capacity of the affected node begins to ramp back up to its normal level. An assumption is made that the disruption duration is the same for all scenarios. Realistically speaking, the disruption duration would not be known at its moment of occurrence and would vary by supplier due to response capability. The duration is held constant in the proposed scenarios to simplify interpretation of the results. The study is repeated with four points of disruption origin: cartridge assembly, toner, power supply, and PCBA suppliers. To study the effect of the disruption’s start time and severity, the experiments are repeated using combinations where the disruption begins at hour 1680, midway through quarter four, and with 50% loss of capacity. The full list of scenarios is summarized in Table 7.1. The full table is conducted for both baseline and revised segmentation methods.

Table 7.1: Summary of disruption scenarios

Scenario	Dis. Origin	Start Time	Severity
1	CAR Dis1	Q2	0%
2	CAR Dis2	Q4	0%
3	CAR Dis3	Q2	50%
4	CAR Dis4	Q4	50%
5	TON Dis1	Q2	0%
6	TON Dis2	Q4	0%
7	TON Dis3	Q2	50%
8	TON Dis4	Q4	50%
9	POW Dis1	Q2	0%
10	POW Dis2	Q4	0%
11	POW Dis3	Q2	50%
12	POW Dis4	Q4	50%
13	PCBA Dis1	Q2	0%
14	PCBA Dis2	Q4	0%
15	PCBA Dis3	Q2	50%
16	PCBA Dis4	Q4	50%

In sections 7.2.1 – 7.2.4 the results form scenarios 1, 5, 9, and 13 are studied in detail to demonstrate the propagation in impact in inventory levels from disruption origin to the DCs. The results from the remaining scenarios are summarized in section 7.3.

7.2.1 Disruption at Cartridge Supplier

Scenario 1: Baseline Segmentation Method

The first disruption scenario assessed occurs at cartridge supplier location 1. Information regarding the section of the supply chain directly connected to the disrupted node is summarized in Figure 7.7. The use of single or dual sourcing strategy for each component is indicated by the number of houses, and the facility that will be affected by the disruption is shown with red fill color. In the baseline case, management is using a single-source strategy for cartridge assembly. However, cartridge assembly also occurs in two separate geographic locations. Production facilities shown inside the same green box exist in the same geographic location.

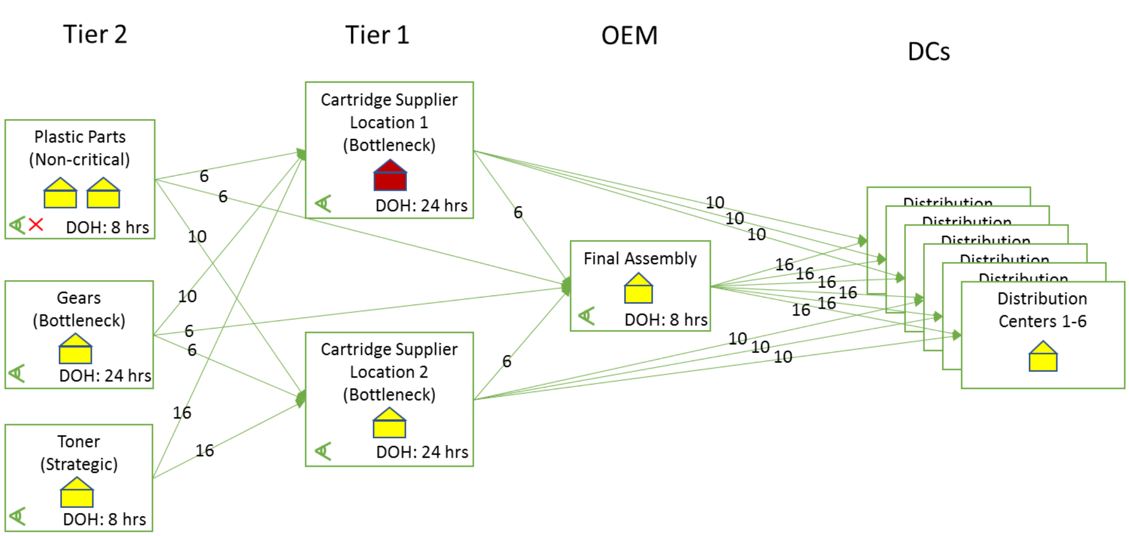

Figure 7.7: Partial SC map showing disruption at cartridge supplier location 1 (Baseline)

The transportation delay required between geographic locations (in terms of number of ticks in the simulation model) is indicated by the number along the link between boxes. If the suppliers for a given component have visibility into the buyer's production rate, a small eye is shown in the bottom left corner of the box. If there is no visibility, a red 'x' is shown next to the eye. Finally, the desired on-hand (DOH) inventory at each supplier is indicated in the bottom right of each box in terms of the number of hours of production. The values for DOH apply to each facility. If the number shown is eight hours for a dual-sourced product, then both the primary and dual aim to keep eight hours of inventory. Although each supplier may or may not be able to maintain its DOH, this number provides an indication of which nodes have goals of maintaining a larger or smaller inventory buffer.

The cartridge supplier has a direct connection to the DCs. It supplies aftermarket cartridges directly to the DC's. These aftermarket cartridges are sold separately from the printer and have a separate demand. The cartridge supplier is also a 1st tier supplier to final assembly (FIN). Each printer that is assembled at FIN must be equipped with a printer cartridge. The disruption affects the supply chain's ability to meet demand for both the aftermarket cartridge and the printer itself, since the printer cannot be shipped without a cartridge.

The cartridge inventory response to the disruption at cartridge supplier location 1 is shown in Figure 7.8. Enlarged versions of the plots within Figure 7.8 can be found in Appendix C.

Each plot is based on data from thirty simulation replications. Inventory data is output at each tick in the simulation, so the plotted result is the average of thirty data points for each time step. For clarity, the upper and lower half-widths are excluded from the plots.

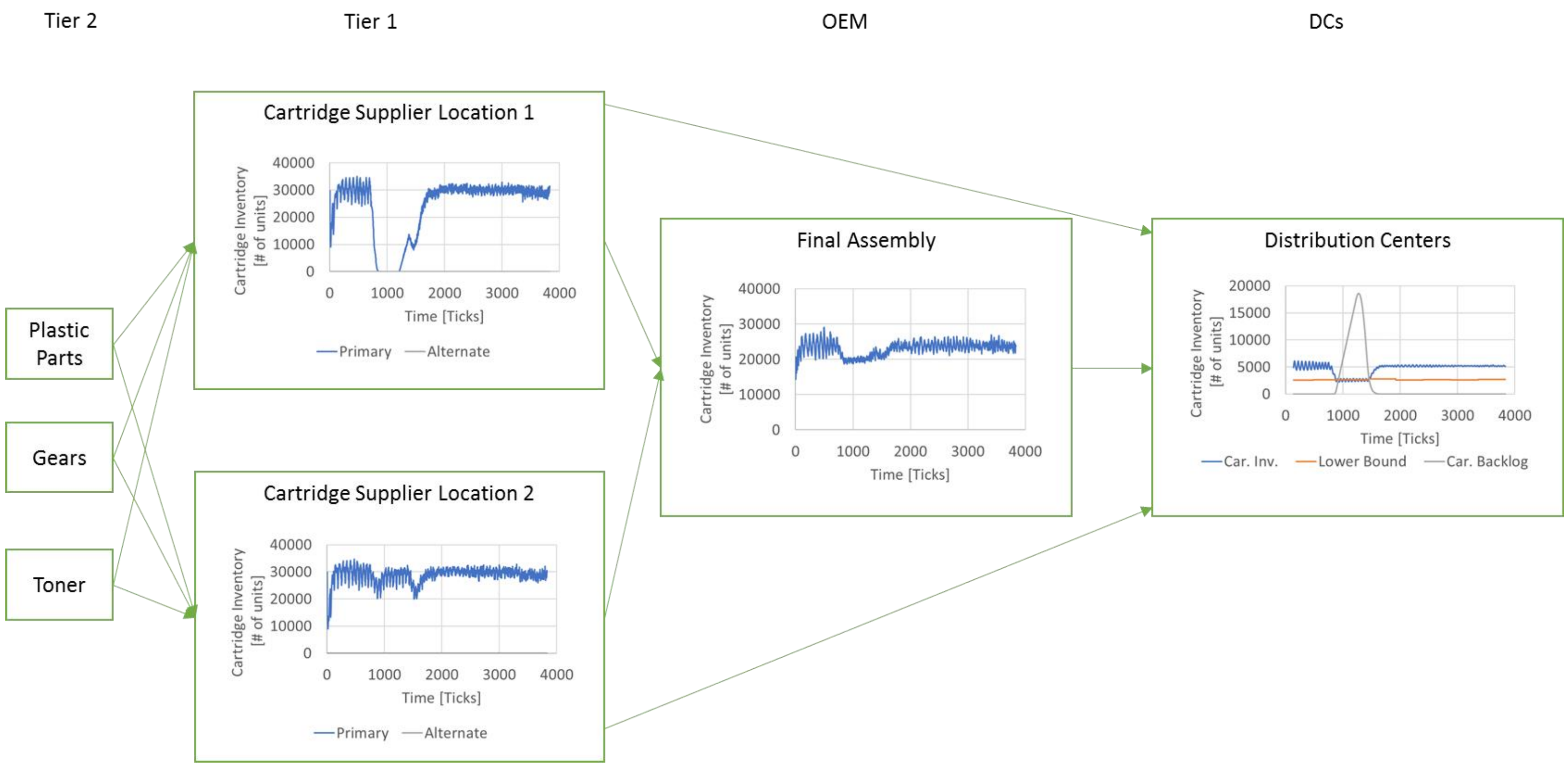

Figure 7.8: Inventory response to disruption at cartridge supplier location 1 (Baseline)

The immediate response to the disruption is seen in the plot of cartridge inventory at cartridge supplier location 1. Since the cartridge supplier loses its capacity, its inventory is depleted to zero soon after the disruption start at hour 720 (see Appendix C for larger chart). Although the option is present, no alternate supplier engages during the disruption or recovery periods. The signal to open the alternate is triggered, but the alternate startup delay is not reached before the disruption ends and orders shift back to the primary supplier. At the final assembly node, the cartridge inventory is depleted and a significant amount of backlog is accrued. The figure showing the cartridge inventory at the DCs is the average inventory over the six DCs. Upon closer examination, it is determined that the backlog only occurs at DCs 1-3, while normal inventory levels are maintained at DCs 4-6. This behavior is logical as the disrupted cartridge supplier is connected to DCs 1-3, and DCs 4-6 are supplied by the unaffected cartridge supplier location. The response gives an indication that when the backlog does arise, the information is not being effectively communicated to the final assembly node, so it is not delivering cartridges to reduce the backlog, even when it has some availability in supply.

The response of total supply chain cost to the disruption at the cartridge supplier is shown in Figure 7.9. It can be clearly noted that the supply chain cost increases above the normal operating bound around the time of the disruption. This increase may be due in part to the increase in material cost during the disruption period. During the disruption, the material cost increases by 50%, but this effect is soon balanced out as the amount of available inventory is depleted.

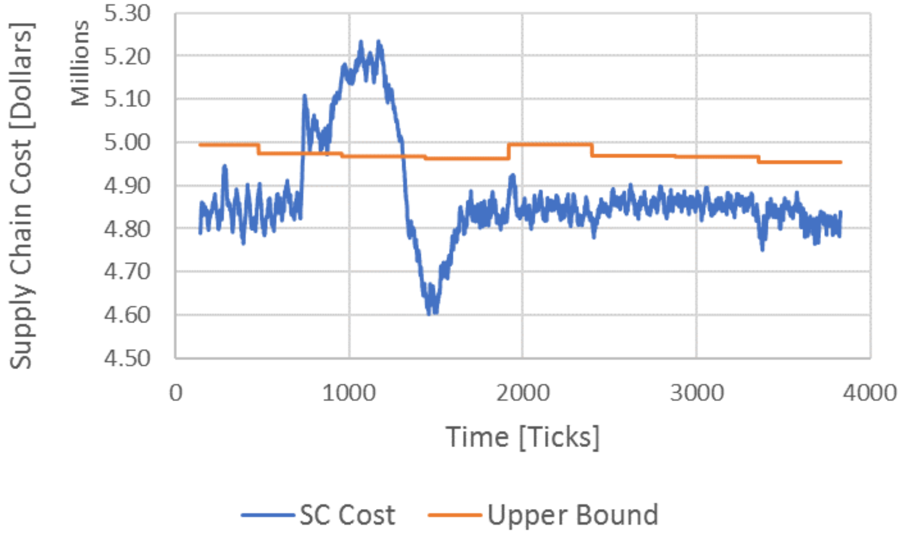

Figure 7.9: Total SC cost (Baseline)

Scenario 1: Revised Segmentation Method

Strategic changes resulting from use of the revised segmentation method are shown in Figure 7.10. Changes include dual sourcing at the cartridge supplier and removal of visibility at the cartridge and gear suppliers. Also, the overall DOH at all the cartridge supplier locations is reduced from the baseline method.

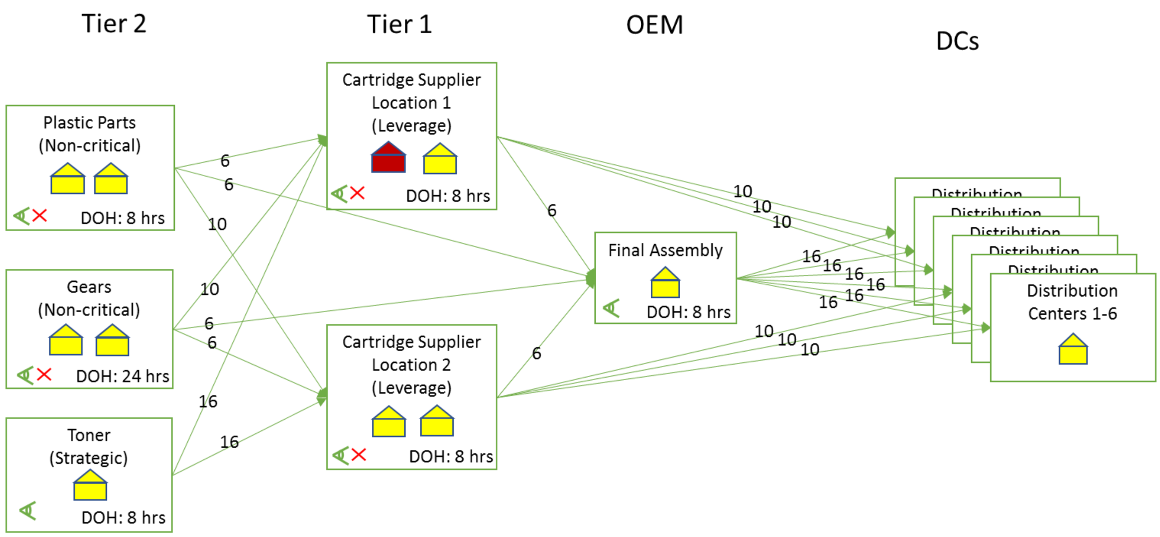

Figure 7.10: Partial SC map showing disruption at cartridge supplier location 1 (Revised)

The supply chain's disruption response profile when the revised segmentation method is used, shown in Figure 7.11, can be starkly contrasted to the response of the baseline case.

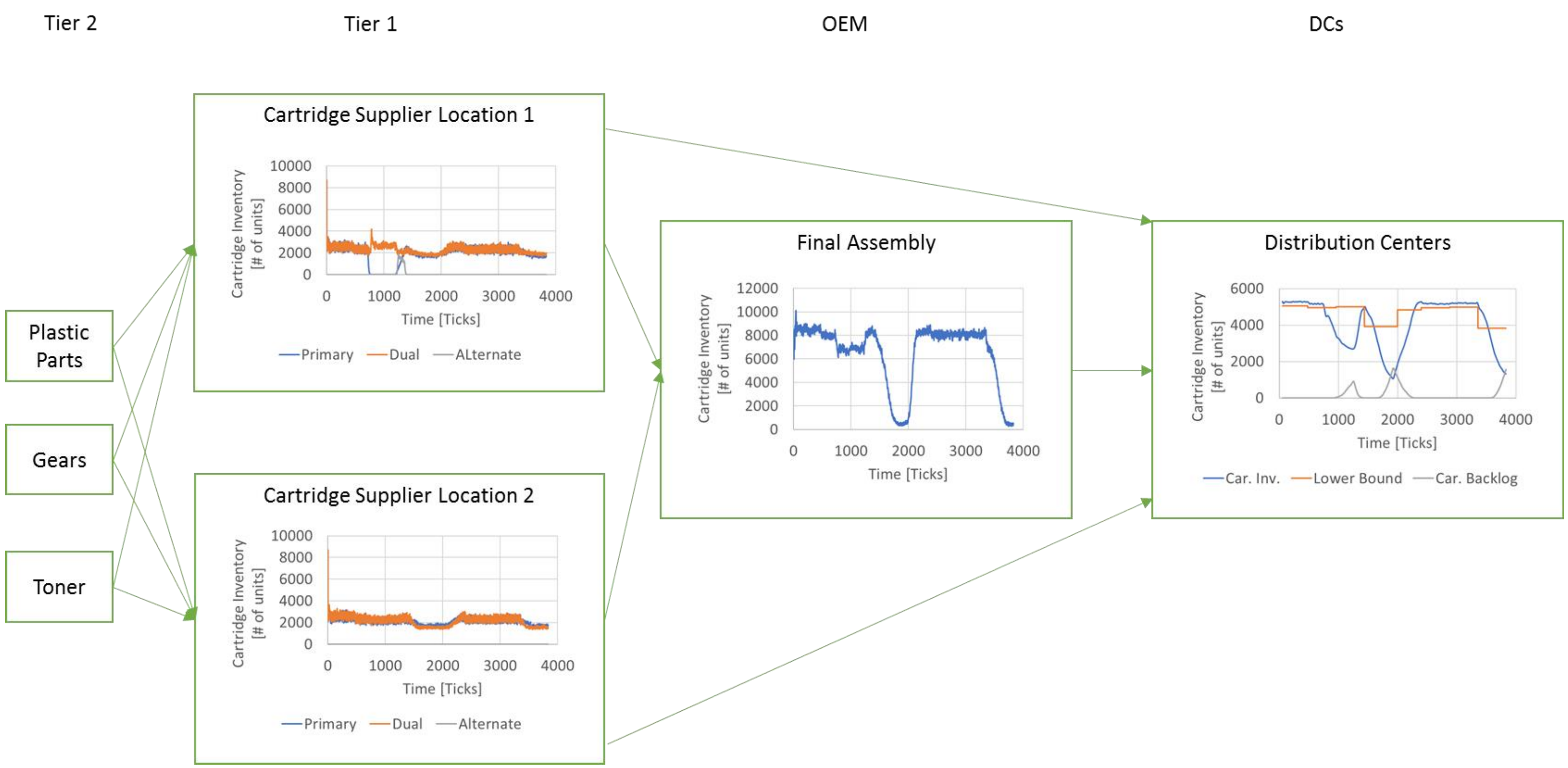

Figure 7.11: Inventory response to disruption at cartridge supplier location 1 (Revised)

The effect of removed visibility at the cartridge suppliers can be seen in cartridge inventory at the DCs. As it was observed in the non-disruption analysis, the cartridge inventory at DCs shows a marked decrease during quarters four and eight, in alignment with the periods of increased demand. The decrease in cartridge inventory during the second quarter is due to the disruption at cartridge supplier location 1. An increase in cartridge buffer inventory at the DCs prevents the accumulation of the magnitude of backlog seen in the baseline case. This result is an early indication that buffer inventory held at the DCs is more effective at reducing disruption impact than inventory held further back in the supply chain.

The behavior of supply chain cost, shown in Figure 7.12, does not appear to be significantly affected by the occurrence of the disruption. A decrease in the cost is observed in quarters four and eight, corresponding to the depletion of inventory due to higher demand. A brief increase in cost is observable in quarter two, but the levels are never in excess of the upper bound determined during the non-disruption case.

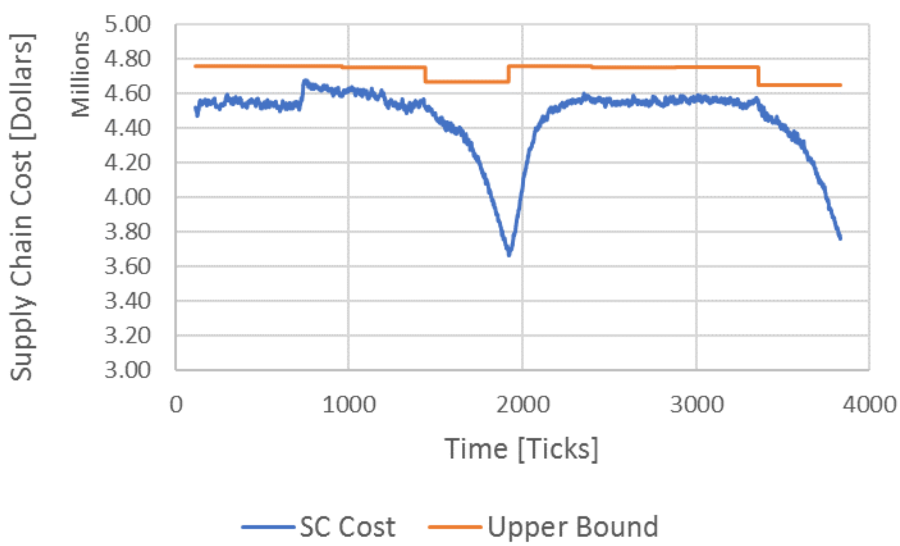

Figure 7.12: Total supply chain cost (Revised)

7.2.2 Disruption at Toner Supplier

Scenario 5: Baseline Segmentation Method

The disruption scenarios originating at the toner supplier are subject to the same network structure and strategic options as previously indicated in Figure 7.7 and Figure 7.10. However, the disruption originates at the tier 2 supplier. Figure 7.13 demonstrates how the interruption of toner supply propagates from the toner supplier to the cartridge supplier locations, and ultimately affects delivery of cartridges to the DCs.

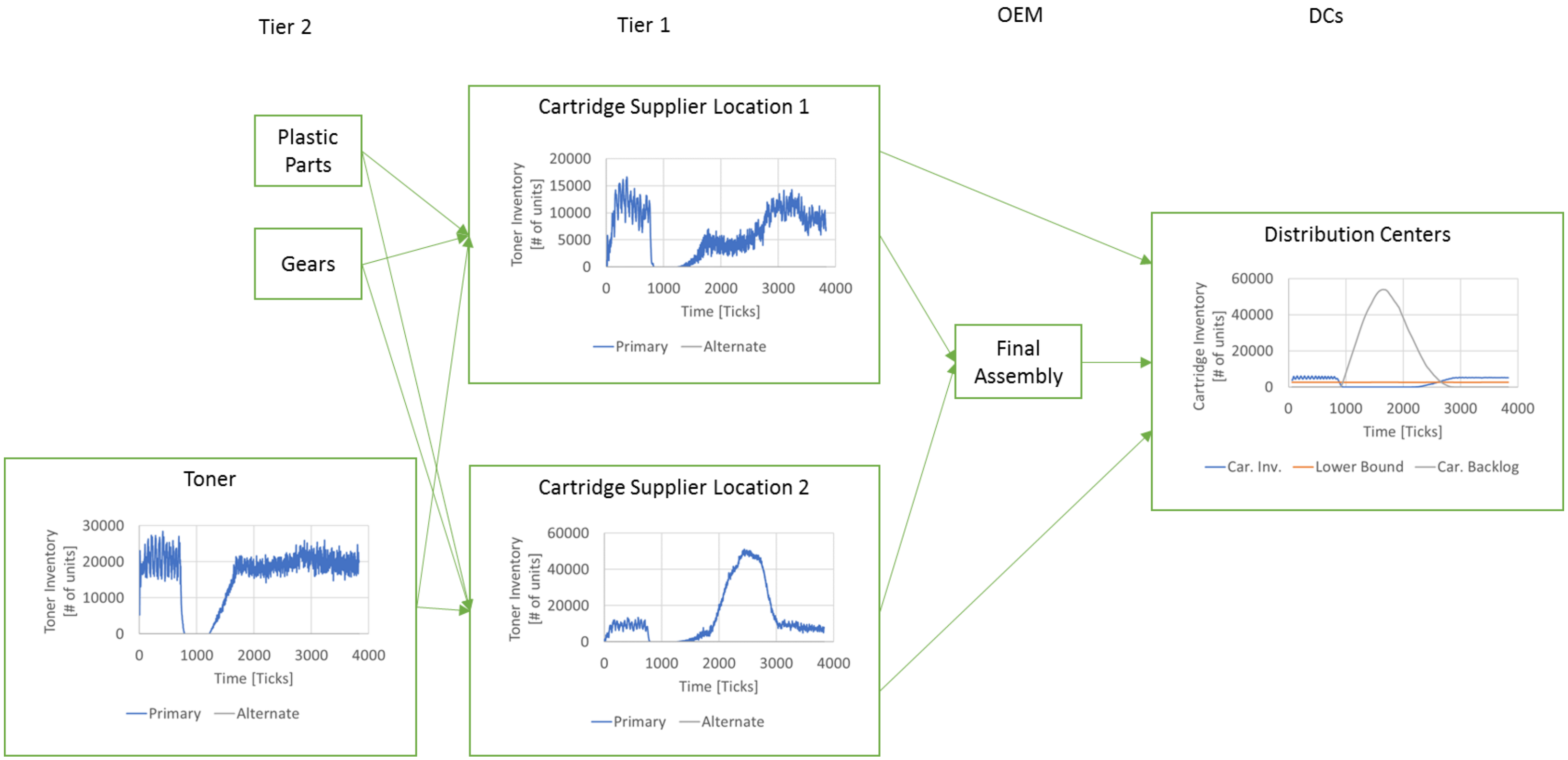

Figure 7.13: Inventory response to disruption at toner supplier (Baseline)

The toner supply is segmented as a strategic supplier for both the baseline and revised segmentation methods. Toner is single sourced due to its strategic nature and has the potential to disrupt both cartridge supplier locations. From Figure 7.13, it is seen that the disruption in toner supply is immediately passed on to the cartridge suppliers and the inventory does not fully recover until mid-way through the second year. The alternate startup delay at the toner supplier is much longer than the disruption duration of 480 hours, and so the alternate supplier is no able to engage and reduce the impact. The cartridge inventory at the DCs is thus subject to a long disruption with significant backlog accumulation. Although now shown in Figure 7.13, a similar response is observed in the final assembly inventory at the DCs because each final assembly must be equipped with at cartridge.

The total supply chain cost response is shown in Figure 7.14. The cost decrease seen results from the depletion of both final assembly and cartridge inventory at both DCs and the final assembly node. Although the response indicates a reduction in cost, it should be noted that the calculation of cost does not account for any penalty for late delivery. The response should therefore not be misconstrued as an indication of a cost advantage during the disruption recovery.

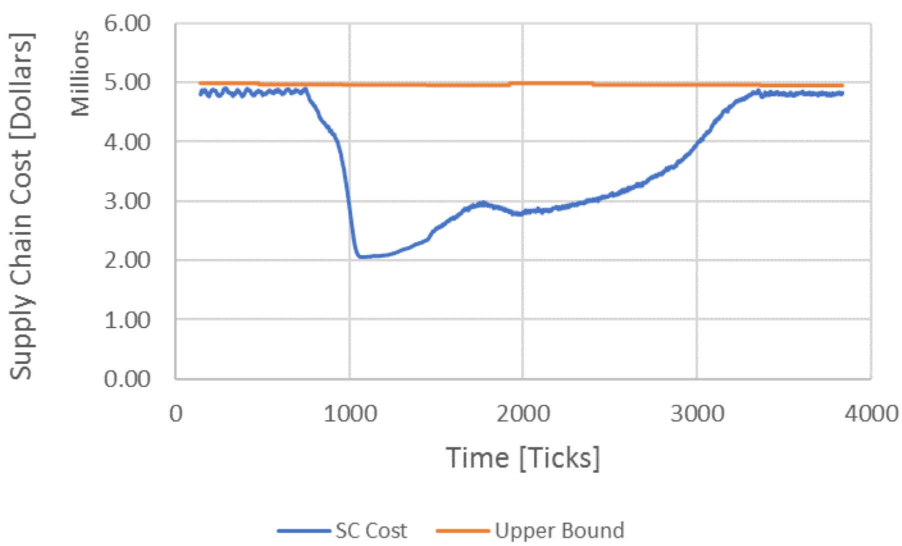

Figure 7.14: Total SC cost with disruption at toner supplier (Baseline)

Scenario 5: Revised Segmentation Method

The toner supplier is segmented in the strategic category when both the baseline and revised methods are used. For this reason, a substantial change in the inventory and cost response is not expected. However, the cartridge suppliers are directly connected between the toner supplier and the DCs, and the strategic changes for the cartridge suppliers still apply and may have an effect although they are not at the origin of the disruption. The toner and cartridge inventory response is summarized in Figure 7.15. Upon closer examination of the result, the difference in strategy at the cartridge suppliers appears to have minimal effect. There are no major differences in the disruption response between baseline and revised methods. Total supply chain with the disruption at the toner supplier is shown in Figure 7.16. These results are indicative of the potential vulnerability associated with a strategic supplier.

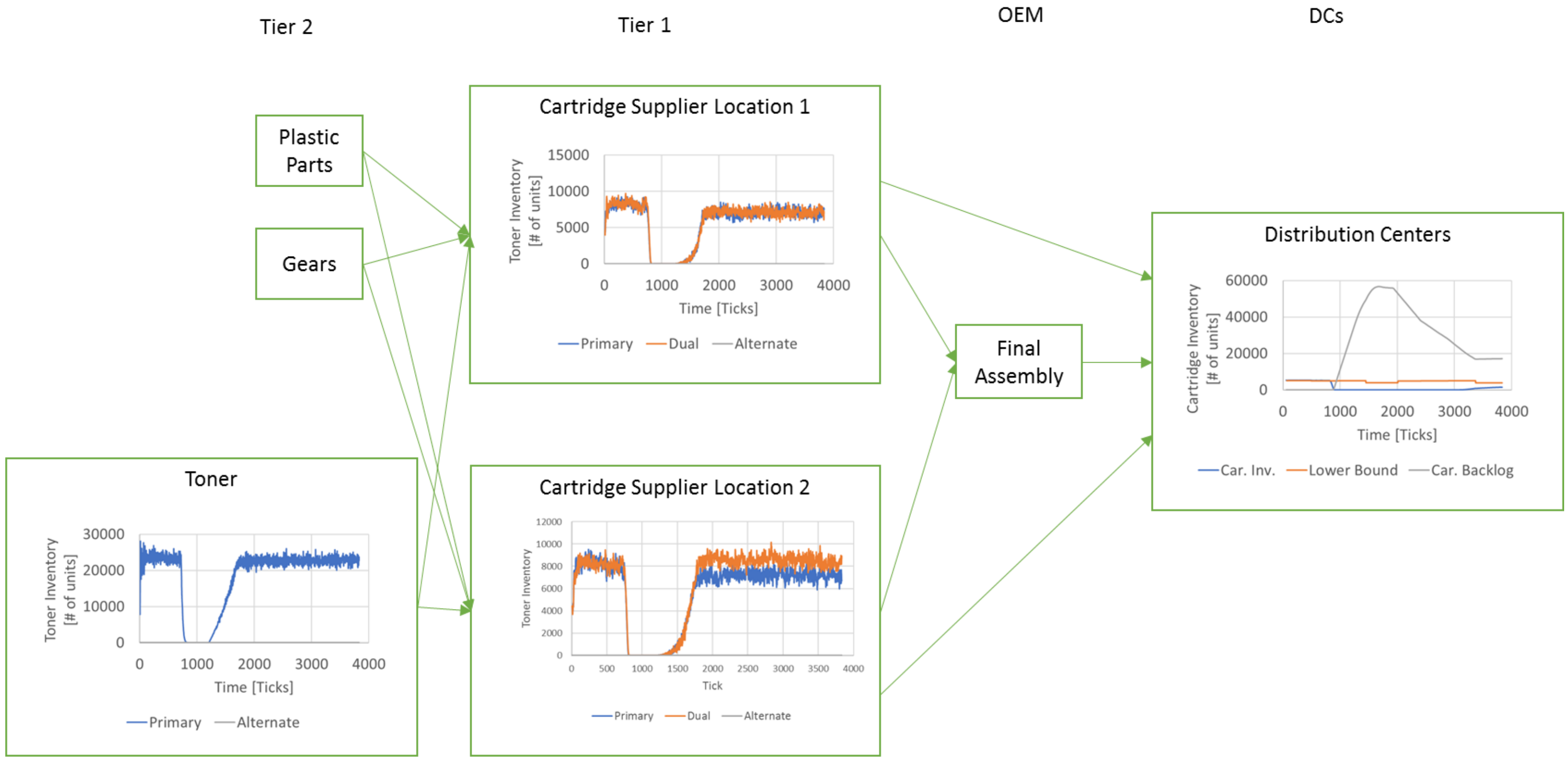

Figure 7.15: Inventory response to disruption at toner supplier (Revised)

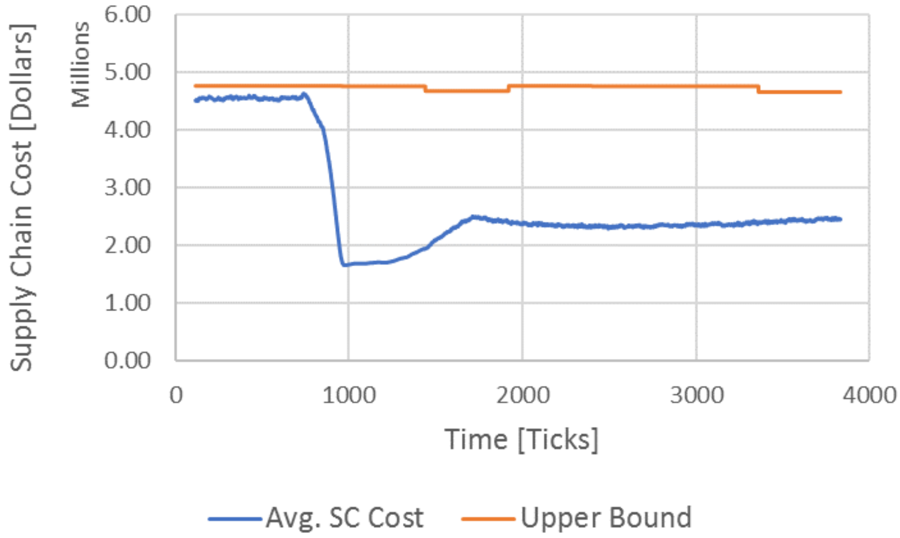

Figure 7.16: Total SC cost with disruption at toner supplier (Revised)

7.2.3 Disruption at Power Supply Supplier

Scenario 9: Baseline Segmentation Method

Power supply is a tier 1 supplier to final assembly. The portion of the printer supply chain linking power supply to the DCs is depicted in Figure 7.17. In the baseline case, power supply is segmented as a bottleneck supplier. A single sourcing strategy is used, with visibility and a higher level of DOH.

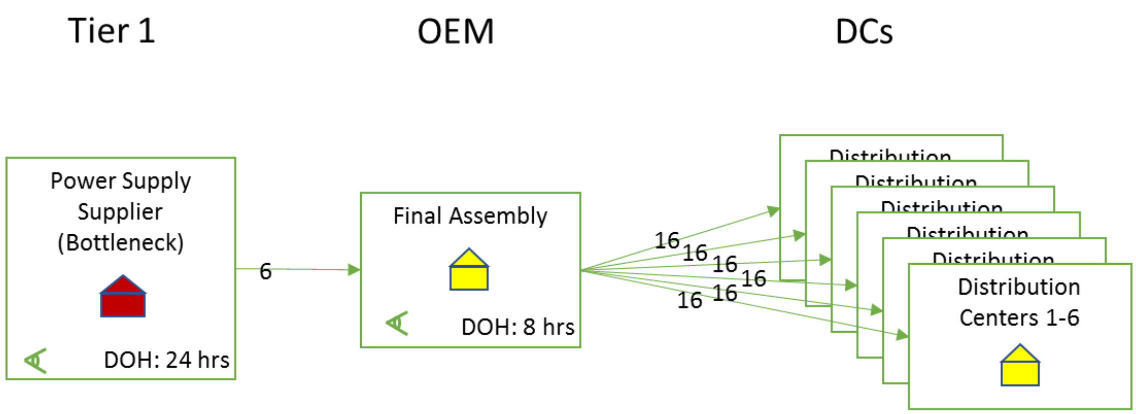

Figure 7.17:Partial SC map showing disruption at power supply supplier (Baseline)

Figure 7.18 presents the power supply inventory at the power supply supplier and final assembly. Also depicted are the final assembly inventory at final assembly and at the DCs.

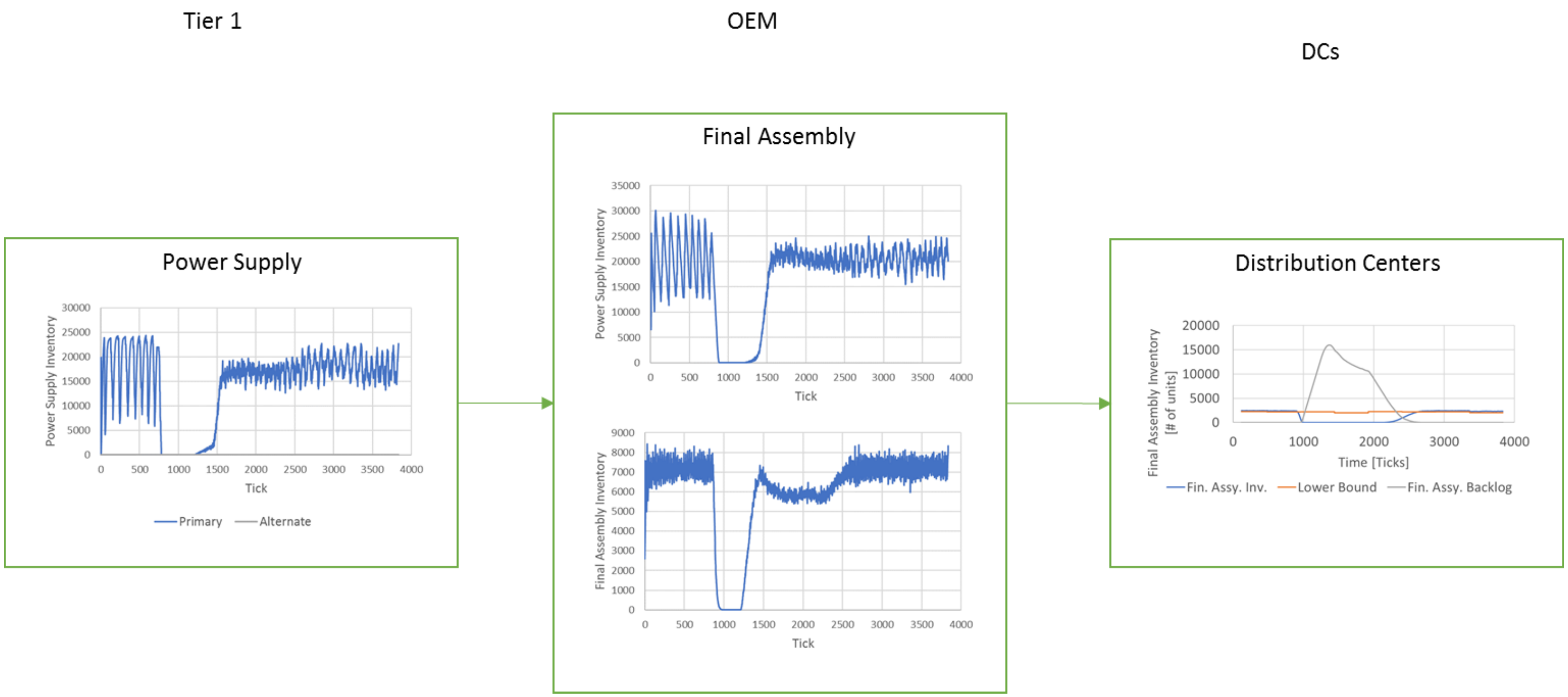

Figure 7.18: Inventory response to disruption at power supply supplier (Baseline)

The power supply and final assembly inventory is quickly depleted after the disruption begins at the power supply supplier. Despite a seemingly quick recovery after the disruption ends at tick 1200, the effects of limited final assembly inventory at the DCs extend well beyond the end of the disruption, with normal levels not achieved again until around tick 2600. By contrast, inventory levels at the power supply supplier and final assembly are largely recovered by tick 1500. The peak of final assembly backlog does occur around tick 1500, but due in part to the capacity limitations of final assembly, it takes substantial time to eliminate the backlog at each DC. As shown in Figure 7.19, the extended time-to-recovery also applies to the total supply chain cost.

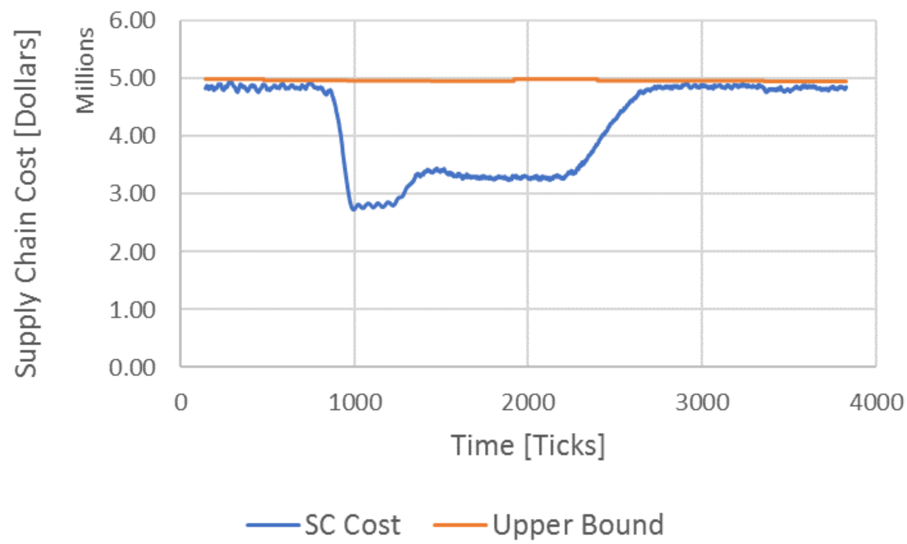

Figure 7.19: Total supply chain cost with disruption at power supply (Baseline)

Scenario 9: Revised Segmentation Method

When the revised segmentation method is employed, the power supply suppliers falls into the non-critical category. Implications of the change in segment include removal of visibility, addition of dual sourcing, and reduction in the DOH at each facility. The section of the supply chain as described is shown in Figure 7.20.

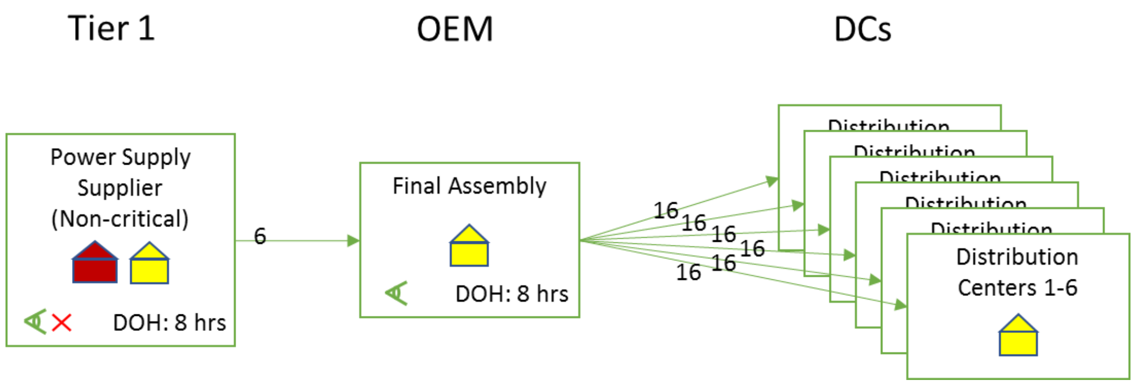

Figure 7.20: Partial SC map showing disruption at power supply supplier (Revised)

The inventory response for the supply chain segmented by the revised method is summarized in Figure 7.21. The adjustment in strategy has significant improvement both resilience and robustness.

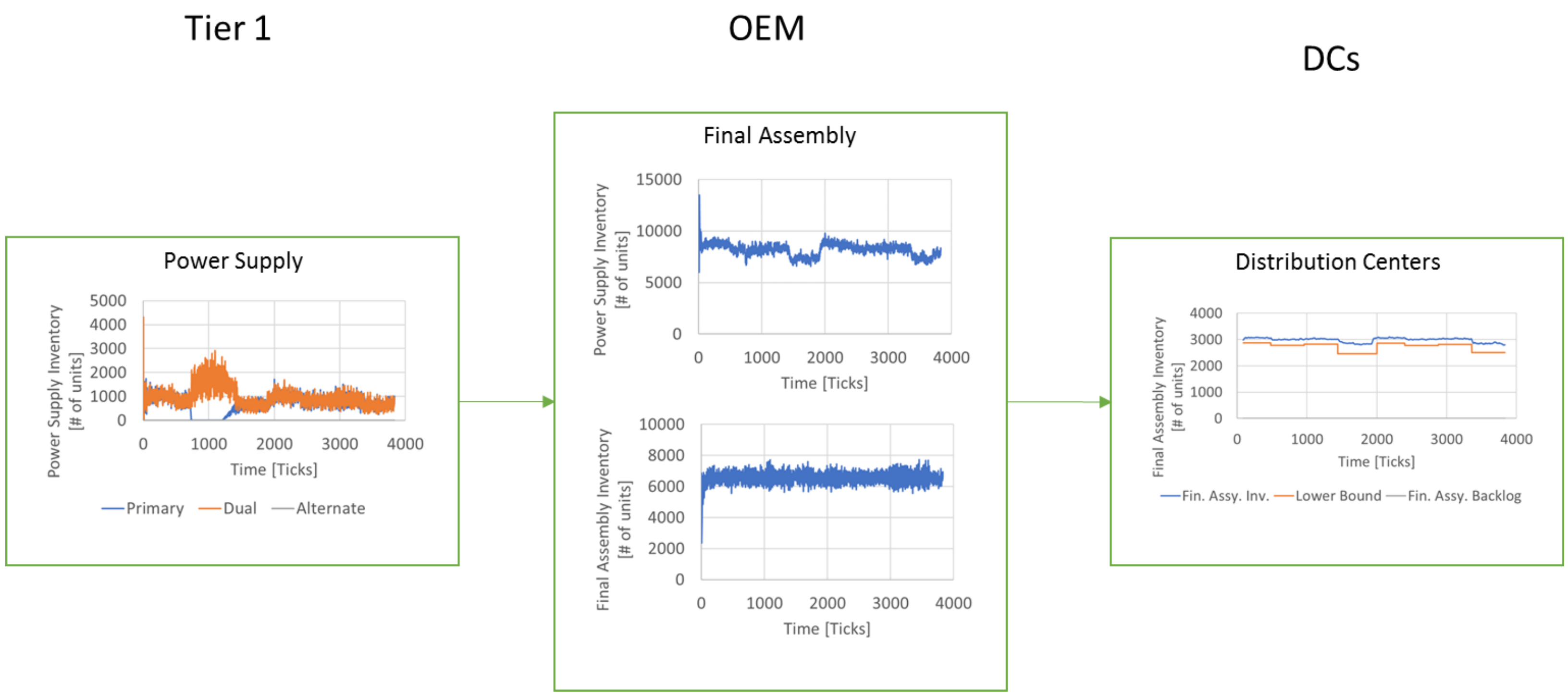

Figure 7.21: Inventory response to disruption at power supply supplier (Revised)

In fact, the disruption at the power supply location does not have any significant impact on the inventory of final assembly at the DCs. The dual supplier at the power supply location is sufficiently capable of handling the orders when the primary supplier fails. As a result, there is no noticeable change in the inventory levels at final assembly when compared to the no-disruption scenario. It is also shown, in Figure 7.22, that the improved disruption recovery is achieved without any significant change from the normal operating cost levels. The result indicates a possible advantage to using dual sourcing with lower DOH as compared to single sourcing with higher DOH.

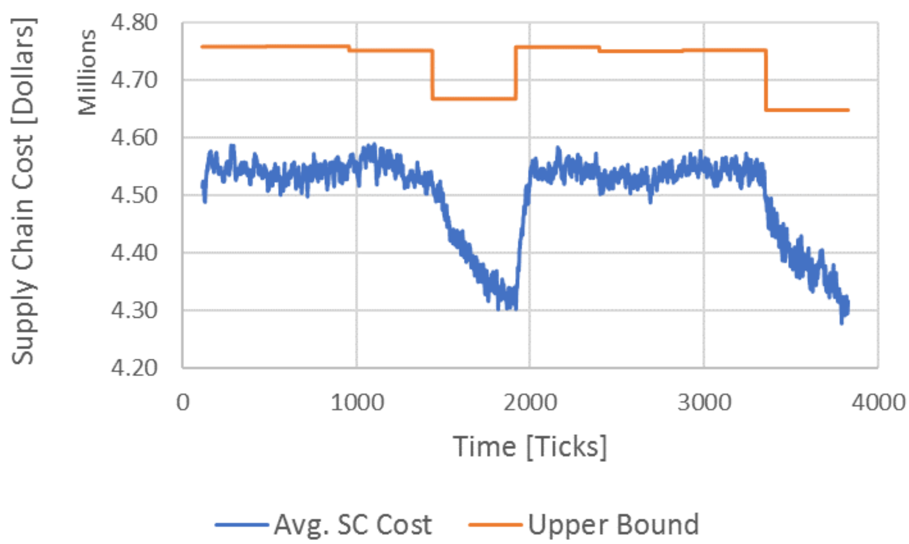

Figure 7.22: Total SC cost with disruption at power supply supplier (Revised)

7.2.4 Disruption at PCBA Supplier

Scenario 13: Baseline Segmentation Method

The PCBA supplier falls into the leverage category with both baseline and revised segmentation methods. The portion of the supply chain most closely linked to the PCBA supplier is shown in Figure 7.23. Strategic options for PCBA include the use of dual-sourcing, no visibility, and a lower DOH level. It is also relevant to note that PCBA is a relatively highly-connected node, acting as a middle tier between displays, ASCIS, and final assembly.

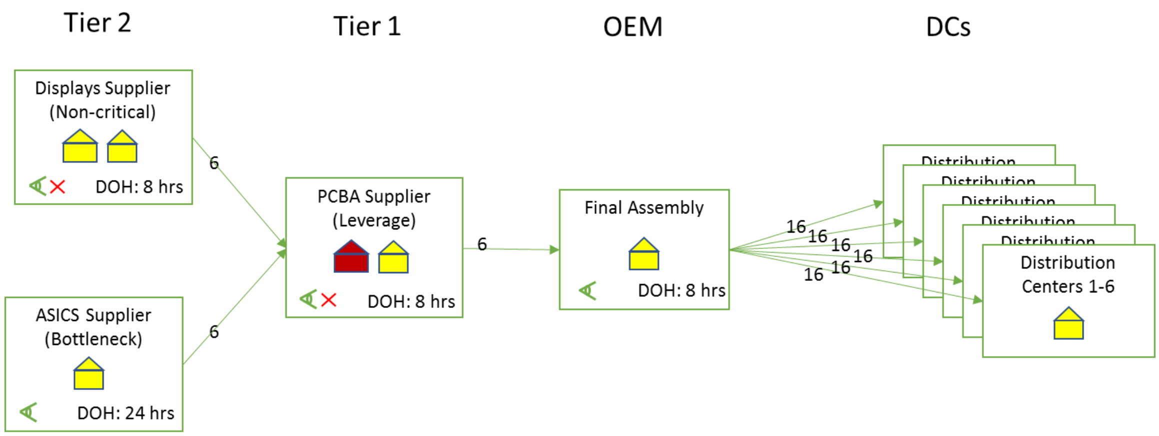

Figure 7.23: Partial SC map showing disruption at PCBA supplier (Baseline)

Figure 7.24 summarizes the response of PCBA and final assembly inventory to a disruption at the PCBA supplier.

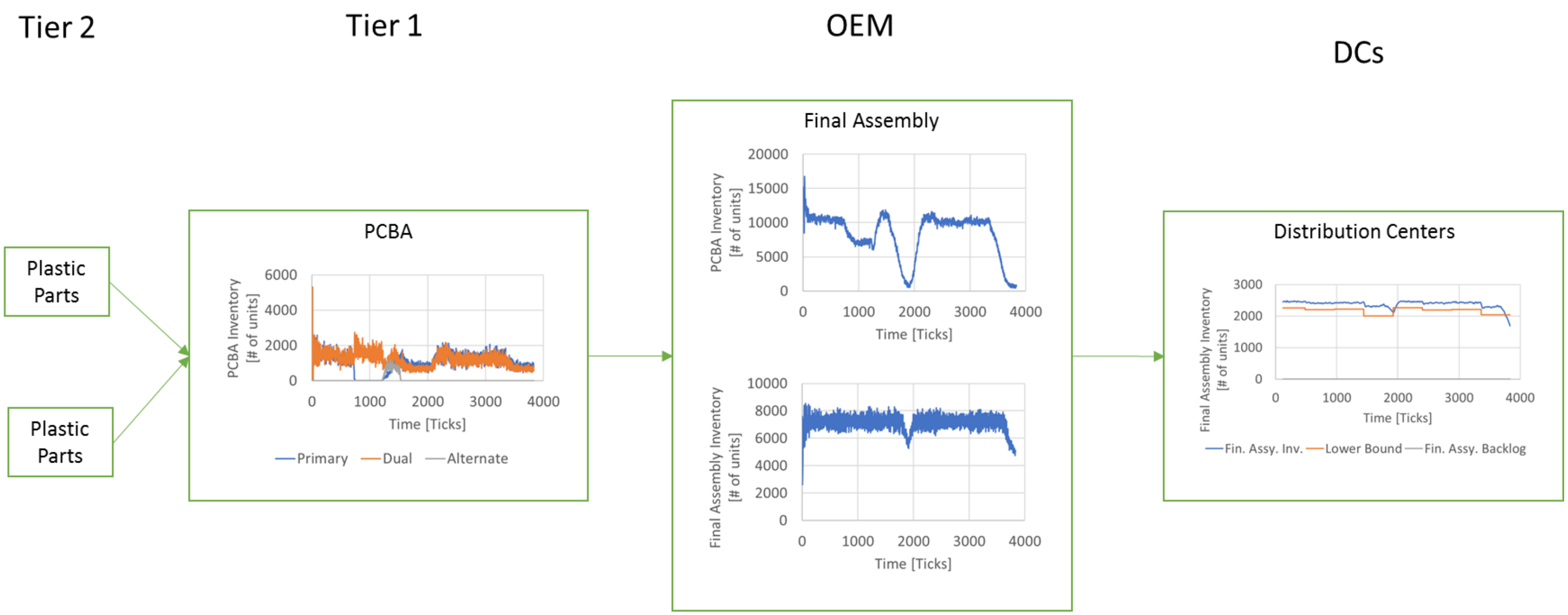

Figure 7.24: Inventory response to disruption at PCBA supplier (Baseline)

The effects of the disruption are seen at the final assembly node during the second quarter. During quarters four and eight the inventory levels drop in association with the periods of increased demand. The dual source for PCBA continues to deliver products to final assembly throughout the disruption, and the alternate supplier becomes active for a brief period as the primary supplier is ramping its capacity back to normal operating levels. The PCBA disruption does not appear to have a substantial impact on the inventory of final assemblies at the DCs. The supply chain cost, shown in Figure 7.25, diminishes during quarters four and eight during which the inventory levels are reduced because of high demand.

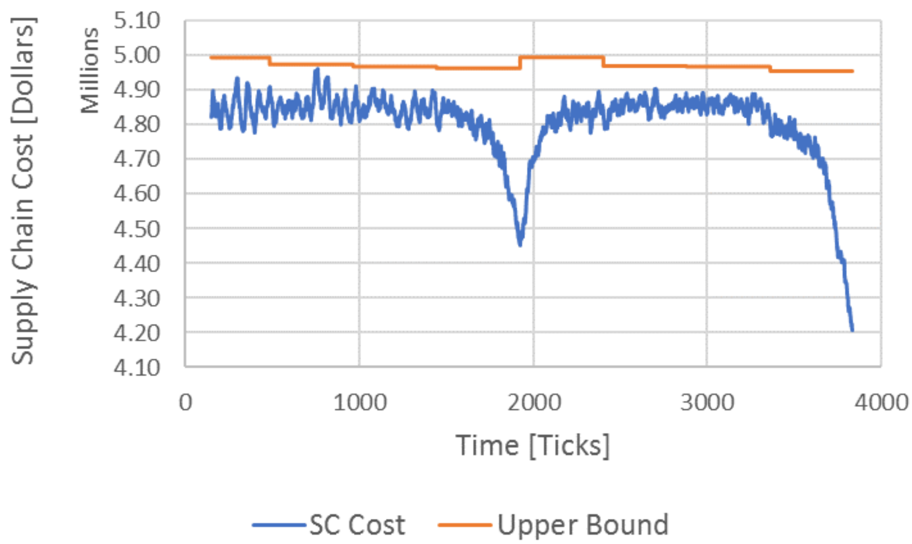

Figure 7.25: Total SC cost with disruption at PCBA supplier (Baseline)

Scenario 13: Revised Segmentation Method

There is no change in the strategic choices within the portion of the supply chain directly linked to PCBA inventory when the revised segmentation method is applied. Therefore, Figure 7.23 is still a good representation for effective strategies in the pertinent disruption scenario and need not be repeated. As demonstrated in Figure 7.26, the supply chain's resilience and robustness are reduced when the revised segmentation method is applied.

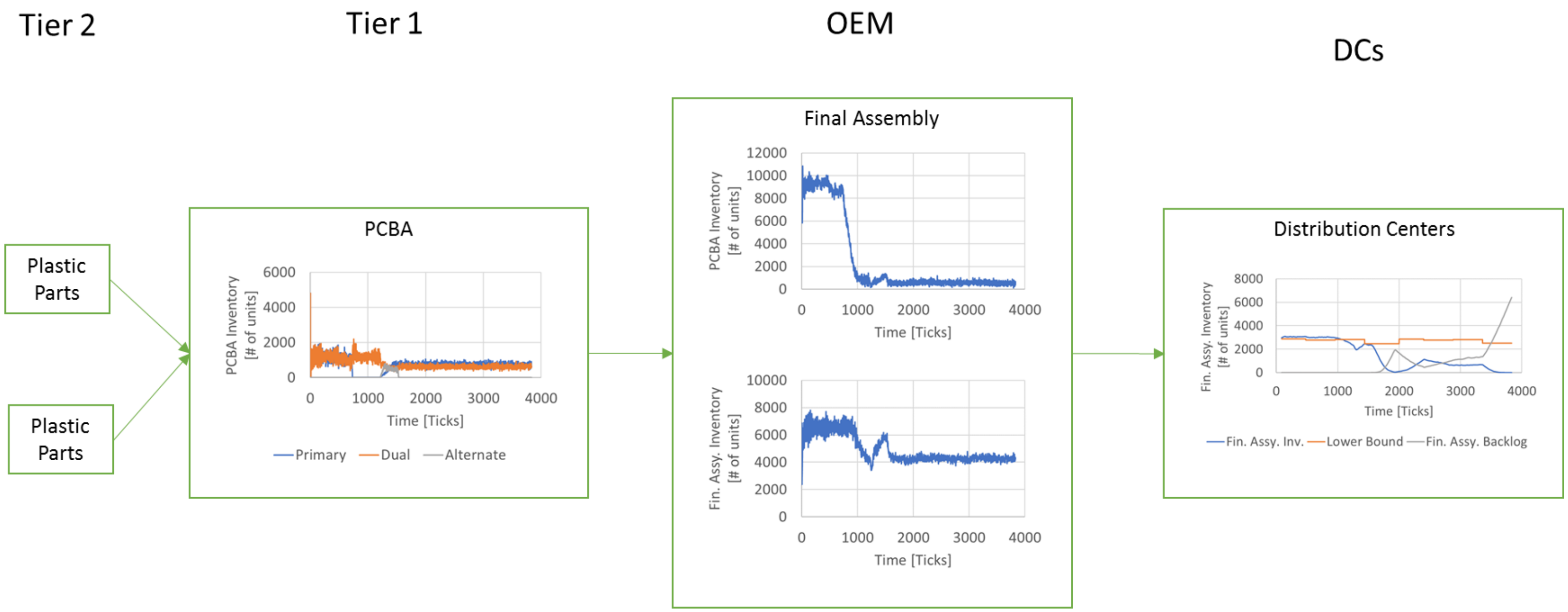

Figure 7.26: Inventory response to disruption at PCBA supplier (Revised)

Because there is no change in the strategies at the PCBA supplier itself, the increase in severity of impact must be due to the behavior of the surrounding suppliers. The response in PCBA inventory at the PCBA supplier itself follows nearly the same pattern in both baseline and revised cases. The distinction in the response of the two scenarios is most evident at the final assembly and DCs. The inventory response was observed at the displays and ASICS suppliers, which supply the PCBA node with raw material. It is discernable that after the PCBA disruption, the raw material inventory of displays at the PCBA node is not able to recover its normal operating levels. Without the displays, the PCBA supplier cannot complete production at the required rate to fully supply the final assembly operation. The inability of the PCBA supplier to recover its raw material of displays can be attributable to a combination of low DOH and a lack of visibility at the displays supplier. After the disruption, the final assembly production continues until its supply of PCBAs is exhausted. During recovery, the PCBA supplier must increase its production rate to replenish the lost inventory as well as satisfy new demand. Without visibility, the displays node does not update its DOH or its production rate. If the DOH at the displays supplier were sufficiently high, it would still be able to resupply the PCBA node. However, in the revised case, production capacity and by association, DOH, are set at lower levels than during the baseline case. The higher DOH and production capacity at displays explains its ability to withstand the effects of the disruption despite its lack of visibility.

Total supply chain cost response to the PCBA disruption reflects the inventory pattern and is shown in Figure 7.27.

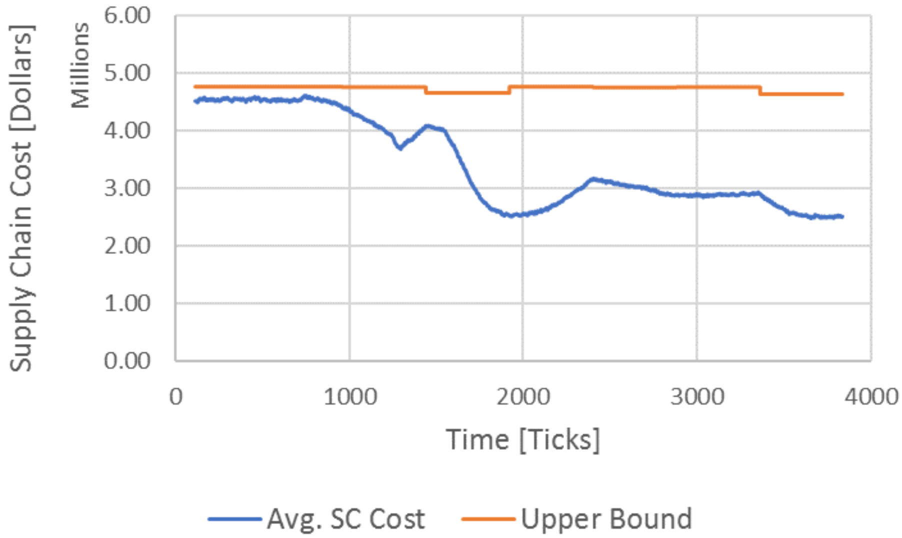

Figure 7.27: Total SC cost with disruption at PCBA supplier (Revised)

7.3 Effects of Demand Seasonality and Disruption Severity

The disruption scenarios are repeated with start time either in quarter 2 (Q2) or quarter 4 (Q4) to determine the effects of demand seasonality on robustness and resilience. Q2 is a period of typical demand whereas the demand in Q4 is higher than other periods of the year. For this reason, it is reasonable to expect a disruption that occurs in Q4, when production rate is more likely to be close to its capacity, to have greater impact. It is also possible to examine the effects of disruption severity on impact. In some disruption scenarios, an incomplete loss of production capacity may occur. It is interesting to study the effects that severity might have on the selection of the most resilient and robust procurement strategies.

Figure 7.28 demonstrates how the resilience and robustness of the supply chain are affected by the start time and severity of a disruption at the cartridge supplier. Robustness, as measured by the maximum deviation from the lower bound appears to be better when the disruption occurs in Q2. As expected, the complete loss of capacity results in a greater maximum deviation from the lower bound, regardless of the disruption start time. It appears that the supply chain may be more sensitive to disruption severity when the disruption occurs in Q2. The supply chain resilience for the same disruption originating at the cartridge supplier shows some unexpected behavior. The time-to-recovery decreases with increased severity when the disruption starts in Q4, the period of higher demand.

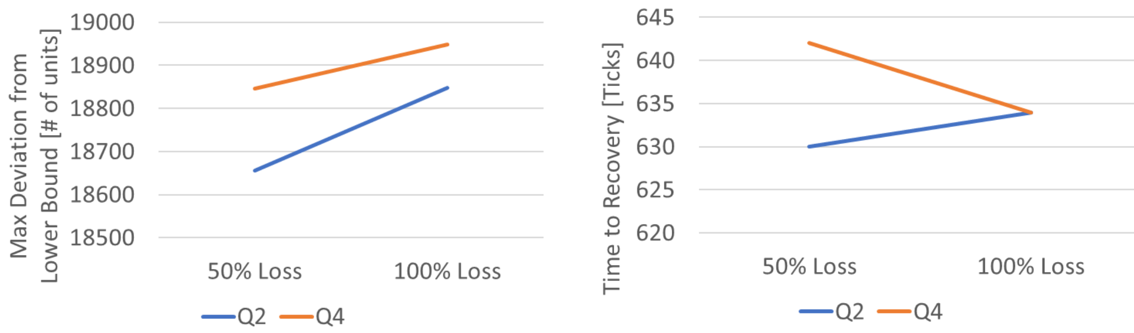

Figure 7.28: Seasonality and severity effects with disruption at cartridge supplier (Baseline)

As shown in Figure 7.29, the resilience and robustness show a different response to disruption start time and severity when the revised segmentation method is used.

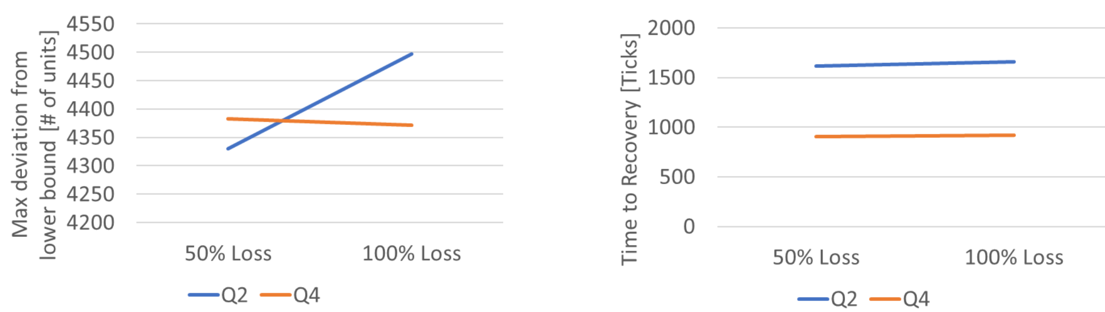

Figure 7.29: Seasonality and severity effects with disruption at cartridge supplier (Revised)

The maximum deviation from inventory lower bound is sensitive to the disruption severity only when the disruption starts in Q2. The time-to-recovery is longer when the disruption begins in Q2, the period with lower demand. Looking back at the inventory response at the DCs, the increased time-to-recovery can be explained by the high sensitivity of the cartridge inventory to the periods of high demand. When the disruption occurs in Q2, the cartridge inventory is reduced and makes the supply chain more susceptible to the high demand in Q4. When the disruption occurs in Q4, both the disruption and the high demand period coincide, isolating the disruptive effects.

The supply chain segmented with the baseline method appears to have similar resilience and robustness to a disruption at the toner supplier, according to the result shown in Figure 7.30. The maximum deviation from lower bound and the time-to-recovery each increase with disruption severity, as expected. Maximum deviation is slightly higher with the disruption starts in Q2, but not to a significant degree.

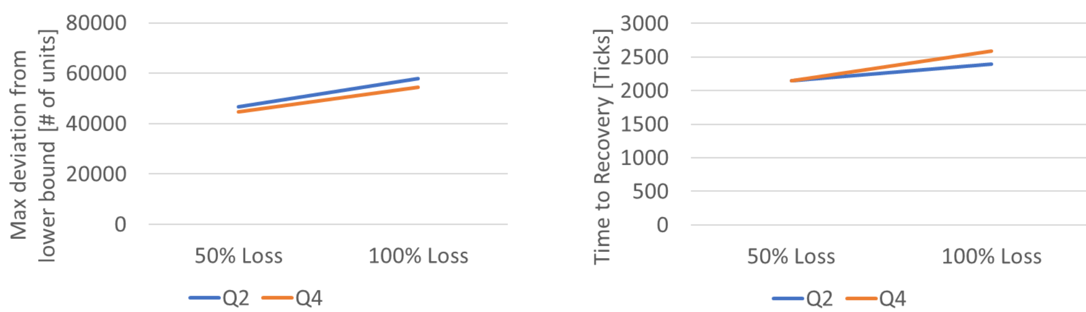

Figure 7.30: Seasonality and severity effects with disruption at toner supplier (Baseline)

As seen in Figure 7.31, maximum deviation from the lower bound shows a similar sensitivity to start time and severity in the revised segmentation case.

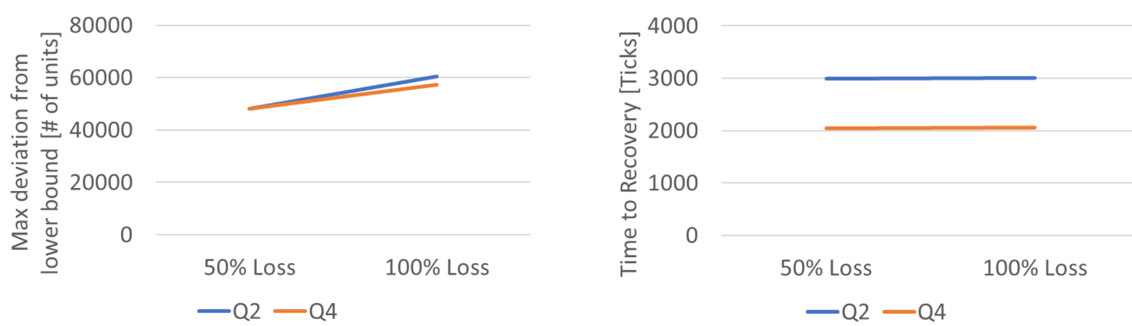

Figure 7.31: Seasonality and severity effects with disruption at toner supplier (Revised)

For the revised case the time-to-recovery does not show a sensitivity to the severity of the disruption. The dependence of time-to-recovery on start time is more significant in the revised segmentation case, with time-to-recovery being longer when the disruption occurs in Q2. The supply chain is not able to fully recover from the impact of the disruption at the toner supplier by the end of the simulation runtime. The time-to-recovery reflects the fact that the disruption starting in Q2 occurs earlier and the supply chain spends a longer time in the disrupted state.

Figure 7.32 summarizes the resilience and robustness of the supply chain to disruptions at the power supply supplier. Unexpected patterns seen in the response include a reduction in robustness as the disruption severity increases, and a higher resilience to disruptions starting in Q4.

Figure 7.32: Seasonality and severity effects with disruption at power supply supplier (Baseline)

The results shown in Figure 7.33, which indicate the resilience and robustness of the supply chain segmented with the revised method, are provided for completeness. However, only one of the four disruption scenarios originating at the power supply caused a disruption in the final assembly inventory at the DCs. The supply chain shows good robustness against this type of disruption when the revised segmentation strategies were used.

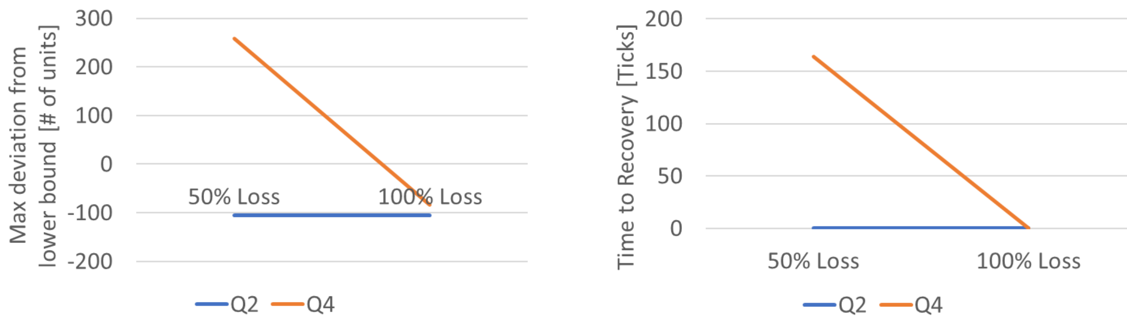

Figure 7.33: Seasonality and severity effects with disruption at power supply supplier (Revised)

The supply chain response to disruptions at the PCBA supplier are shown in Figure 7.34. The resilience and robustness for the supply chain segmented with the baseline method follow the expected trends. Robustness and resilience both decrease when 100% disruption severity is realized and when the disruption occurs during the period of higher demand.

Figure 7.34: Seasonality and severity effects with disruption at PCBA supplier (Baseline)

When the revised segmentation method is used, the supply chain becomes for susceptible to PCBA disruptions beginning during Q2. This effect is observed in Figure 7.35. Similar to the disruption at the toner supplier, the supply chain in these scenarios cannot fully recover due to an inability of the displays node to properly resupply the PCBA node with raw material after the production recovers from the loss of capacity. The disruptions starting at Q2 subject the supply chain to this effect for a longer period of time.

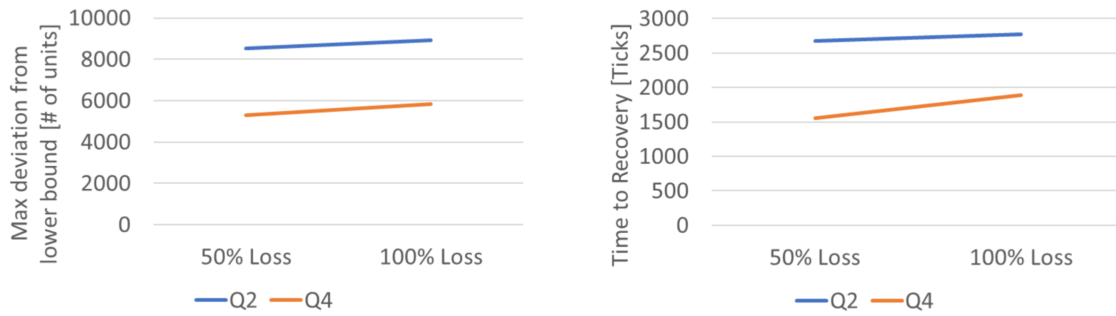

Figure 7.35: Seasonality and severity effects with disruption at PCBA supplier (Revised)

7.4 Baseline vs. Revised Comparison for all Scenarios

Some general observations can be made regarding the overall effectiveness of the baseline and revised segmentation methods at guarding the supply chain against disruption impact. First, for disruptions at the cartridge supplier, mixed results are seen depending on the objective. As shown in Figure 7.36, the maximum deviation from lower bound is lower when the revised segmentation method is used, while time-to-recovery is higher.

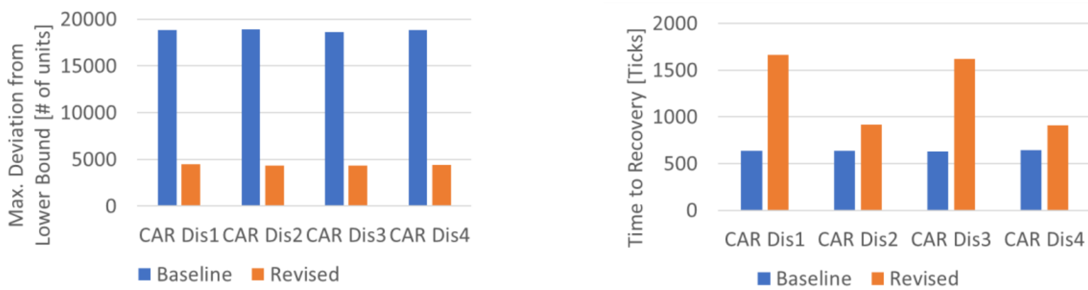

Figure 7.36: Resilience & robustness to disruption at cartridge supplier

A closer examination of the cartridge inventory response at the DCs reveals the supply chain with the revised segmentation strategies provides better protection against the initial disruption, but then due to the sensitivity to the high demand periods takes an extended time to fully recover. The supply chain with the baseline strategies shows a more distinct pattern of disruption and recovery, but allows the cartridge inventory levels to decrease more drastically immediately after the disruption occurs.

As indicated in Figure 7.37, the effectiveness of the baseline and revised segmentation methods is similar, but slightly favoring the baseline method when the disruption originates at the toner supplier. Neither method, however, protects the supply chain well which indicates the significance of a disruption occurring at a strategic supplier.

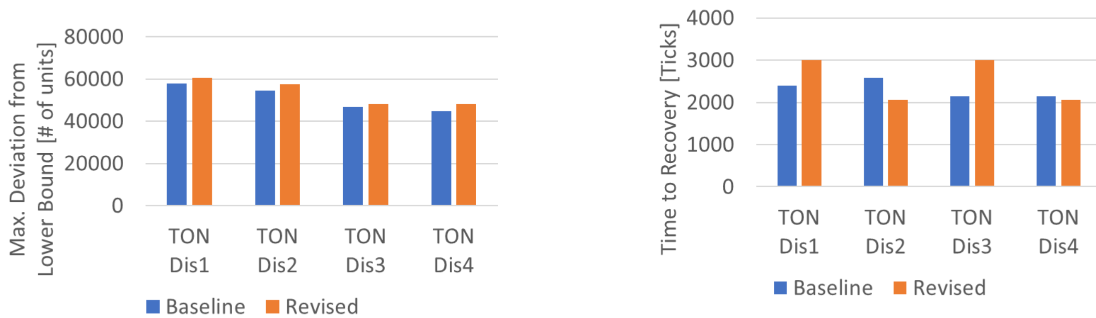

Figure 7.37:Resilience and robustness to disruption at toner supplier

The disruption impact for the scenarios starting at the power supplier show a clear advantage to the revised segmentation method in Figure 7.38. As indicated by the descriptions of section 7.2.3, the benefits are derived from the shift to a dual sourcing strategy at the power supply supplier.

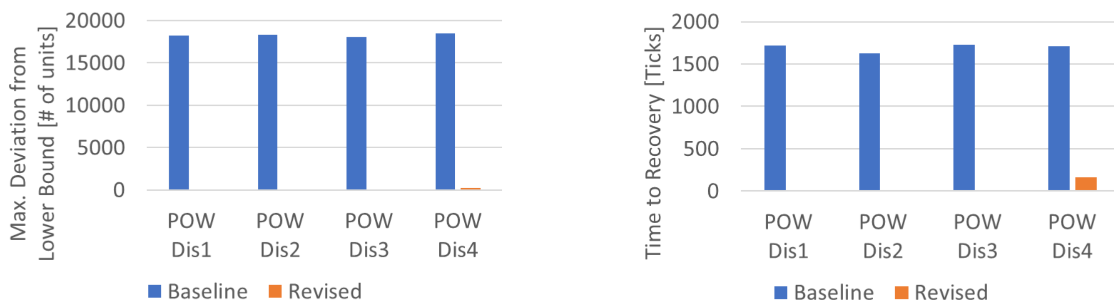

Figure 7.38: Resilience and robustness to disruption at power supply supplier

The disruption at the PCBA supplier, on the other hand, is better-handled by the baseline case as indicated in Figure 7.39.

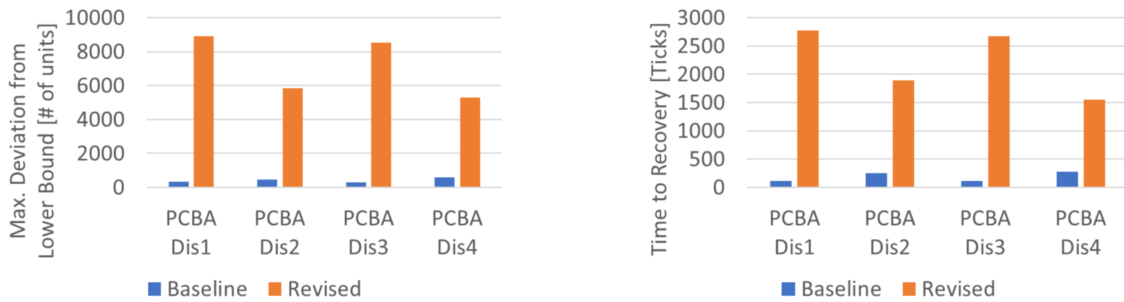

Figure 7.39: Resilience and robustness to disruption at PCBA supplier

The reduction in resilience and robustness observed when the revised segmentation method is used is attributable to a lack of visibility at the displays supplier, which provides raw material to the PCBA supplier, combined with an insufficient DOH at the displays supplier. It is interesting to note that the problem in this case does not originate at the supplier that was directly affected by the disruption. Rather, the after-effect and lack of preparation and communication between the affected node and its supplier is the source of vulnerability. This observation highlights the importance of considering the possible impacts of a disruption throughout the entire supply chain rather than only at the first-tier suppliers.

8 Discussion

Through examination of the simulation results, general conclusions can be drawn about how to select the best segment for a given supplier and possibilities for future improvement of segmentation methods. First, the observed results are examined with respect to the initial hypotheses a – d.

a) The revised segmentation method will increase resilience of the supply chain compared to baseline method.

Disruption impact assessment of the different scenarios indicates mixed results regarding the effectiveness of the two segmentation methods at increasing resilience and robustness. Better disruption response at the DCs is observed in the scenarios with disruption originating at the power supply and cartridge suppliers. For the cartridge disruption, a more contained period of disruption and recovery is observed with the baseline method than the revised method, as seen in Figure 7.8 and Figure 7.11. However, the backlog that compiles in the baseline case is much greater than in the revised case, so the revised case is judged as offering the preferable response. On the other hand, for the disruption scenarios originating at the toner and PCBA suppliers, the baseline segmentation method appears to offer superior resilience and robustness. The resilience and robustness observed in the inventory at the DCs is a result of the strategies of all suppliers in the supply chain. Therefore, it is difficult to explain the behavior as a result of a change in segmentation of any one node. However, some general observations are made.

The analysis of the cartridge disruption scenarios provides an indication that maintaining buffer inventory at the DCs increases robustness better than maintaining buffer at the final assembly node and farther up the supply chain. The buffer at the DCs is more capable of meeting the new demand that arises during the disruption period. Keeping inventory at the final assembly node increases cost significantly because of the number of types of raw material and the value of the finished goods. At the suppliers, the DOH is designed to last no more than around 24 hours. It is not cost-feasible to maintain enough finished goods inventory at a supplier to last throughout the duration of significant disruption.

Strategies of dual sourcing and visibility appear to be more important to increasing resilience and robustness. From analysis of disruptions at the power supply, there seems to be a clear advantage to the dual source strategy as opposed to the single source strategy with higher buffer inventory. This observation may be predicated on a requirement that the dual supplier has sufficient capacity so that it can ramp up its production during the period in which the primary supplier is not producing.

Observations from the disruption response at the PCBA supplier indicate that the disrupted supplier's suppliers, namely the displays supplier, needs visibility to know how and when to send more material for replenishment of depleted inventory once the disrupted production capacity is regained. Lacking visibility, it is necessary for the lower tier supplier to have a combination of enough capacity and high enough DOH so that it can replenish material with an increased demand, despite the fact it does not see the problem.

Although the baseline and revised segmentation methods show mixed results, it can generally be concluded that strategies of dual sourcing & visibility are most effective at increasing resilience and robustness. Increased DOH, and the extra capacity associated with it, is more important for nodes near the disruption. As the suppliers to the disrupted node experience a demand surge during and after disruption recovery, sufficient DOH and capacity are important for rapid replenishment of the disrupted node. In the printer supply chain case study, the revised method shifted suppliers toward the leverage and non-critical segments. As per the general observations relating to strategy, the suppliers which could be managed as leverage or non-critical generally showed increased resilience and robustness.

It is interesting to note the cause for the cartridge, power supply, and gears suppliers shift to the left-hand side of the segmentation matrix. First, each of these suppliers scored low on the additional resilience-oriented variables used in the revised segmentation method. The suppliers had fast to moderate ramp up time and low variability in transportation time. In addition, each of these suppliers was near the cutoff point between high and low ranking for market complexity based on the baseline segmentation variables. Other suppliers showed greater increase in market complexity due to the additional resilience-oriented variables. Ramp-up time and logistics variability relate to a supplier's ability to open a new location quickly and switch efficiently between sourcing locations. Suppliers without switching and ramp up capability are less effectively managed with dual source strategy and may show greater vulnerability to disruption.

b) A disruption at a strategic supplier is likely to have a more severe impact on the supply chain than a disruption at a non-critical supplier. The impact after a disruption at bottleneck or leverage suppliers is likely to fall into a middle range of severity.

The disruption at the toner supplier demonstrates the potential significance of a disruption at a strategic supplier. Both strategic and bottleneck nodes are shown to be vulnerable to disruption primarily because they do not employ dual sourcing, which is because of higher market complexity and limited supplier availability for the components. Strategic nodes appear to be most vulnerable because they also maintain lower DOH and generally are used for suppliers of higher cost components. A company tends to become dedicated to its strategic suppliers in business, which can be a point of strength but also a source of vulnerability as it may be difficult to find an alternate supply source. If a strategic supplier relationship is desired, it might be worthwhile to consider having a highly responsive alternate supplier with minimal startup delay. Contrary to the hypothesis, the results indicate that disruptions at strategic and bottleneck suppliers would both have a tendency toward more severe impact to disruptions. Leverage and non-critical suppliers would tend to suffer from less severe impact.

c) Disruptions that start during a period of high demand are likely to have a stronger impact than those that occur during normal demand periods.

As shown in section 7.3, disruptions which begin in periods of higher demand, namely during the fourth quarter of the simulated runtime, tend to cause greater disruption impact. Exceptions include observations for the cartridge disruption with revised segmentation and toner disruption with revised segmentation. The influence of the demand pattern is highly dependent on the amount of inventory buffer at the DCs. In the revised case, the cartridge buffer is reduced and therefore the demand increase and disruption have a combined effect. Offsetting the disruption and period of increased demand only has the effect of elongating the period of disruption. There is a general indication from this result that having a larger finished goods buffer at the DCs can protect against the combined effects of demand escalation and disruption. Therefore, it would be logical in future planning to increase the finished goods inventory during the periods of expected high demand.

d) Disruptions that cause a greater reduction in production capacity will have a greater impact on the supply chain.

The results indicate mixed response to changes in disruption severity from 50% loss of capacity to 100% loss. In several cases, the robustness or resilience show no sensitivity to the disruption severity. For the baseline segmentation case with cartridge disruption starting in Q4 the time-to-recovery was negatively associated with disruption severity. One possible explanation for the mixed result is that although only 50% of the production capacity was lost, the disruption increased demand during Q4 prevented the remaining capacity from keeping up with the desired production rate. In general, the effects of the segmentation method and the seasonal demand appear to outweigh the effects of disruption severity.

In addition to the observations on resilience and robustness, some general conclusions can be drawn with respect to the normal operating cost resulting from each segmentation method. Higher inventory and higher visibility strategies tend to result in a higher normal operating cost. As noted in section 7.1 the cost is dominated by holding cost, and holding cost is largely determined by DOH. Strategies of higher DOH level are associated with the bottleneck segment. Visibility can also increase cost because a supplier with visibility may increase its production rate to match the expected demand of its buyer. In so doing, the supplier can exceed its DOH, while this would not happen at a supplier with no visibility. Therefore, from a cost perspective it makes sense to segment most suppliers as leverage or non-critical if it is feasible to do so. Feasibility of segmenting as leverage or non-critical largely relates to the availability of a dual source, and the length and variability of transportation delay from the dual source. In the printer case study, the revised segmentation method showed a stronger tendency to segment suppliers into the lower cost segments, and in general the cost of the revised supply chain was reduced. It then would be appropriate to use strategic or bottleneck strategies when there is no dual source available, or a dual source is available but is far away with variable transportation delay, or otherwise unreliable delivery. Availability of suppliers and transportation delay and reliability should weigh in highly when assessing market complexity, which essentially differentiates the dual and single-source suppliers.

Results indicate an advantage to segmenting most suppliers as leverage or non-critical with respect to normal operating cost, resilience, and robustness. However, in cases of high market complexity it is not always possible to use these strategies. The inability to use a dual sourcing method largely determines if a supplier should be moved to bottleneck or strategic segments. When deciding between bottleneck and strategic segments, the cost of the component is a primary consideration, along with the connectedness of the supplier and component criticality. Criticality can refer to the importance of the component to the customer's purchase decision, and the potential for design innovations relating to that component. Due to limitations in the simulation model, not all factors of purchasing importance could be considered, but opportunity exists for further extension and study of different indicators for using bottleneck vs. strategic segments.

This research presents an argument that the portfolio segmentation methods similar to the approach presented by Kraljic (1983) are limited by their focus on operational risk and general goal of selecting the best strategies for normal operating conditions. Realistically, the established strategies for buyer-supplier interaction also affect disruption response capability. The results from the presented case study and ABMS indicate that the choice of dual or single sourcing, whether to establish buyer-supplier visibility in production planning, and the DOH at nodes near a disruption each have a significant effect on the supply chain resilience and robustness. Post-disruption recovery strategies should be developed and are important to mitigate the disruption impact, but the results of this research indicate that the effectiveness of these recovery actions depends on the state of disruption preparedness provided by day-to-day procurement strategy. The revised segmentation method demonstrated mixed capability for improving the resilience and robustness of the supply chain. There is a need to further-examine the connection between the individual segmentation variables and their implications on choice of procurement strategy.

9 Summary and Future Work

From the research perspective, this work contributes an organized set of factors that should be considered in a supplier segmentation method oriented toward the enhancement of resilience and robustness. Furthermore, a revised segmentation method was specified which incorporated a subset of resilience-oriented factors. The incorporation of the resilience-oriented factors had the general effect of creating a greater distinction between suppliers with higher and lower potential for disruption impact. An agent-based model and simulation was developed to study the impact of different disruption scenarios on the supply chain as segmented with the revised segmentation method.

The revised segmentation method was compared to a baseline method based on an assessment of suppliers during normal conditions. The two segmentation methods were compared in the context of a laser printer supply chain. Practical results from the research include general observations from the disruption scenarios. It was indicated that the procurement strategies associated with the leverage and non-critical segments were advantageous from both the normal operating cost and disruption response perspective. However, these strategies are not always feasible in which case strategic or bottleneck strategies should be employed.

Opportunities exist for further study and improvement of the segmentation method. The importance of the alternate supplier should be studied in greater detail. Decision processes relating to how and when the alternate supplier is signaled to open should be incorporated in the simulation. The costs and time delays relating to the opening and ramp up of an alternate supplier have potential to greatly affect the practicality of using a single-sourcing method. Additional resilience-enabling factors could be considered in the segmentation process as the decision models associated with the new factors are included in the simulation. Given the availability of supplier data, it would be worthwhile to consider using clustering techniques or principal component analysis to go beyond the original portfolio segmentation approach. The revised portfolio segmentation methods employed rely on a relative ranking of suppliers. It would be worthwhile to seek out fixed cutoff points for the two segmentation dimensions. For example, it could be determined if there is a fixed amount of market complexity for which dual or single sourcing strategy is more effective from the operational and disruption response perspectives.

The complexity of the decision processes modeled in the ABMS was controlled to simplify interpretation of results. The supplier behavior was differentiated enough to test the hypothesis regarding the effects of strategy associated with different supplier segments. There is opportunity to extend the ABMS capabilities to better-reflect the intricacies of decision making processes.

A limitation in the work is that disruptions are assumed to have the same length, regardless of the supplier or the associated disruption source. Eliminating this assumption, the duration of the disruption would be dependent on internal supplier capabilities. In future work, the connection between supplier characteristics and ability to regain capacity after disruption could be explored in greater detail.

In addition, customer behavior patterns could be explored. The customer response to stockouts at the DCs may vary depending on the type of customer. In some cases, the customer may be very loyal and willing to wait for inventory to become available. The company may attempt to retain customers by absorbing a late fee. These factors affect the cost response due to disruption and may be interesting to explore in future simulation models. The ABMS modeling paradigm lends itself well to the study of supplier relationship behaviors. For example, supplier characteristics can be included in the model that specify whether a supplier would favor the focal company or possibly another of its customers.

This research assumes that capacity at the supplier is dedicated to the printer supply chain for the focal company. In some instances, a supplier may share its production capacity across multiple customers. These considerations can be explored with future developments of the supply chain ABMS. Finally, it is worthwhile to consider modifying the supply chain ABMS to improve flexibility, so that it can be more easily applied to different supply chain networks. The improved flexibility for multiple applications would allow repeated studies of different segmentation methods so that their effectiveness could be demonstrated in different contexts.

Appendix

A Comparison of Segmentation Methods

Table A.1: Comparison of segmentation methods

Model Type	Dimensions	Associated variables/criteria	Differentiated Segments	Unit of Classification	Reference
Partnership	Potential Benefit of Partnership	asset/cost efficiencies; customer service; marketing advantage; profit stability/growth	Arm's length; Type I, II, and III partnerships; joint ventures; vertical integration	Relationship	(Lambert et al., 1996)
	Corporate Environment - Support	corporate compatibility; managerial philosophy and techniques; symmetry; exclusivity; shared competitors; physical proximity; prior history of working with the partner; shared high value end user			
Portfolio	Profit Impact	volume purchased; percentage of total purchase cost; impact on quality or bustiness growth	Strategic; bottleneck; leverage; noncritical	Product	(Kraljic, 1983)
	Supply Risk	availability; number of suppliers; competitive demand; make-or-buy opportunities; storage risk; substitution possibilities			
	Supplier strength	market size vs. supplier capacity; market growth vs. capacity growth; capacity utilization or bottleneck risk; competitive structure; ROI and/or ROC; cost and price structure; break-even stability; uniqueness of product and technological stability; entry barrier (capital and know-how requirement); logistics situation	Action Plans: exploit; balance; diversify	Relationship	
	Company strength	purchasing volume vs. capacity of main units; demand growth vs. capacity growth; capacity utilization of main units; market share vis-à-vis main competition; profitability of main end products; cost and price structure; cost of non-delivery; own production capability or integration depth; entry cost for new sources versus cost for own production; logistic			

Table A.1 continued

Model Type	Dimensions	Associated variables/criteria	Differentiated Segments	Unit of Classification	Reference
Involvement	Nature of Products	interface complexity; rate of technological change; end consumer perception influence	Critical systems (high cost, OEM provides supplier with performance specifications); hidden components (low cost simple components defined by physical specifications); invisible subassemblies (moderate cost, suppliers are provided with performance specification and detailed physical dimensions); simple differentiators (moderate cost simple assemblies; suppliers are provided with detailed physical specifications)	Product	(Laseter and Ramdas, 2002)
	Cost Structures	unit product cost; amortized development cost; manufacturing scale			
	Nature of OEM-Supplier Interaction	type of specifications passed to the supplier			
Portfolio	Product Complexity	technicality of product; need for user input in making a sound purchase; importance of tight product specifications; criticality of product performance with high differentiation between various suppliers' products	close relationships; strategic partnerships; simple contracts; global trading	Relationship	(Hadeler and Evans, 1994)
	Product Value Potential	dollar volume; potential for significant price reduction; potential for getting significant value-added benefits from suppliers; risk to profit or safety in case of supply shortage or quality problems			
Partnership	Collaboration	26 variables from NIST 'Quickview' manufacturing survey; 5 most influential: early supplier involvement in product development; strategic vision; customer/material supplier certification; insufficient employee training; equipment supplier certification	commodity supplier; collaboration specialist; technology specialist; problem-solving supplier	Supplier	(Kaufman et al., 2000)
	Technology	22 variables from NIST 'Quickview' manufacturing survey; 5 most influential: expert machine utilization; quality function deployment; process manufacturing know-how; inexpert machine utilization; advanced process technology management			

Table A.1 continued

Model Type	Dimensions	Associated variables/criteria	Differentiated Segments	Unit of Classification	Reference
Portfolio	Strategic Importance of the Purchase	competence (of buyer), economic, and image factors	bottleneck; strategic; non-critical; leverage	Product	(Olsen and Ellram, 1997)
	Difficulty of Managing the Purchase Situation	product, supply market, and environmental characteristics			
	Relative supplier attractiveness	financial and economic, performance, technological, organizational/cultural/strategic, flexibility to environmental changes, and safety factors	action plans: strengthen supplier relationship; improve supplier attractiveness or relationship performance; reduce resources allocated to the relationship	Relationship	
	Strength of Relationship	economic factors, character of the exchange relationship, cooperation between buyer and supplier, distance between buyer and supplier			
Portfolio	Buyer's Specific Investments	tangible: buildings, tooling, equipment; intangible: people, time, knowledge	captive buyer; strategic partnership; market exchange; captive supplier	Relationship	(Bensaou, 1999)
	Supplier's Specific Investments	tangible: plant location/layout, specialized facilities/dies; intangible: guest engineers, information system development			
Portfolio	Buyer Dependency Risk	value added to the customer; irreplaceability of the supplier	non-strategic; strategic; asymmetric	Relationship	(Hallikas et al., 2005)
	Supplier Dependency Risk	value added to the supplier; irreplaceability of the customer			
Portfolio	Willingness to Maintain Relationship	21 variables identified	described by quadrant, not otherwise characterized	Supplier (specific functions)	(Rezaei and Ortt, 2012)
	Performance Capability	46 variables identified			
Involvement	Strategic Nature of Inputs	necessary but non-strategic; strategic	durable arm's-length relationship; strategic partnerships	Supplier	(Dyer et al., 1998)

B Resilience-Enabling Factors Literature Review Summary Tables

Table B. 1: Elements of visibility and data analysis

Reference	Extent or timeliness of information collection and/or exchange	Uncertainty in the shared information	Ability to convert information into useful knowledge	Types of information collected and/or shared	Use of tools, methods, and procedures
(Blackhurst, Craighead et al. 2005)	real-time information sharing	correctness of shared information	predictive analysis to foresee problems	dynamic risk indices at each node	
(Brandon-Jones, Squire et al. 2014)				sharing inventory and demand levels	Information Technology and support technology
(Basole and Bellamy 2014)					visualization tools
(Craighead, Blackhurst et al. 2007)	dissemination of pertinent disruption information		detection of pending or realized disruptions		
(Pettit, Croxton et al. 2013)	information exchange			business intelligence gathering knowledge of status of product, equipment, and people	Information Technology
(Shao 2013)	information accessibility frequency of information sharing real-time information sharing/timely sharing of supply information	correctness of shared information		knowledge on status of material flow	
(Jüttner and Maklan 2011)				event monitoring (environment) event monitoring (internal to the supply chain) knowledge on status of material flow	
(Sheffi and Rice Jr 2005)			Statistical Process Control/anomaly detection		shipment visibility systems/RFID

*Table B. 1*Table B. 1: Elements of visibility and data analysis *continued*

Reference	Extent or timeliness of information collection and/or exchange	Uncertainty in the shared information	Ability to convert information into useful knowledge	Types of information collected and/or shared	Use of tools, methods, and procedures
(Ojha, Gianiodis et al. 2013)			awareness of optimal operating performance levels		
(Hohenstein, Feisel et al. 2015)	real-time monitoring		early warning indicators		
(Scholten, Scott et al. 2014)				event monitoring (internal to the supply chain) knowledge on status of material flow	
(Wieland and Wallenburg 2013)	screening and signaling timeliness of sharing disruption data			knowledge of changes currently occurring	
(Olcott and Oliver 2014)	common knowledge base				integrated knowledge sharing routines/Information Technology infrastructure
(Ambulkar, Blackhurst et al. 2015)			awareness of pending disruptions		
(Kleindorfer and Saad 2005)					use of compatible communication and information technologies
(Ponis and Koronis 2012)					knowledge management systems
(Ellis, Henry et al. 2010)		difficulty forecasting future developments due to technological uncertainty volatility of standards for product price and quality performance			

Table B. 2: Elements of Collaboration and Supplier Development

Reference	Mutual efforts: working towards a common objective	Decision Synchronization: shared use of information for mutual benefit	Supplier openness and efforts to meet buyer requirements	Presence of incentive alignment and risk sharing	Planning, organization and unification of employee efforts	Compatibility: cultural alignment
(Hohenstein, Feisel et al. 2015)	supplier development joint development of business continuity plan joint efforts	information sharing joint decision making	supplier certification			
(Mandal 2012)		joint decision making on optimal order quantity and inventory requirements joint planning on promotional events and product assortment information sharing on price changes and supply disruptions		availability of incentives to both suppliers and customers		
(Shao 2013)	joint planning for potential problems				on-site location of employees cross-function and cross-company teams	
(Peck 2005)	mergers and other high-level consolidation	collaborative forecasting	forced reconfiguration or operational changes due to power/dependency relationship			
(Olcott and Oliver 2014)			social capital - sense of obligation	heedfulness of needs and roles of those interacting	shared mental models - common way of thinking	
(Kleindorfer and Saad 2005)		collaborative planning and forecasting		incentive alignment - seek ‘win-win’ outcomes risk avoidance or reduction by all partners		

Table B. 2 continued

Reference	Mutual efforts: working towards a common objective	Decision Synchronization: shared use of information for mutual benefit	Supplier openness and efforts to meet buyer requirements	Presence of incentive alignment and risk sharing	Planning, organization and unification of employee efforts	Compatibility: cultural alignment
		aversion to opportunistic decision making				
(Jüttner and Maklan 2011)		decision synchronization	willingness to share sensitive information	incentive alignment		
(Venkateswaran, Simon-Agolory et al. 2014)					establish role and responsibility assignments	
(Blackhurst, Dunn et al. 2011)	partnering with customs programs coordination of available resources				cross-functional risk management teams	
					knowledge of available expertise within the collaborative network	
(Scholten, Scott et al. 2014)	sharing of resources	joint decision making/application of shared knowledge			cross-functional teams	
(Kapucu and Van Wart 2006)	effectiveness of resource coordination	interagency (emergency response agency) communication				knowledge of consistent motives and integrity

Table B. 2 continued

Reference	Mutual efforts: working towards a common objective	Decision Synchronization: shared use of information for mutual benefit	Supplier openness and efforts to meet buyer requirements	Presence of incentive alignment and risk sharing	Planning, organization and unification of employee efforts	Compatibility: cultural alignment
(Wieland and Wallenburg 2013)		integration of supplier and customer information for internal planning formal and informal sharing of meaningful and timely information	willingness to make sensitive information available	shared sense of responsibility		psychological connections formed for mutual gain
(Kovács 2009)	develop common knowledge base regarding mandates and capabilities of each organization division and coordination of activities joint training efforts				specification of potential collaboration partners	
(Chiang, Kocabasoglu-Hillmer et al. 2012)	activities undertaken by the buyer to improve supplier's performance or capabilities					strengthening of relationship to reduce risk of opportunistic behavior

Table B. 3: Elements of Training, Learning, and Business Continuity Planning

Reference	Learning from past events	Learning from training exercises and simulations	Employee skills for preparation and recovery	Risk-oriented culture	Continuity or Contingency Planning	Use of metrics
(Sheffi and Rice Jr 2005)	culture of learning from errors and "near miss" disruptions	disruption training simulations	empowerment of front-line employees to take initiative			
(Scholten, Scott et al. 2014)	capacity for learning from past disruptions	learning exercises and simulations		training to raise risk/resilience awareness	establish role assignments/restrictions during recovery develop disruption response plan and training for execution of the plan	
(Hohenstein, Feisel et al. 2015)		train/educate employees in how to deal with risk events		risk sensitive culture and mindset	business continuity plans for detecting critical suppliers and assessing recovery time establish cross-functional teams predefine contingency plans and communication protocols	
(Golgeci and Ponomarov 2013)	openness to change		innovation capability			
(Ponis and Koronis 2012)	study and learning from past disruptions					

Table B. 3 continued

Reference	Learning from past events	Learning from training exercises and simulations	Employee skills for preparation and recovery	Risk-oriented culture	Continuity or Contingency Planning	Use of metrics
(Kapucu and Van Wart 2006)	lessons learned from past events	intra/inter sector training exercises	technical competence to conduct response decreases reliance on central authority			
(Ambulkar, Blackhurst et al. 2015)	learning from prior disruptions			dedicated risk/disruption department dedicated information systems for risk & disruption management awareness of environment/situational awareness		consistent set of performance indicators to monitor risk & disruption management process
(Blackhurst, Dunn et al. 2011)	effective post-disruption analysis		understanding of cost/benefit trade-off of recovery decisions	develop Supplier Relationship Management programs to mitigate risk and increase trust	developing self-executing plans port diversification planning predefined and practiced contingency plans	
(Venkateswaran, Simon-Agolory et al. 2014)		simulated practice exercises	education on disaster prevention, preparedness, mitigation, and recovery training for recovery of critical business processes and operations		vulnerability study periodic testing of continuity plan	

Table B. 3 continued

Reference	Learning from past events	Learning from training exercises and simulations	Employee skills for preparation and recovery	Risk-oriented culture	Continuity or Contingency Planning	Use of metrics
(Ojha, Gianiodis et al. 2013)	learning from past failures		training to improve communication and interpersonal skills technical skills to formulate prevention and recovery plans training to respond as a team to system failures empowerment of knowledgeable employees		training for creation and management of BCP	
(Kleindorfer and Saad 2005)					prioritization of mitigation strategies design and rehearsal of organizational and communications architecture periodic review of implementation plans	
(Pettit, Croxton et al. 2013)	post-disruption discussion and reporting implementation of improvements after a disruption learning from experience/past disruptions		cross-training of workforce in multiple skills			regular use of feedback and benchmarking tools
(Revilla and Sáenz 2014)	analysis of past incidents to identify process improvements	simulation of various supply chain risks and disruptions				

Table B. 4: Elements of Redundancy and Inventory Management

Reference	Maintenance of buffer inventory	Maintenance of extra capacity	Use of multiple suppliers	Strategic positioning and routing of inventory	Control of inventory levels: strategic inventory management	Labor availability
(Zsidisin and Wagner 2010)	safety stock; inventory help at suppliers to prevent stakeouts	low capacity utilization rates extra production capacity	maintaining dual or multiple suppliers			
(Klibi, Martel et al. 2010)	insurance inventory	insurance capacity		inventory location and routing		
(Mandal 2012)	optimal investment in inventory to meet demand forecast and prevent stockouts	optimum capacity to meet demand forecasts and prevent stockouts				
(Sheffi and Rice Jr 2005)	safety stock	low capacity utilization rates	use of multiple suppliers despite higher costs		strategic inventory management systems, special authority is necessary to release inventory	
(Peck 2005)	inventory buffer	redundant production capacity			safety lead-time	redundant expertise capability; maintenance of HR
(Blackhurst, Dunn et al. 2011)	buffer inventory kept on hand to last X number of days	implementation of employee overtime		strategic location of inventory		labor availability
(Kleindorfer and Saad 2005)		slack in production			slack in operations planning	
(Hohenstein, Feisel et al. 2015)	suppliers holding excess inventory	slack transport capacity slack resources in production	dual or multiple suppliers			
(Boone, Craighead et al. 2013)					inventory management approach; system or item level objectives	
(Suzuki 2012)	extra fuel inventory for transportation					

Table B. 5: Elements of Flexibility, Velocity, and Agility

Reference	Ability to adjust production rate	Logistics rerouting capability	Speed of supply chain reconfiguration	Number of possible supply chain configurations	Labor and process inter-changeability	Ability to replace or redesign parts and/or components
(Hohenstein, Feisel et al. 2015)	flexible production systems acceleration of production speed in response to customer	multiple distribution channels; material rerouting	ramping up of other manufacturing plants speed of supply chain redesign	ease of switching between alternate suppliers	multi-skilled workforce	
(Jüttner and Maklan 2011)	flexible capacity utilization		speed of reaction to market changes or events speed of flexible adaptations	number of possible states a supply chain can take; possible through dual and multiple sourcing		
(Kleindorfer and Saad 2005)						delayed differentiation; postponement of product specialization modularity of product and process design
(Sheffi and Rice Jr 2005)				alignment of supplier relationship with procurement strategy; use of multiple sources or single source with close relationship	cross-trained workforce interoperable processes and systems	demand shifting; ability to influence customer to available product
(Christopher and Peck 2004)	ability to change production velocity quickly in response to unpredicted changes in demand or supply		speed of reconfiguration			
(Wieland and Wallenburg 2013)			speed of adaptation to marketplace uncertainty speed of system reconfiguration	supplier relationship dependence		

Table B. 5 continued

Reference	Ability to adjust production rate	Logistics rerouting capability	Speed of supply chain reconfiguration	Number of possible supply chain configurations	Labor and process inter-changeability	Ability to replace or redesign parts and/or components
(Mandal 2012)		use of many supply channels	logistical response to unforeseen events; timeliness of reconfiguration of supply chain resources in response to supply and demand changes timeliness of reconfiguration of supply chain resources in response to changes in daily supply chain execution			
(Chiang, Kocabasoglu-Hillmer et al. 2012)	supply flexibility: supplier's ability to satisfy buyer's dynamically changing specifications in terms of quality, time, and product mix process flexibility: competence to adjust production processes and volumes based on the changing needs of the marketplace		organizations ability to change or react with little penalty in time, cost, or performance capability to respond quickly to a change in marketplace			product design flexibility: competence of the system to develop new products, make minor design changes, and adjust product mix to satisfy dynamic market demand in timely and cost-effective manner
(Yusuf, Musa et al. 2014)		ability to adjust delivery quantities			flexible workforce	
(Ambulkar, Blackhurst et al. 2015)				formalization of risk management processes		
(Pettit, Croxton et al. 2013)		alternative logistics distribution channels; rerouting capability		flexible supplier contracts multiple suppliers		part commonality modular product design postponement

Table B. 5 continued

Reference	Ability to adjust production rate	Logistics rerouting capability	Speed of supply chain reconfiguration	Number of possible supply chain configurations	Labor and process inter-changeability	Ability to replace or redesign parts and/or components
(Shao 2013)	adjustable production capacity		ability to complete an activity as quickly as possible ability to identify changes and respond quickly		ability to implement different processes at different facilities to achieve goals	
(Scholten, Scott et al. 2014)			speed of supply chain reaction to changes in demand speed of adaptation of initial supply chain configuration			
(Zsidisin and Wagner 2010)			supplier certification programs	closeness of buyer-supplier relationship		

Table B. 6: Elements of Network Structure

Reference	Network size	Density or geographic dispersion	Connectedness and/or flow complexity	Network stability	Node risk and criticality relative to the rest of the network
(Adenso-Diaz, Mena et al. 2012)	total number of nodes in the network number of distinctive raw materials suppliers required for the final product average number of nodes in a regional cluster	variance in density of different regional clusters	total number of forward, backward, and within tier material flows		
(Hearnshaw and Wilson 2013)			clustering coefficient: probability that two neighboring nodes connected to a local node are also connected to each other connectivity distribution: the average number of connections possessed by each node in the network characteristic path length: the average number of firms or tiers that must be traversed between any two randomly chosen nodes		
(Brandon-Jones, Squire et al. 2014)	number of suppliers	geographic dispersion			
(Greening and Rutherford 2011)			network density: how many connections exist compared to the number of connections the network could sustain	structural stability or evolution of the network	shortest connecting path to the disruptive event

Table B. 6 continued

Reference	Network size	Density or geographic dispersion	Connectedness and/or flow complexity	Network stability	Node risk and criticality relative to the rest of the network
(Craighead, Blackhurst et al. 2007)	total number of nodes in the network	supply chain density: inversely related to geographical spacing; average inter-node distance	total number of forward, backward, and within-tier material flows		node criticality: value-added by or flowing through the node
(Basole and Bellamy 2014)	network size; number of nodes that can be reached in each tier				betweenness centrality: amount of control a node exerts over the interactions of other firms in the network; the node's use as an intermediate connection
(Revilla and Sáenz 2014)					geographic location; required interaction across national cultures
(Kovács 2009)					geographic location; challenges specific to certain regions such as available infrastructure, risk exposures common to the region
(Pettit, Croxton et al. 2013)	number of members in the supply chain	decentralization of customer base degree of outsourcing; global distribution of supply chain distributed capacity and assets distributed decision making decentralized sourcing of key inputs			
(Blackhurst, Dunn et al. 2011)	number of nodes in the supply chain; supply chain length	geographic clustering			volatility of supplier's location
(Yusuf, Musa et al. 2014)Yusuf et al. 2014		geographic clustering; involvement in industrial cluster			
(Shao 2013)		geographic dispersion of suppliers, production facilities, distributors, and customers			

Table B. 7: Elements of Power and Dependency

Reference	Resource control	Strength in market	Importance of the component
(Greening and Rutherford 2011)	power of affected node; determined by its preferential access to resources or information prevalence of high-dependency ties; cases where few options exist to renegotiate for access to scarce resources		
(Peck 2005)	availability of switching options	relative strength of organizations	
(Pettit, Croxton et al. 2013)	product differentiation reliance upon specialty sourced components	customer loyalty to products strength and duration of customer relationships effective communication with customers market share financial strength: ability to absorb fluctuations in cash flow strength of brand recognition	
(Sheffi and Rice Jr 2005)		market share; competitive position	
(Adenso-Diaz, Mena et al. 2012)	reliance on single-source supplier		
(Ellis, Henry et al. 2010)	switching costs due to customer-specialization concentration of resource control; few alternative suppliers for the resource		importance of the resource; strategic importance of the sourced component

C Simulation Results Figures

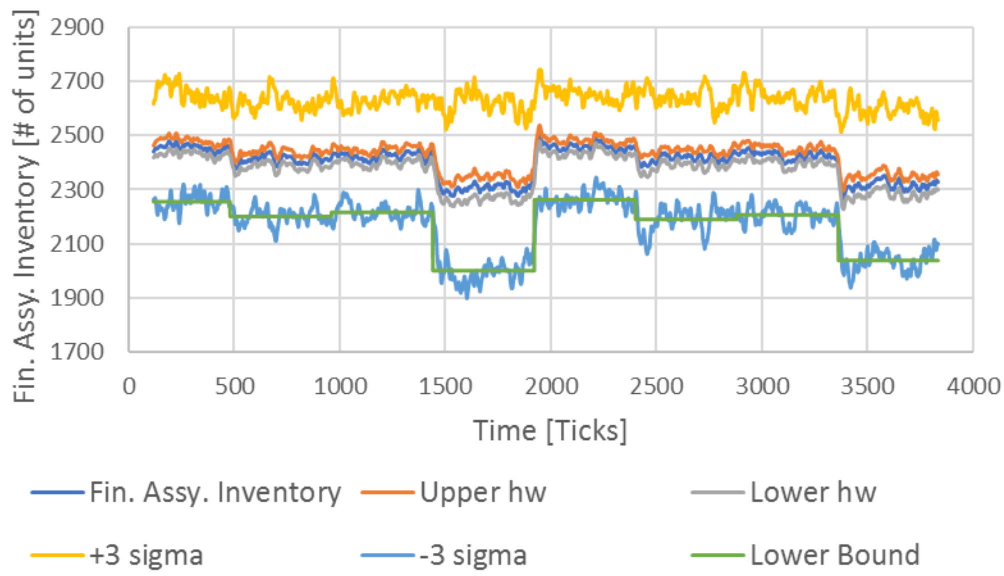

Figure C. 1: Final assembly inventory at DCs: Baseline segmentation method

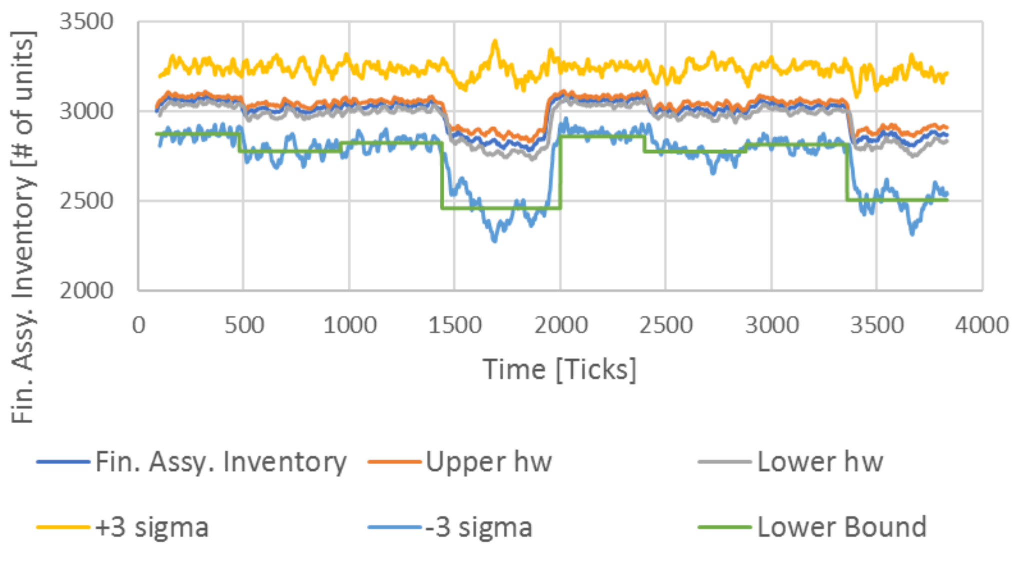

Figure C. 2: Final assembly inventory at DCs: Revised segmentation method

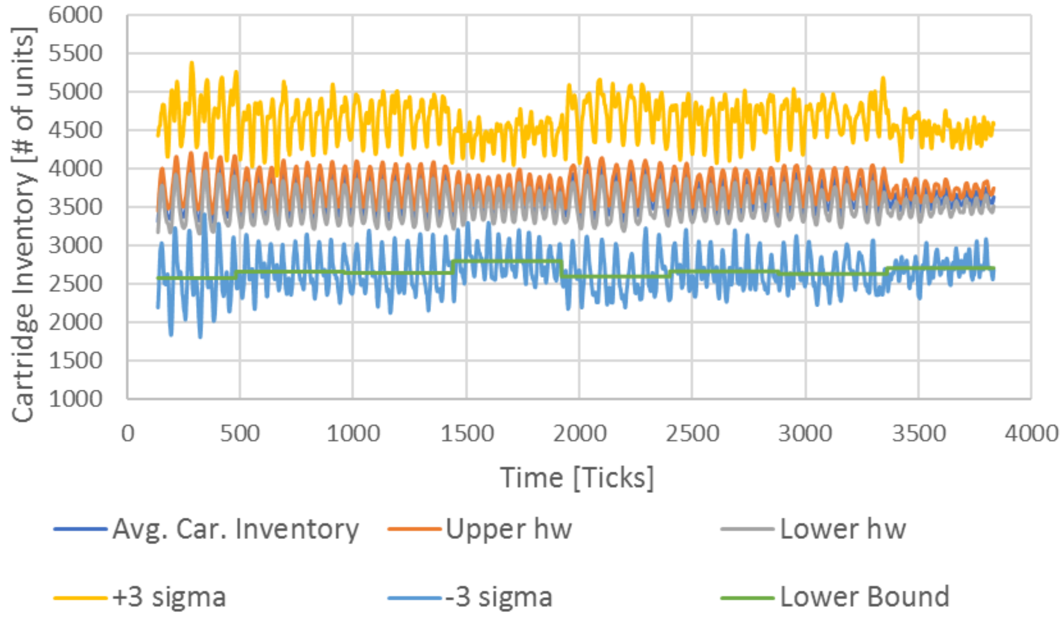

Figure C. 3: Cartridge inventory at DCs: Baseline segmentation method

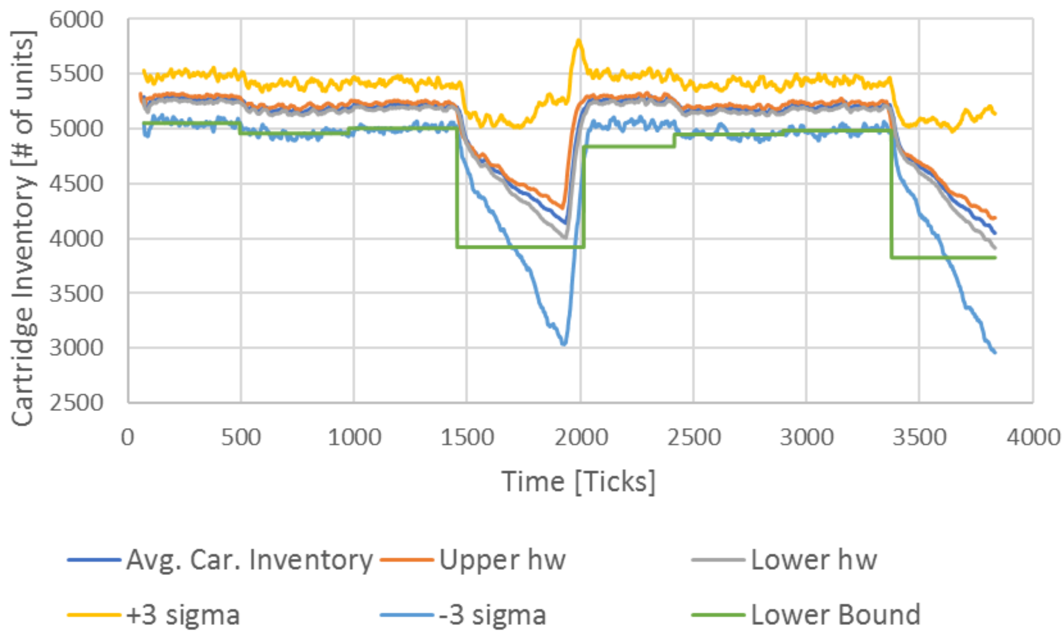

Figure C. 4: Cartridge inventory at DCs: Revised segmentation method

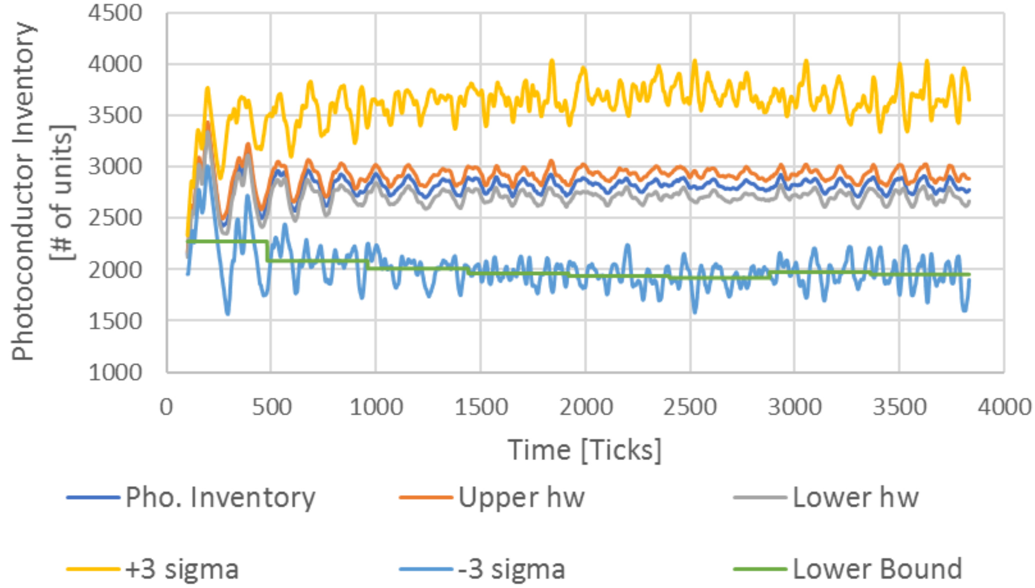

Figure C. 5: Photoconductor inventory at DCs: Baseline segmentation method

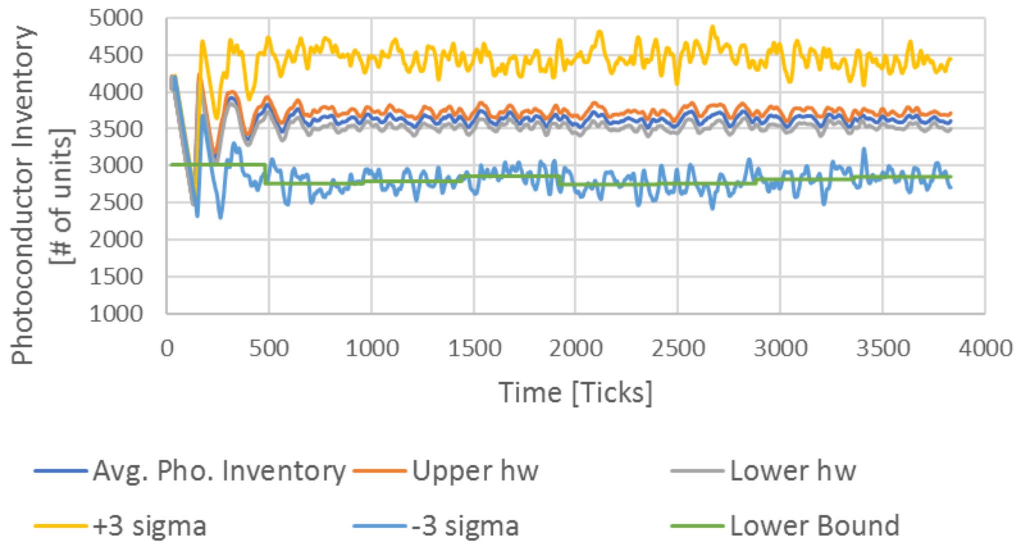

Figure C. 6: Photoconductor inventory at DCs: Revised segmentation method

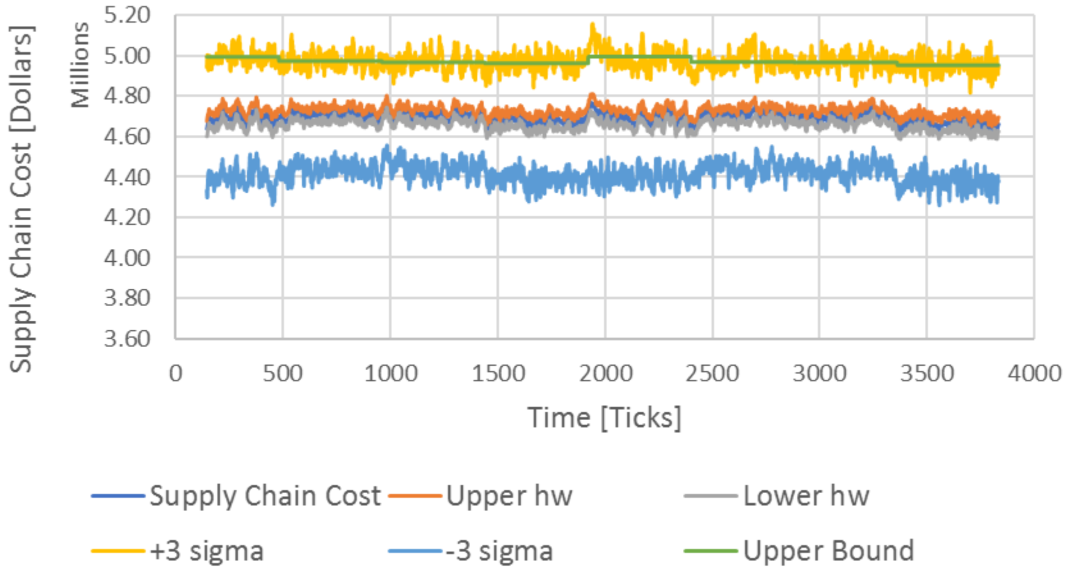

Figure C. 7: Total supply chain cost: Baseline segmentation method

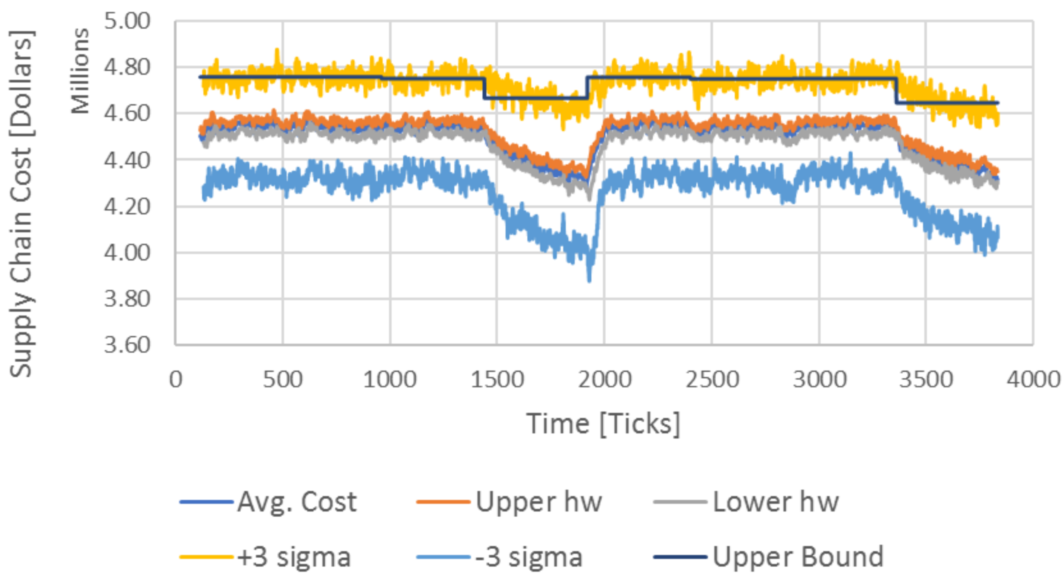

Figure C. 8: Total supply chain cost: Revised segmentation method

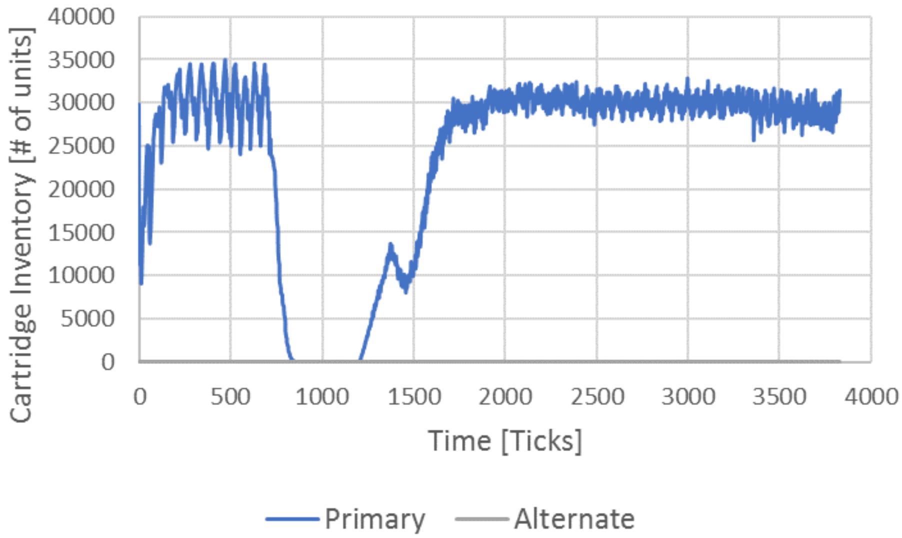

Figure C. 9: Cartridge inventory at cartridge supplier location 1 (Baseline) – cartridge disruption

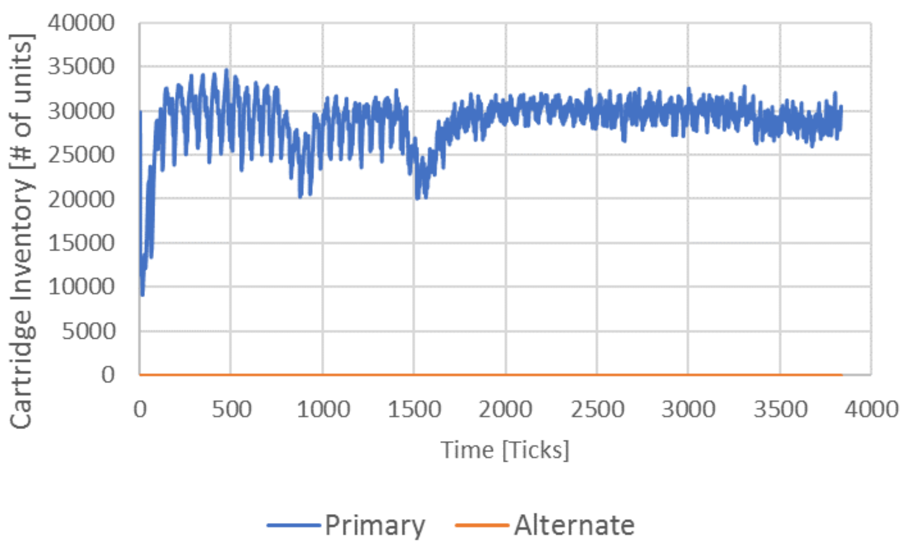

Figure C. 10: Cartridge inventory at cartridge supplier location 2 (Baseline) – Cartridge disruption

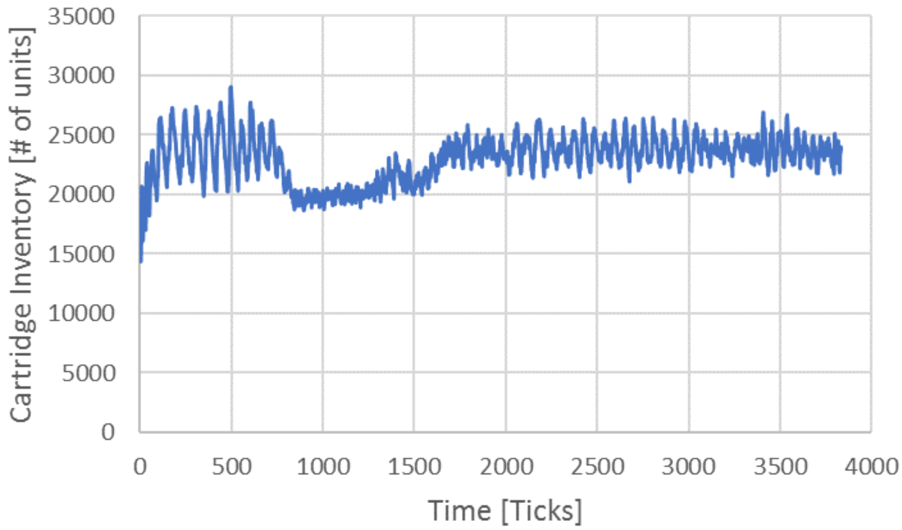

Figure C. 11: Cartridge inventory at final assembly (Baseline) – cartridge disruption

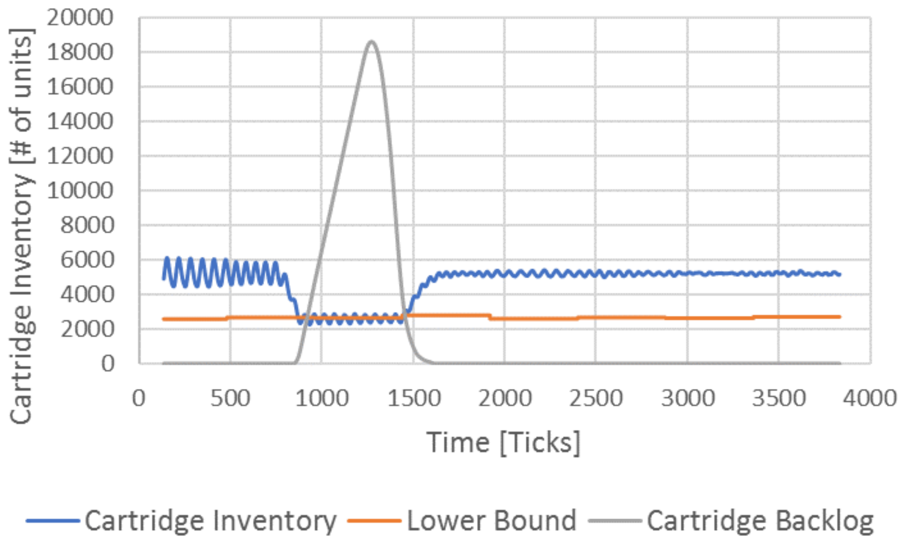

Figure C. 12: Cartridge inventory at DCs (Baseline) – cartridge disruption

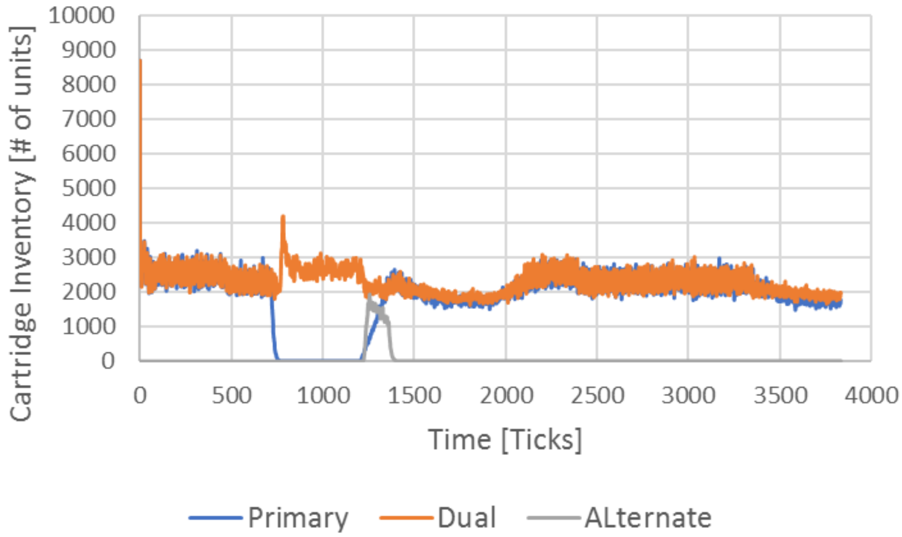

Figure C. 13: Cartridge inventory at cartridge supplier location 1 (Revised) – cartridge disruption

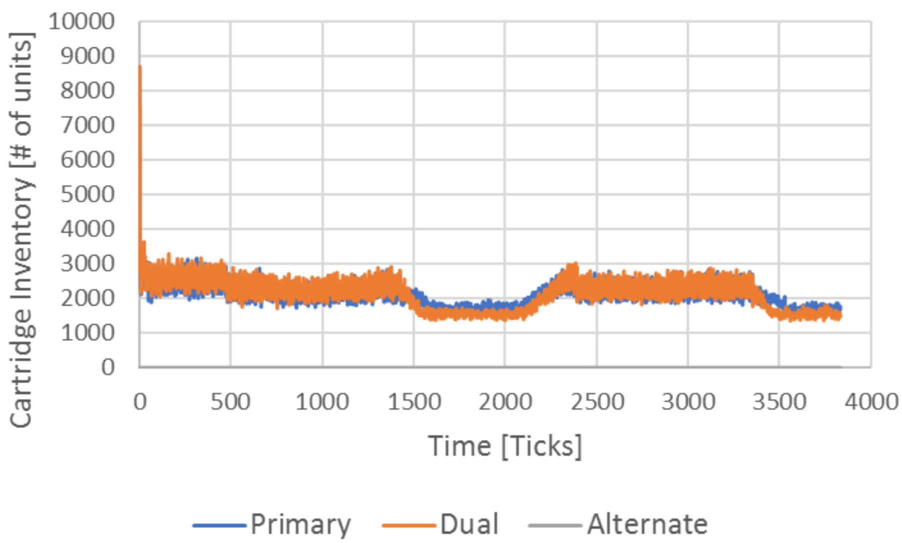

Figure C. 14: Cartridge inventory at cartridge supplier location 2 (Revised) – cartridge disruption

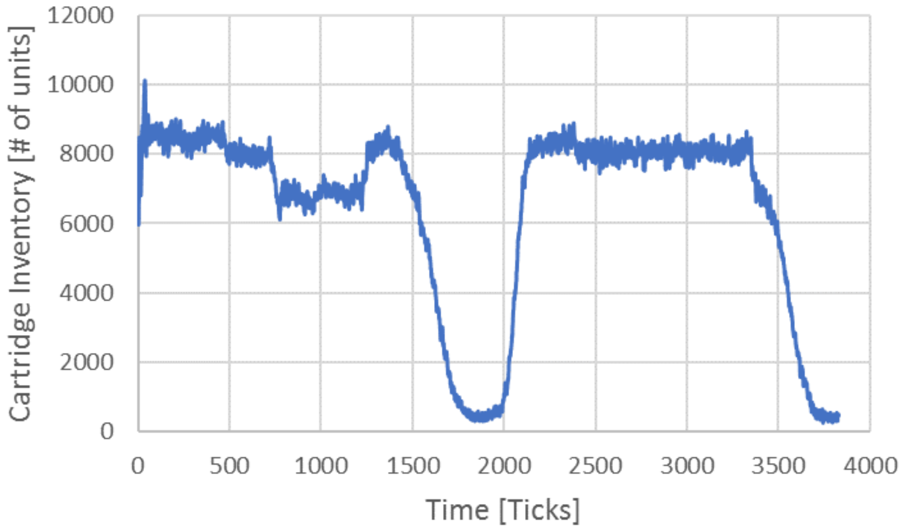

Figure C. 15: Cartridge inventory at final assembly (Revised) – cartridge disruption

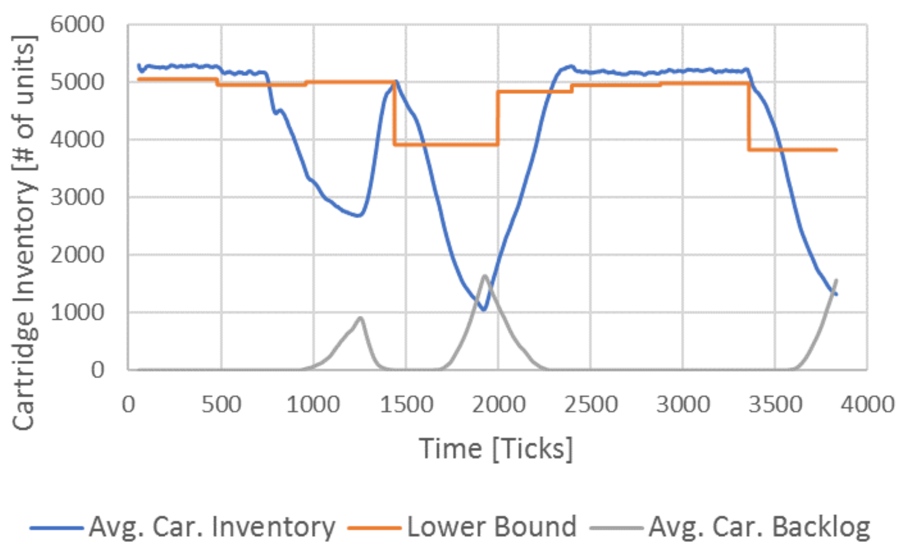

Figure C. 16: Cartridge inventory at DCs (Revised) – cartridge disruption

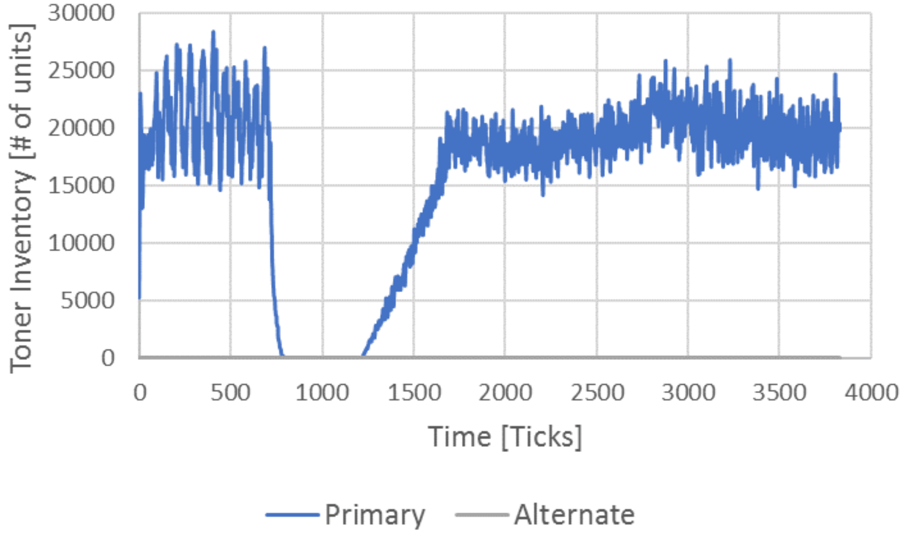

Figure C. 17: Toner inventory at toner supplier (Baseline) – toner disruption

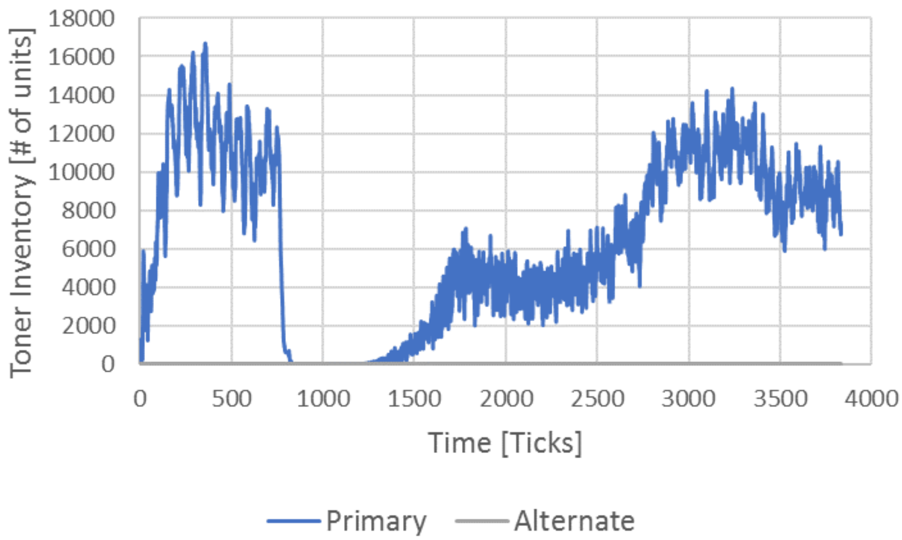

Figure C. 18: Toner inventor at cartridge supplier location 1 (Baseline) – toner disruption

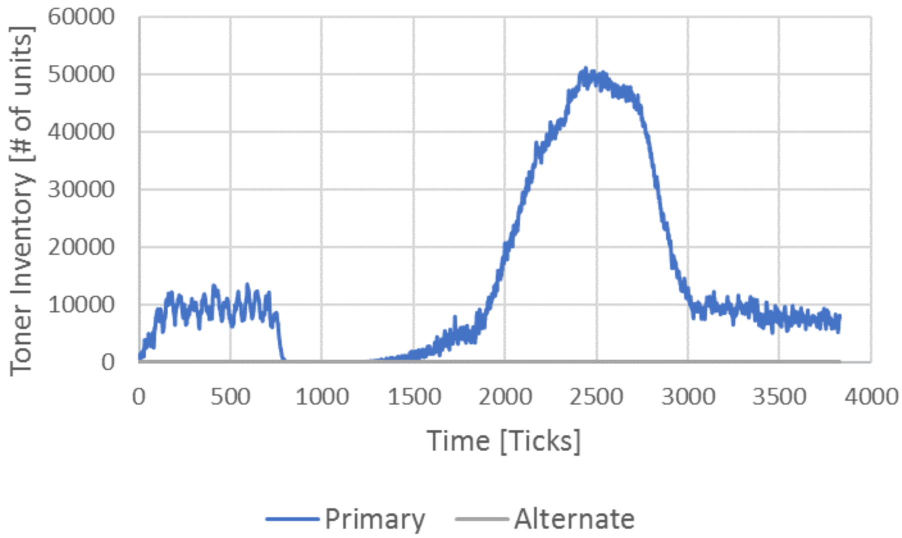

Figure C. 19: Toner inventory at cartridge supplier location 2 (Baseline) – toner disruption

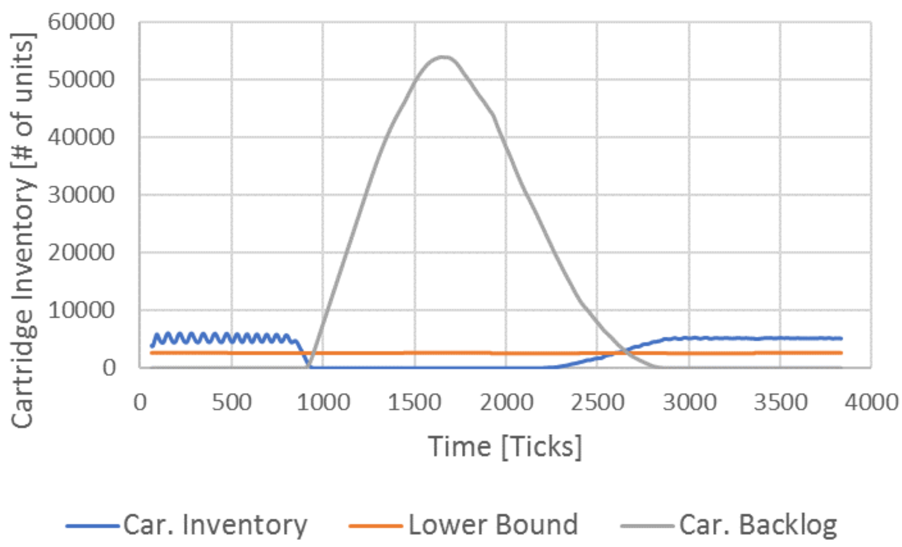

Figure C. 20: Cartridge inventory at DCs (Baseline) – toner disruption

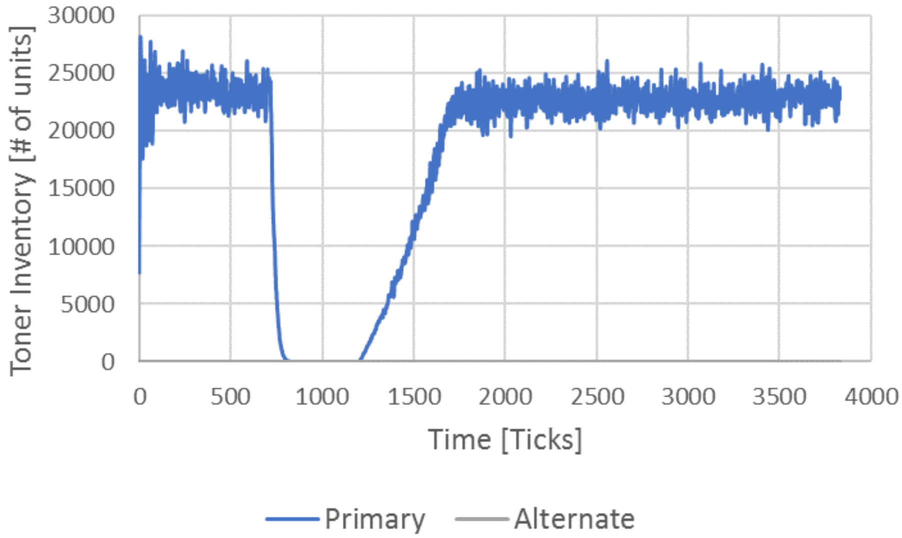

Figure C. 21: Toner inventory at toner supplier (Revised) – toner disruption

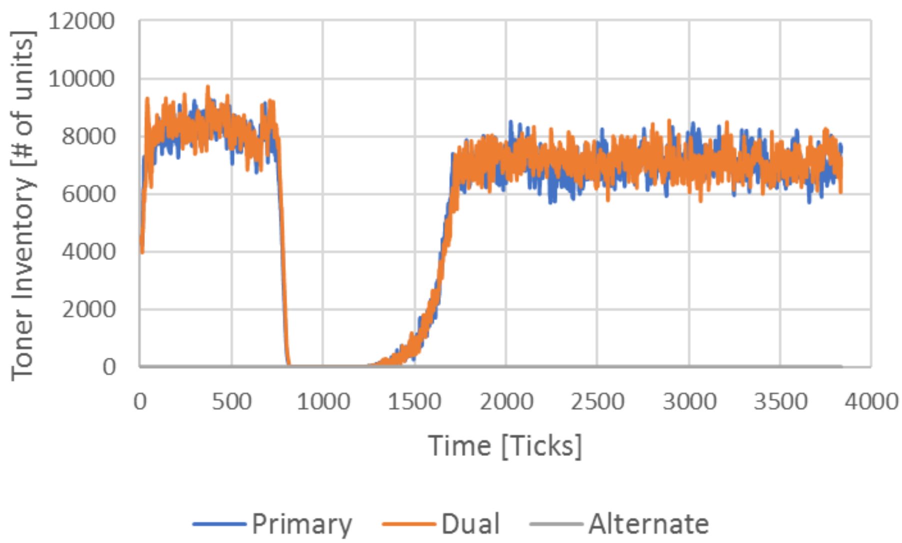

Figure C. 22: Toner inventory at cartridge supplier location 1 (Revised) – toner disruption

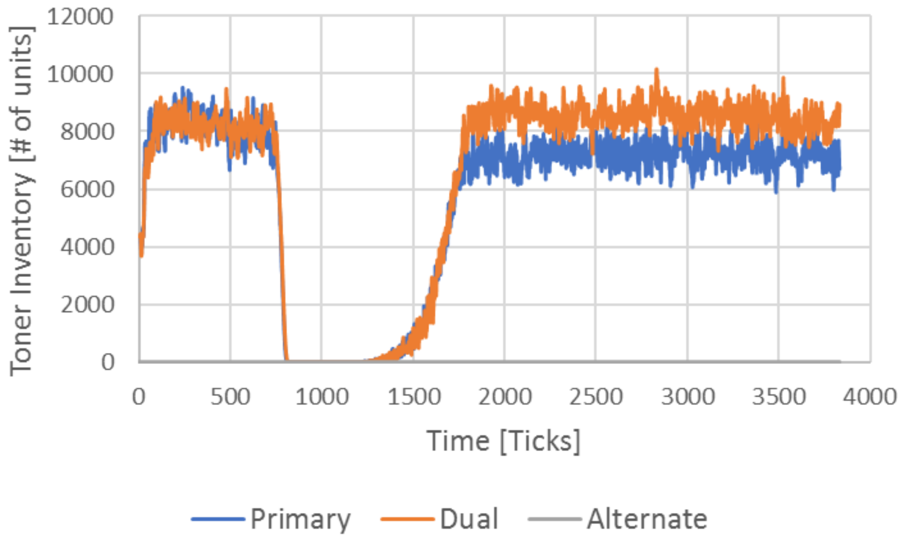

Figure C. 23: Toner inventory at cartridge supplier location 2 (Revised) – toner disruption

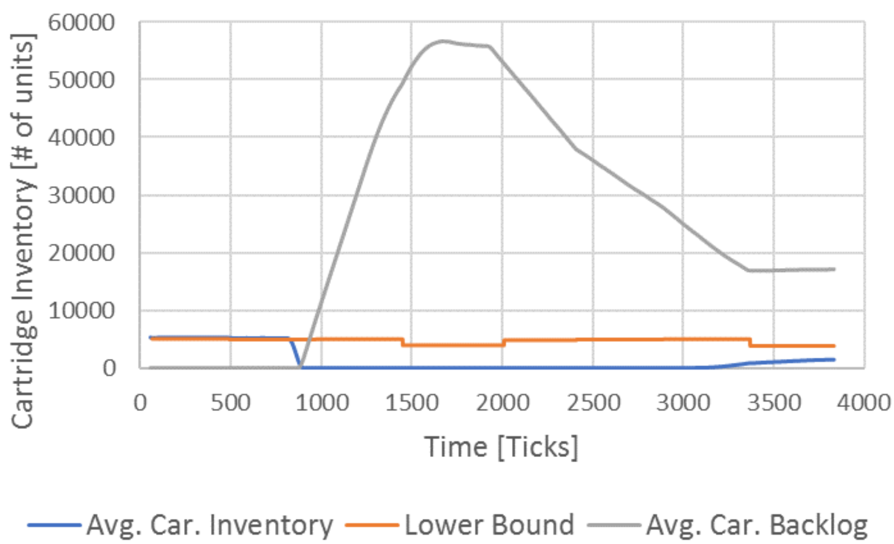

Figure C. 24: Cartridge inventory at DCs (Revised) – toner disruption

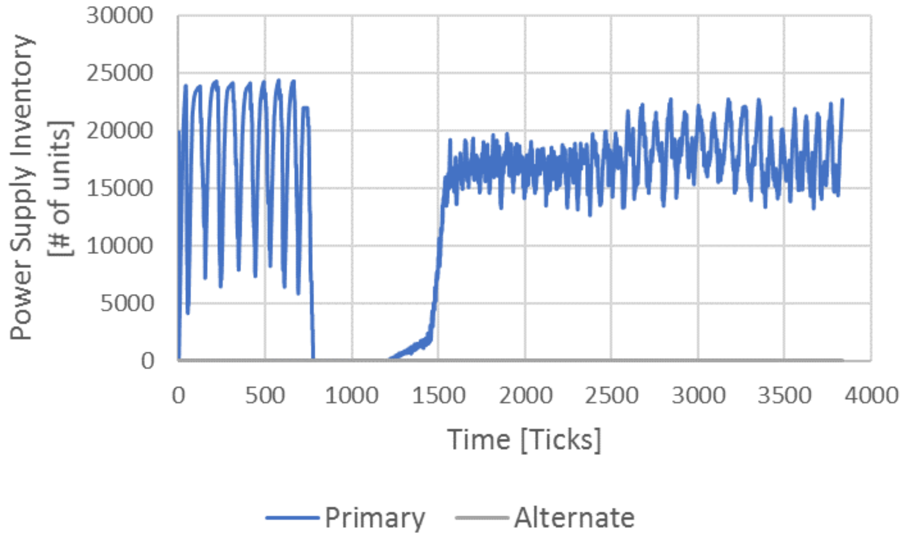

Figure C. 25: Power supply inventory at power supply supplier (Baseline) – power supply disruption

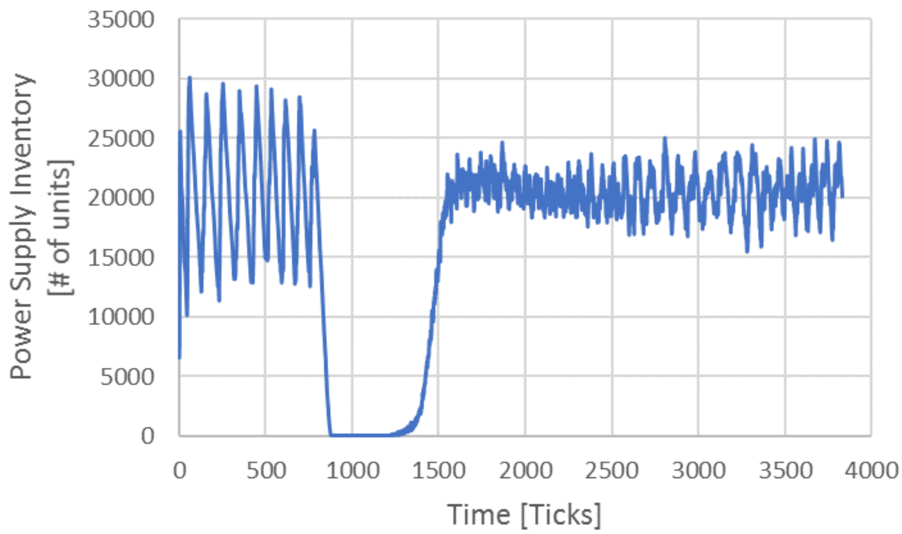

Figure C. 26: Power supply inventory at final assembly (Baseline) – power supply disruption

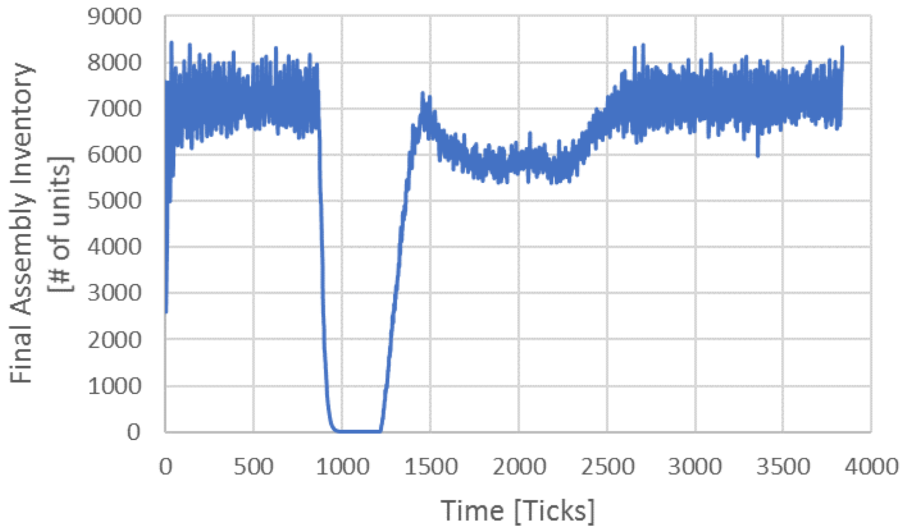

Figure C. 27: Final assembly inventory at final assembly (Baseline) – power supply disruption

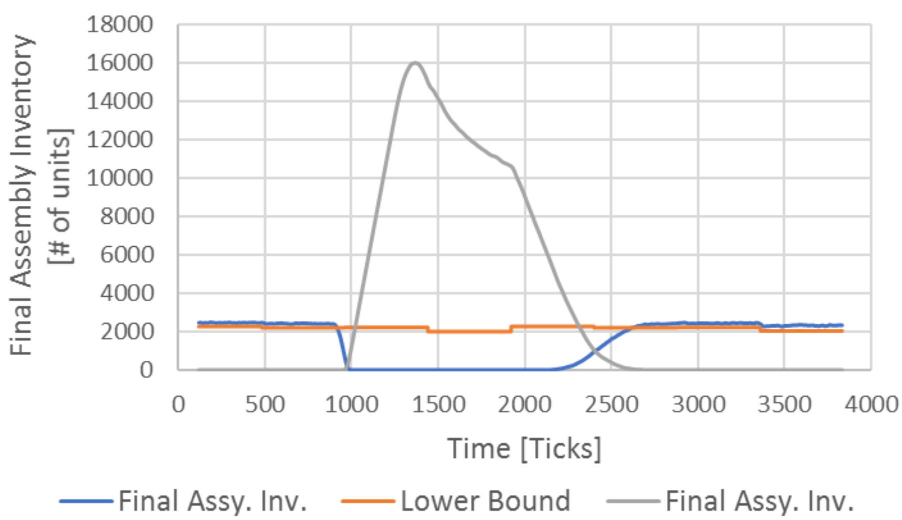

Figure C. 28: Final assembly inventory at DCs (Baseline) – power supply disruptions

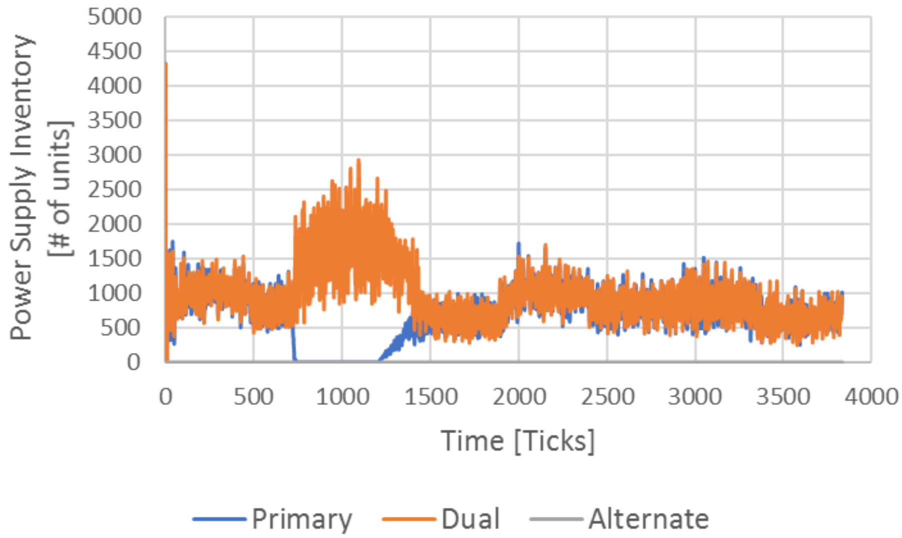

Figure C. 29: Power supply inventory at power supply supplier (Revised) – power supply disruption

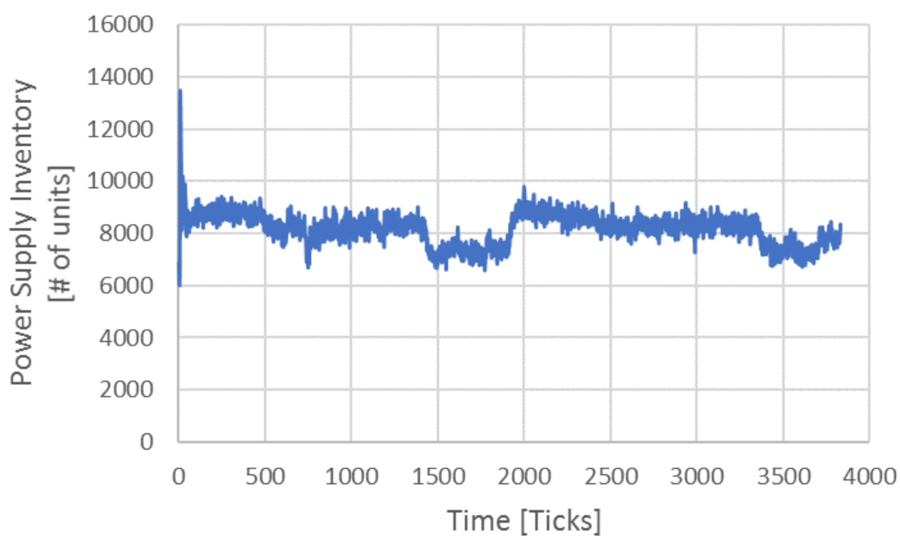

Figure C. 30: Power supply inventory at final assembly (Revised) – power supply disruption

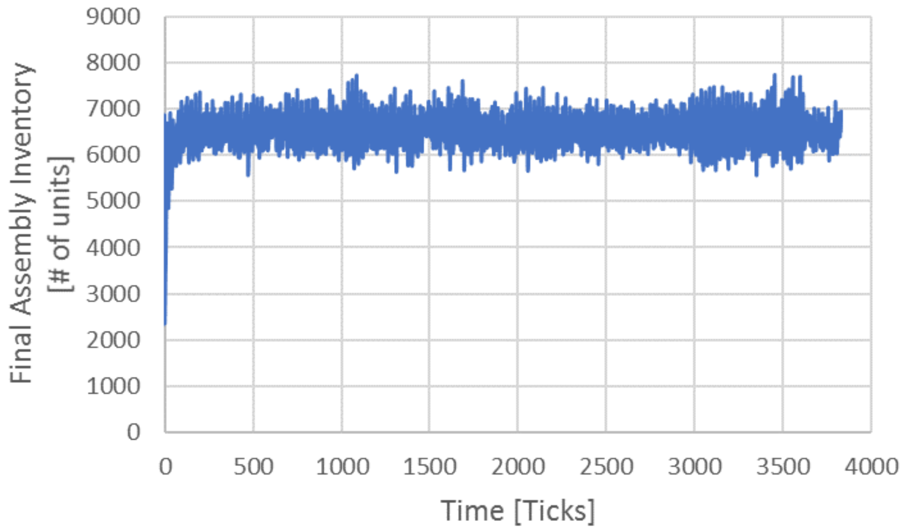

Figure C. 31: Final assembly inventory at final assembly (Revised) – power supply disruption

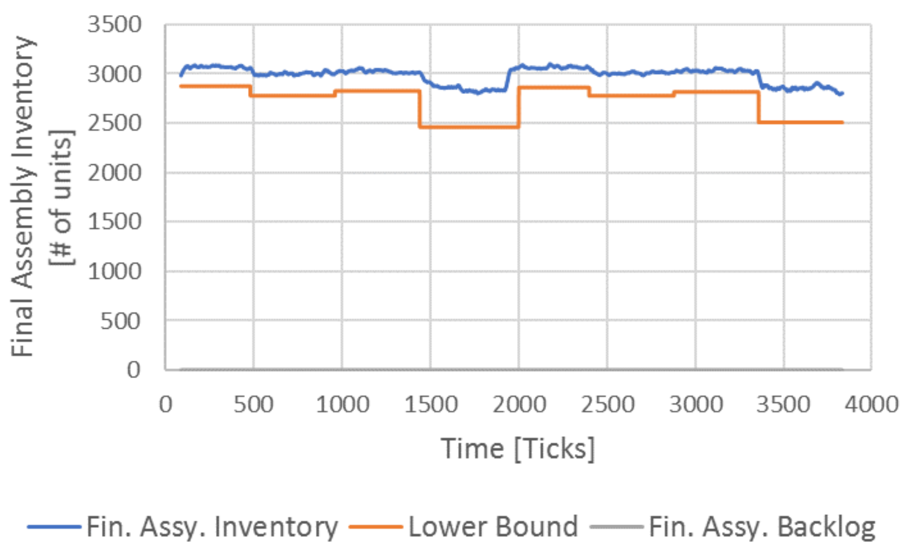

Figure C. 32: Final assembly inventory at DCs (Revised) – power supply disruption

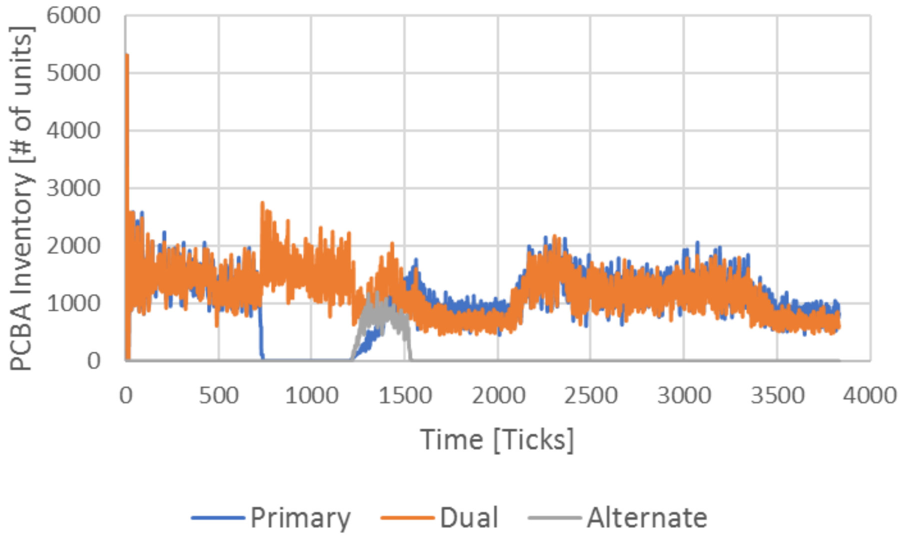

Figure C. 33: PCBA inventory at PCBA supplier (Baseline) – PCBA disruption

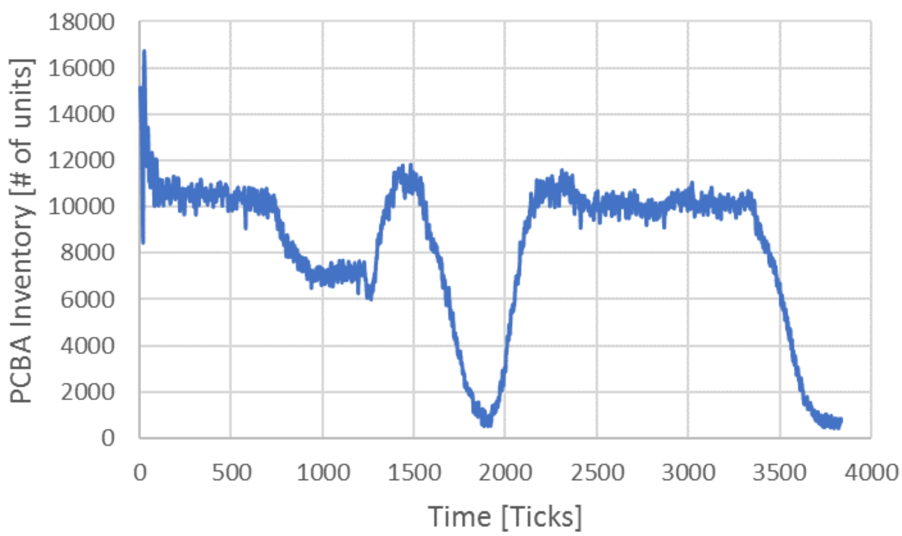

Figure C. 34: PCBA inventory at final assembly (Baseline) – PCBA disruption

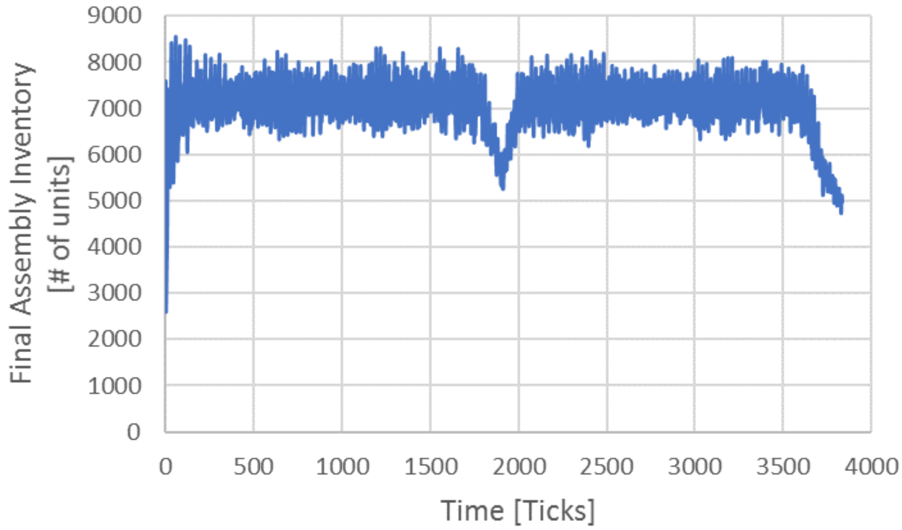

Figure C. 35: Final assembly inventory at final assembly (Baseline) – PCBA disruption

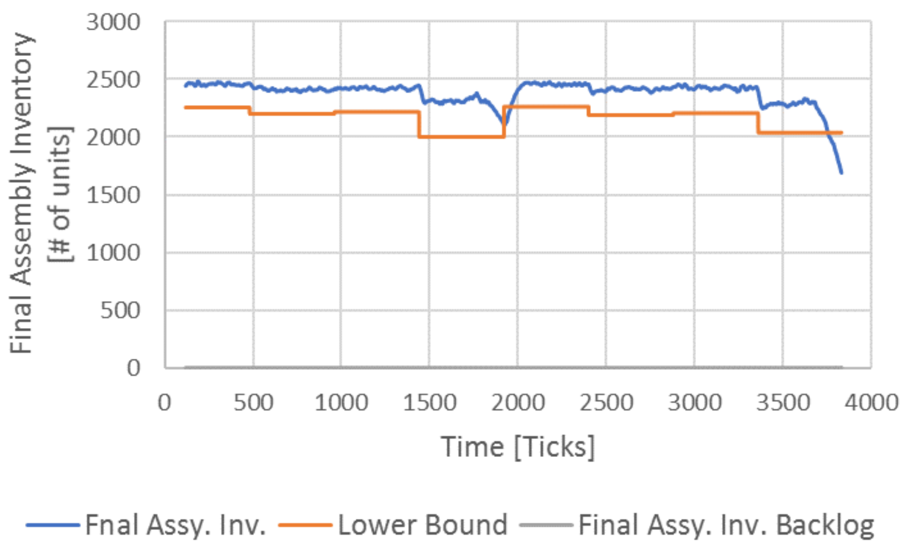

Figure C. 36: Final assembly inventory at DCs (Baseline) – PCABA disruption

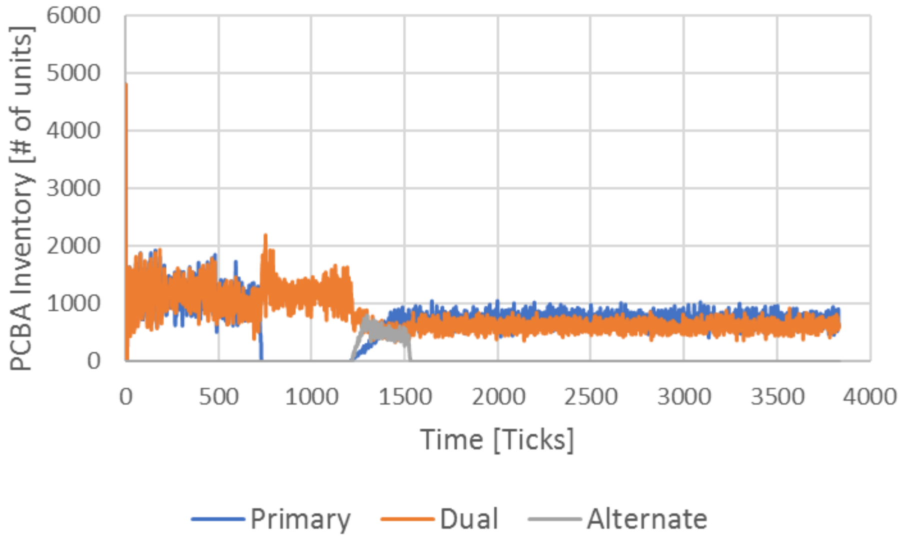

Figure C. 37: PCBA inventory at PCBA supplier (Revised) – PCBA disruption

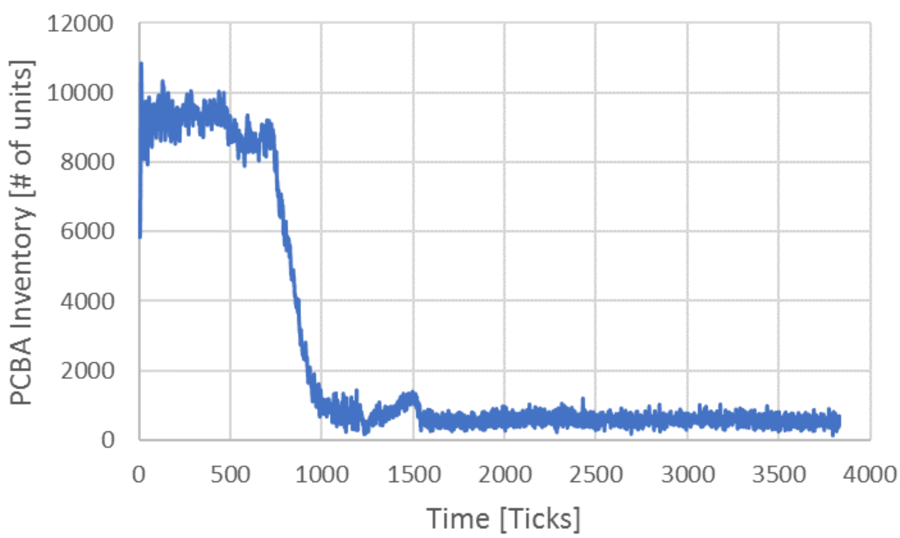

Figure C. 38: PCBA inventory at final assembly (Revised) – PCBA disruption

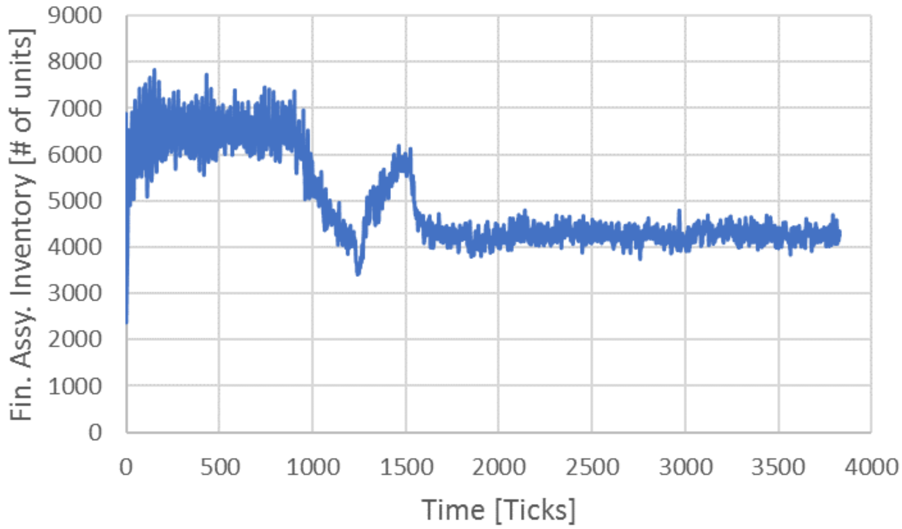

Figure C. 39: Final assembly inventory at final assembly (Revised) – PCBA disruption

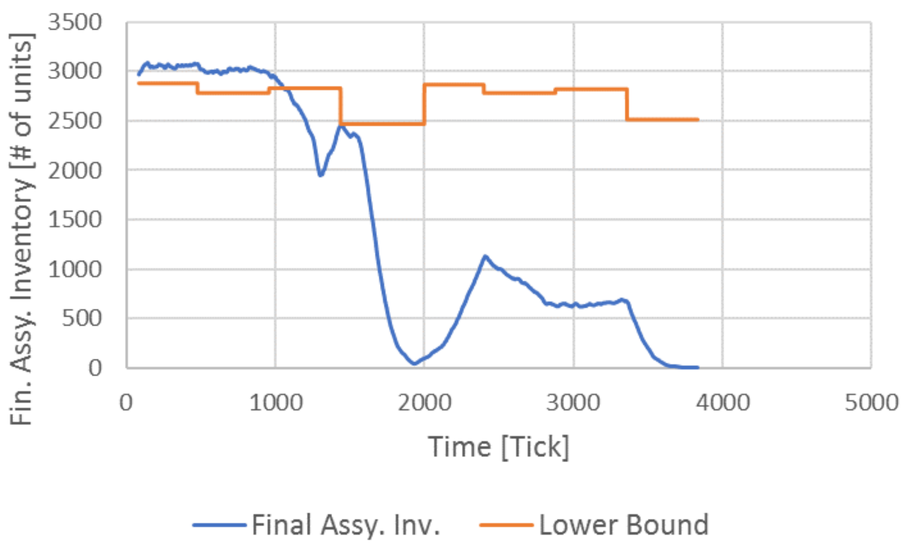

Figure C. 40: Final assembly inventory at DCs (Revised) – PCBA disruption

D Simulation User Guide

D.1 Overview of Data Input Files

Before opening the NetLogo model, several data input files should be updated and saved. Each of the following input files should be saved in the same folder as the main NetLogo (.nlogo) file. The data should be edited in the Excel workbook "network_Lexmark(7)" and copied into the appropriate text files.

initial.txt

Most of the inputs to the simulation model are read from the text file "initial.txt". The information is edited in the Excel worksheet titled "initial node vars." Table D. 1 describes all the data input categories that must be completed in this initialization file. Each variable must be assigned a value for each node-type agent. Each variable must be assigned a value even if the corresponding node-type agent is to remain inactive throughout the simulation. For example, the main fuser node, the secondary fuser node, and the alternate fuser node must be assigned an initial displays inventory of 0 at initialization although its value will not change since no displays are ever sent to or requested from the fuser node.

Table D. 1: Node initialization variables

Variable Name	Description
"inv_DIS"	Inventory of displays at simulation start
"inv_ASI"	Inventory of ASICS at simulation start
"inv_POW"	Inventory of power supplies at simulation start
"inv_DCM"	Inventory of DC motors at simulation start
"inv_FUS"	Inventory of fusers at simulation start
"inv_PAC"	Inventory of packaging materials at simulation start
"inv_LSU"	Inventory of LSUs at simulation start
"inv_SCA"	Inventory of scanners at simulation start
"inv_PHO"	Inventory of photoconductors at simulation start
"inv_PLA1"	Inventory of plastic parts (for main printer assembly) at simulation start
"inv_PLA2"	Inventory of plastic parts (for toner cartridge) at simulation start

Table D. 1 continued

Variable Names	Descriptions
"inv_GEA1"	Inventory of gears (for main printer assembly) at simulation start
"inv_GEA2"	Inventory of gears (for toner cartridge) at simulation start
"inv_TON"	Inventory of toner at simulation start
"inv_PCB"	Inventory of PCBAs at simulation start
"inv_CAR"	Inventory of toner cartridges at simulation start
"inv_FIN"	Inventory of final assemblies at simulation start
"full_cap"	Full production capacity of the node, maximum the node can output in 1 tick
"full_cap2"	Full production capacity of the node for secondary production type (only needed for gears and plastic parts nodes which have 2 types of production)
"hidden?"	True if node is visible (active) and False otherwise
"actives"	# of active trucks (not including hidden trucks) at the node
"doh"	desired on-hand inventory
"doh2"	desired on-hand inventory of secondary type (only needed for nodes which make 2 part types)
"buf1"	The lowest amount of inventory desired of raw material type 1, type of material depends on the node
"buf2"	The lowest amount of inventory desired of raw material type 2
"buf3"	The lowest amount of inventory desired of raw material type 3
"buf4"	The lowest amount of inventory desired of raw material type 4
"buf5"	The lowest amount of inventory desired of raw material type 5
"buf6"	The lowest amount of inventory desired of raw material type 6
"buf7"	The lowest amount of inventory desired of raw material type 7
"buf8"	The lowest amount of inventory desired of raw material type 8
"buf9"	The lowest amount of inventory desired of raw material type 9
"buf10"	The lowest amount of inventory desired of raw material type 10
"buf11"	The lowest amount of inventory desired of raw material type 11
"full_alloc"	% of order allocated to node when it is operating at full capacity
"reg_mat cost"	cost of materials per unit during normal operation
"dis_mat_cost"	cost of materials per unit during disruption
"ramp"	the rate at which capacity increases to reach its full capacity from a diminished state, as in after disruption or upon startup
"disruption?"	True if the node will experience a disruption, False otherwise
"dis_start"	Tick count at which the disruption begins
"dis_duration"	Number of ticks the disruption lasts
"alt_startup_delay"	Number of ticks that must elapse before the alternate supplier can activate once it has been signaled to open
"Vis?"	True if the node has visibility into its buyers' production rate
"severity"	percentage of capacity lost when a node is disrupted

truck_cor.txt

The file "truck_cor.txt" file also contains initialization data for truck-type agents including the starting coordinates for the truck-type agents, and whether they should be hidden and inactive. Any time the "initial.txt" file is updated, the truck-type agent information should also be updated in the "truck_cor.txt" file. For example, if a node was using dual sourcing in one scenario, but the strategy was later changed to single sourcing, both the "initial" and "truck_cor" files should be updated to reflect this. Information is edited in the Excel worksheet "new truck cor." Table D. 2 describes all the data input categories that must be completed in this initialization file. It is important to update the "initial node vars" worksheet before copying the data from "new truck cor" since some values are referenced between the two sheets.

Table D. 2: Truck initialization variables

Variable Name	Description
x cor	X coordinate for truck starting position
y cor	Y coordinate for truck starting position
truckload	Maximum number of units a truck can carry
truck hidden?	True if truck is hidden and inactive, False otherwise
speed	Truck speed, represented by the coordinate distance that can be covered in one tick, value updates each tick based on random-normal to reflect travel time variability
geo distance	The magnitude of transportation time expected between nodes, reflected on a 1-3 scale with 1 corresponding to the shortest time
link lengths	Cartesian distance between two connected nodes
Mu	Average # of ticks the truck will require to cover the distance to its destination
TT_sigma	Standard deviation of # of ticks the truck will require to cover the distance to its destination

cor.txt

The "cor.txt" file contains the coordinates for each node-type agent. These include suppliers, the final printer assembly, and distribution centers. The file also contains the names of each node which will appear next to the node in the simulation interface. This information is only input once when the network configuration is defined. The coordinates are set up to evenly distribute the nodes and to avoid the crossing of links between nodes.

The transportation time between nodes is not affected by the cartesian distance between nodes, but instead is controlled by adjusting the speed of the truck-type agents in proportion to the distance that must be covered in the simulation space. Information is edited in the excel worksheet “coordinates.” Table D. 3 describes the data required for the “cor.txt” file.

Table D. 3: Node coordinate variables

Variable Name	Description
x-cor	X coordinate for node position
y-cor	Y coordinate for node position
name	Name to be displayed next to the node, eg. “Displays”

network.txt

The “network.txt” file defines the linkages between nodes. It is oriented in the form of a from-to matrix. If a 1 is found in the matrix, a directed link is made from the node listed in the row to the node listed in the intersecting column. If a 0 is found, no link is made. After the initial setup, this information is not changed. Links may hide or unhide in coordination with the status of the connected nodes. The information is input in the excel worksheet “links from to.” An example from-to matrix is displayed in Table D. 4. The displays nodes are not linked to the toner nodes, while they are linked to the PCBA nodes. Each node name has three instances in the rows and columns corresponding with the primary, secondary, and alternate suppliers.

Table D. 4: Example from-to matrix for network setup

		Toner	Toner	Toner	PCBA	PCBA	PCBA
0	**Displays**	0	0	0	1	1	1
1	**Displays**	0	0	0	1	1	1
2	**Displays**	0	0	0	1	1	1

demand.txt

As shown in Table D. 5, the "demand.txt" file contains the demand during each period of the simulation for final printer assemblies (FIN), toner cartridges (CAR), and photoconductors (PHO). The file also contains the forecast demand for the next period, one period ahead of the current demand, which the distribution centers use to place orders. The information is edited in the excel worksheet "Demand_extended." In each case the demand values are taken as the average of a normally distributed variable, and the actual demand during each cycle is sampled from the distribution. The forecast value is assumed equal to the average of the demand distribution, and is always read once cycle ahead of the demand. The average demand varies from quarter to quarter, but remain constant within each quarter. Sufficient data should be input to last for a two-year run period.

Table D. 5: Example demand data

				DC1					
quarter	**day**			**FIN**	**forecast**	**CAR**	**forecast**	**PHO**	**forecast**
1	1	tick 8	cycle 1	0	336	0	672	0	134.4
1	2	tick 16	cycle 2	336	336	672	672	134.4	134.4
1	3	tick 24	cycle 3	336	336	672	672	134.4	134.4
1	4	tick 32	cycle 4	336	336	672	672	134.4	134.4
. . .									
4	479	tick 3832	cycle 479	480	336	960	672	192	134.4

Two use cases for the simulation are described. First, a one-time simulation run is performed with no disruptions. The one-time run does not output any data files, but is useful for troubleshooting and demonstration. Next, a multi-replication run is performed for a disruption scenario. For the multi-replication case, the built-in BehaviorSpace tool is used to output the KPI data at each tick to a csv file which can is then used for plotting in Excel.

D.2 Simulation Use-Case 1: Single run with no disruptions

1. “disruption?” column in initial node vars worksheet should read FALSE for all nodes.
    a. No disruptions should occur in this scenario
2. Copy current data into “initial.txt” and “truck_cor.txt”
    a. Copy only data, no column or row header information
    b. Do not copy data highlighted in yellow, which is for reference only
3. Open NetLogo file, “Printer_SC_rev26_baselinebounds_extended_revD” or “Printer_SC_rev27_revisedbounds_extended_revD” corresponding to the input data
    a. “Baselinebounds” is set up for the baseline segmentation method, and “Revisedbounds” is set up for the revised segmentation method
    b. The two NetLogo files, “Baselinebounds” and “Revisedbounds” differ in the values for normal operating bounds, which can be noted in the check-RR procedure in the code tab and in the moving average plots, as in Figure D. 1, found in the bottom right of the simulation interface
    c. Files also differ in network setup and node capacity
    d. Static dataset can be copied from worksheets “initial Revised_Scaled” or “initials Baseline_Scaled” into “intial_node_vars”
    e. Any temporary data changes should only be made in “initial_node_vars” sheet

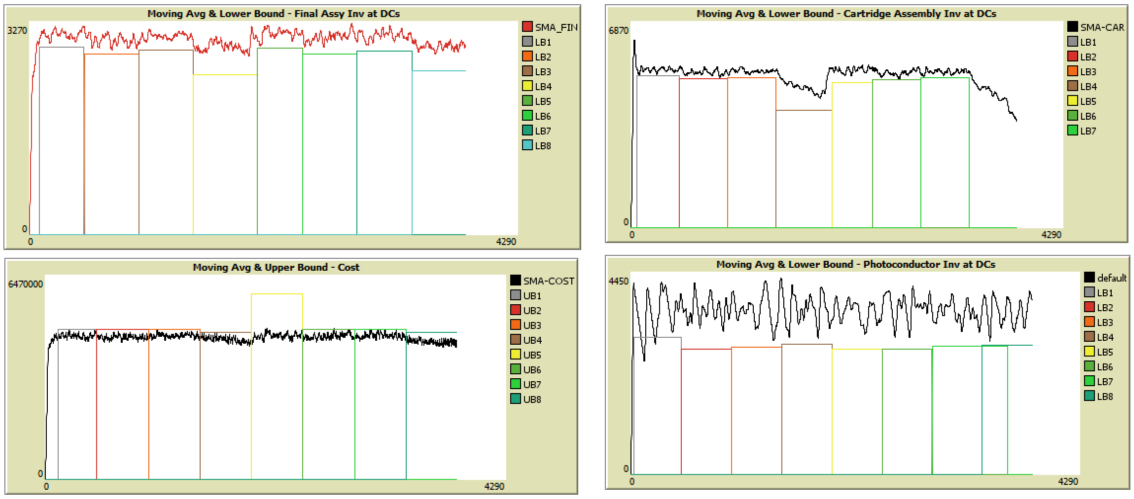

Figure D. 1: Moving average plot with cartridge inventory lower bound

4. Press setup button or shift+S to setup node and truck agents
5. Pres setup-links button or shift+L to setup links
   a. Simulation interface upon opening is shown in Figure D. 2.

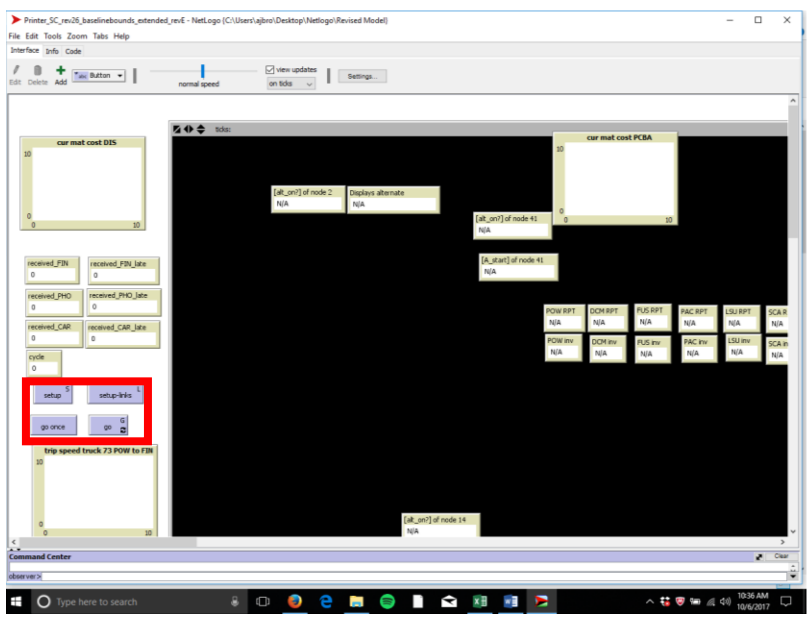

Figure D. 2: Simulation interface upon opening with startup command button highlighted

6. Ensure all trucks are matched with node locations, overlaying yellow house icons
   a. Initial simulation setup with correct truck and node location demonstrated in Figure D. 3

Figure D. 3: Simulation interface showing initial node and truck setup

7. Ensure all nodes are connected with links
    a. Trucks not initialized at an active node location indicates “initial.txt” and/or “truck_cor.txt” file needs to be updated
8. Press go button or shift+G
9. Adjust simulation speed with “normal speed” slider
    a. Mid-range speed is recommended for observing truck behavior and data monitors during troubleshooting
10. For fastest results, maximize the speed slider and turn off “view updates”
11. Simulation will terminate after 2 year run time
    a. Should take approximately five minutes using full speed and no animation updates
12. Observe simulation output
    a. Scroll to far bottom-right in the simulation window to view plots of KPI along with the calculated lower or upper bounds, highlighted in red in Figure D. 4
    b. Observe other plots which include inventory, capacity, and order allocation plots for each node

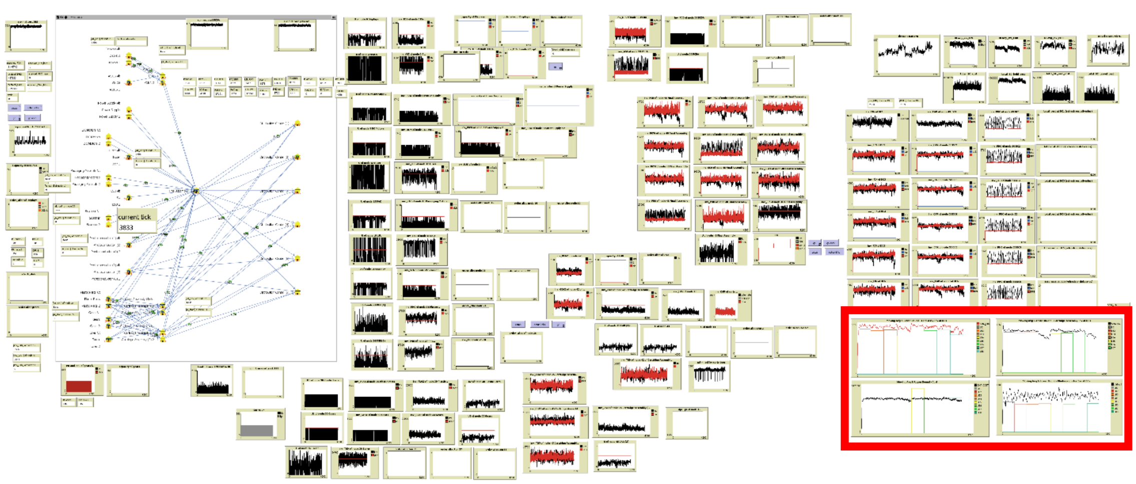

Figure D. 4: Full simulation interface showing all plots and data monitors

D.3 Simulation Use-Case 2: Multi-replication run with a disruption

1. “disruption?” column in initial node vars worksheet should read TRUE for one node which experiences the disruption
    a. Disruption should occur at a primary supplier
    b. Also specify disruption start time, duration, and severity
    c. Data inputs for disruption scenario highlighted in Table D. 6

Table D. 6: Initialization data highlighting inputs for disruption scenario

	"disruption?"	"dis_start"	"dis_duration"	"alt_startup _delay"	"Vis?"	"severity" 0=no capacity; .5=half capacity; 1=full capacity
“Displays”	TRUE	720	480	0	FALSE	0
“Displays 2”	FALSE	3354	0	0	FALSE	1
“Displays Alt”	FALSE	3354	0	480	FALSE	1

2. Copy current data into “initial.txt” and “truck_cor.txt” and open NetLogo file as in previous use-case scenario
3. Open BehaviorSpace in the tools menu or Ctrl+Shift+B
    a. BehaviorSpace menu opens with previous experimental setups, as in Figure D. 5

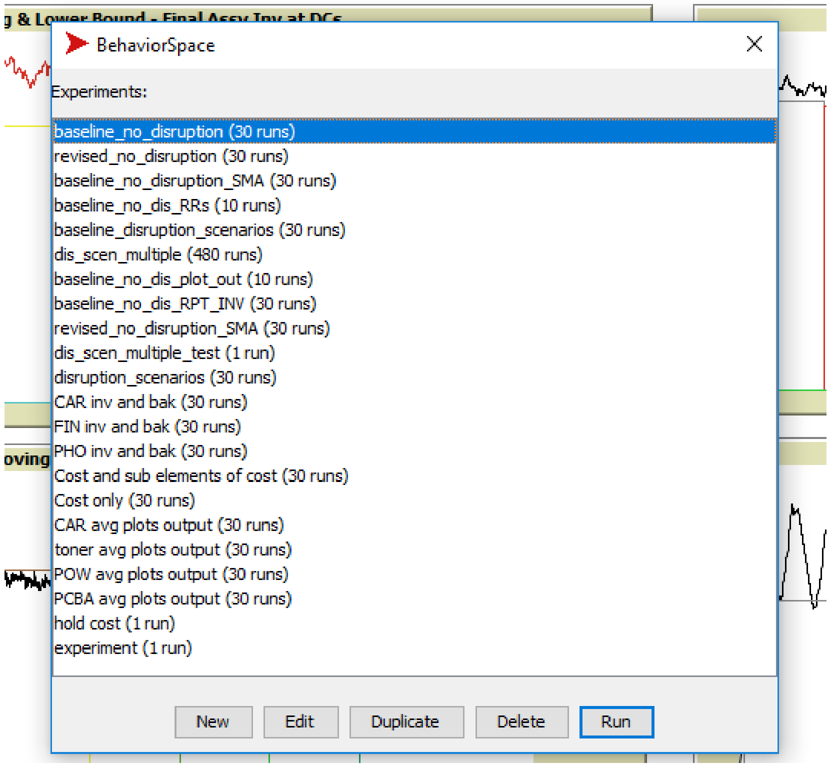

Figure D. 5: BehaviorSpace menu

4. Click edit experiment named “disruption scenarios”
   a. Experiment will run thirty replications and output KPI data at every tick
   b. “disruption scenarios” settings are shown in Figure D. 6

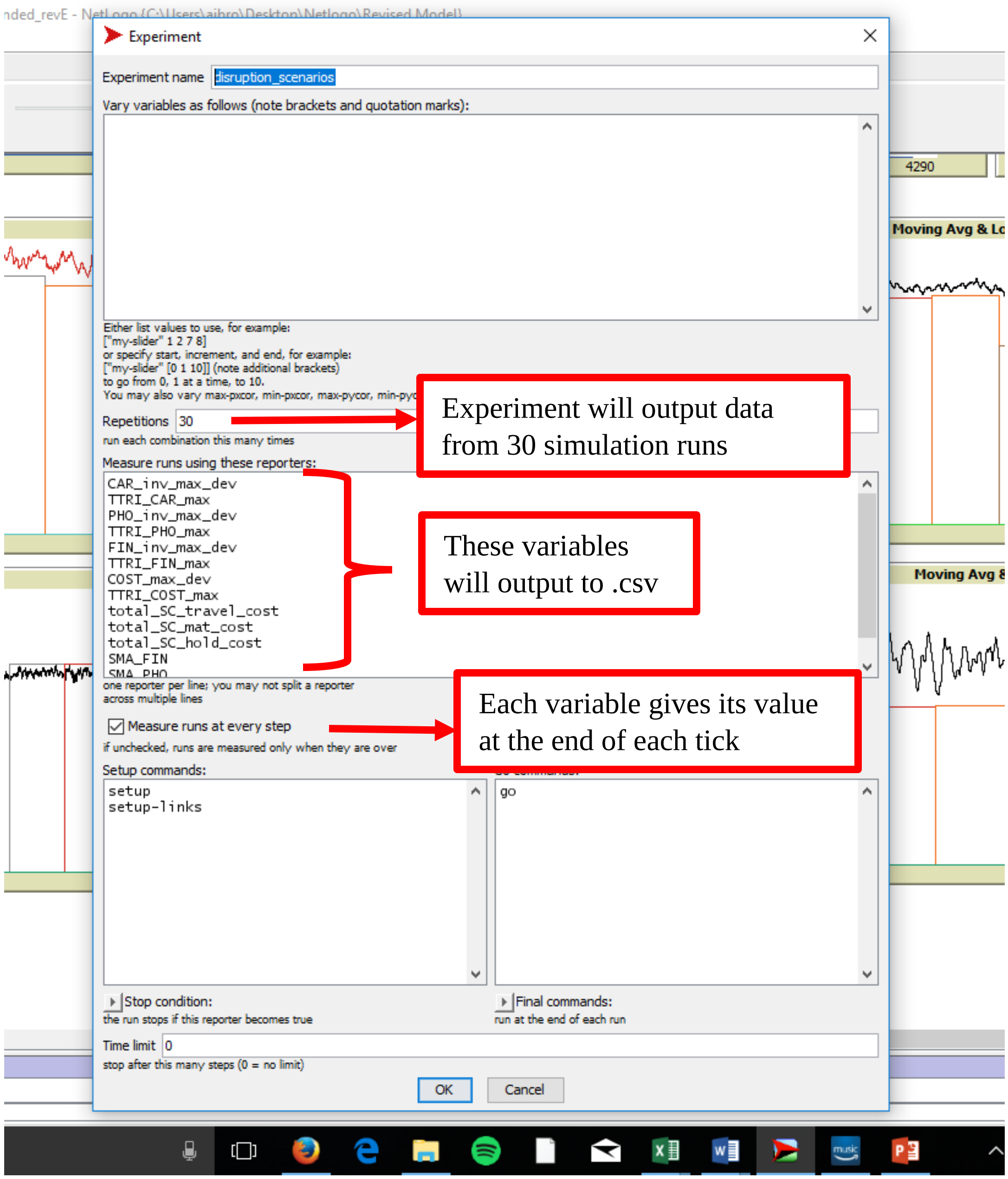

Figure D. 6: disruption scenarios experimental setup

5. Click OK and Run
   a. Select spreadsheet output, as in Figure D. 7
   b. Keep standard, 4 simultaneous simulation runs in parallel
   c. Select name and location for output .csv file

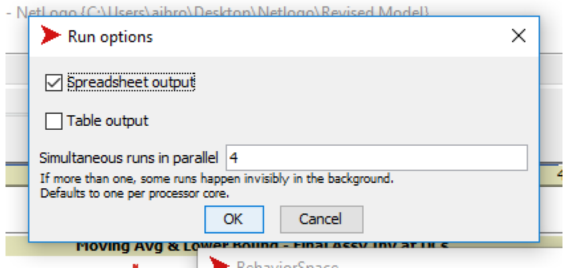

Figure D. 7: BehaviorSpace run options

6. Conduct any additional data formatting and plotting by opening .csv in Excel
   a. After formatting, save as Excel type file

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Journal Publications

1. **Brown, A.**, Amundson, J., Badurdeen, F., 2014, *"Sustainable Value Stream Mapping (Sus-VSM) in Different Manufacturing System Configurations: Application Case Studies",* Journal of Cleaner Production, 85(15), pp. 164-179

2. Badurdeen, F., Shuaib, M., Wijekoon, K., **Brown, A**., Faulkner, W., Amundson, J., Jawahir, I. S., Goldsby, T., Iyengar, D., and Boden, B., 2014, "*Quantitative Modeling and Analysis of Supply Chain Risks using Bayesian Theory*," Journal of Manufacturing Technology Management, 25(5), pp. 631-654

3. **Brown, A.,** Badurdeen, F., *"Structured Literature Review Supporting Development of a Resilience-Oriented Supplier Segmentation Method"*, pending submission to the European Journal of Logistics, Purchasing, and Supply Chain Management

Working Papers

1. Agent-Based Model and Simulation Examining the Effects of Supplier Segmentation on Resilience and Robustness, In preparation for submission to the Journal of Supply Chain Management

2. Development of a Resilience-Enabling Supplier Segmentation Method, In preparation for submission to the Journal of Purchasing & Supply Management

Conference Papers

1. **Brown, A.**, & Badurdeen, F., (2017). *Supplier Segmentation Method for Selection of Resilience-Enabling Procurement Strategies.* Paper accepted for presentation at the Industrial Systems and Engineering Research Conference (ISERC), May 20 – 23, Pittsburgh, PA.
   *** Manufacturing & Design Division Best Track Paper, 3rd Place**
2. Aydin, R., **Brown, A.,** Ali, A., & Badurdeen, F., (2017). Assessment of End-of-life Product Lifecycle *'ilities'.* Paper accepted for presentation at the Industrial Systems and Engineering Research Conference (ISERC), May 20-23, Pittsburgh, PA.
3. **Brown, A**., & Badurdeen, F., (2015). *Increased Supply Chain Resilience through Consideration of Disruption Impact Severity in the Supplier Segmentation Process.* Presented at the Industrial Systems and Engineering Research Conference (ISERC), May 30 – June 2, 2015, Nashville, TN.
4. Badurdeen, F., Baker, J.R., Rouch, K.E., Goble, K.E., Swan, G.M., **Brown, A.,** & Jawahir I.S**.,** (2015). *Development of an Online Master's Degree Program in Manufacturing Systems Engineering*. Proc. 122nd ASEE Annual Conference and Exposition, Seattle, WA, USA, June 14-17, 2015.
5. Badurdeen, F., Sekulic, D., Gregory, B., **Brown, A**., & Fu, H., (2014). *Developing and Teaching a Multidisciplinary Course in Systems Thinking for Sustainability: Lessons Learned through Two Iterations.* Presented at the 121st Annual American Society for Engineering Education Annual Conference & Exposition, June 15-18, 2014, Indianapolis, IN. ***Systems Engineering Division Best Paper Award**
6. **Brown, A**., & Badurdeen, F., (2014). *Supply Chain Disruption Management: Review of Issues and Research Directions.* Presented at the Industrial Systems and Engineering Research Conference (ISERC), May 31 – June 3, 2014, Montreal, Canada.
7. Amundson, J., **Brown, A**., Grabowski, M., & Badurdeen, F., (2014). *Life-cycle risk modeling: alternate methods using Bayesian Belief Networks.* Procedia CIRP, Vol. 17, 2014, pp: 320-325.

8. **Brown, A**., & Badurdeen, F., (2013). *A queuing model for systems with rework and process downtime*. (2013). Presented at the IEEE International Conference on Automation Science and Engineering (CASE), Aug. 17-21, 2013, Madison, WI.
9. **Brown, A,** Amundson, J., & Badurdeen, F., (2013). *Bayesian Informed Simulation for Supply Chain Risk Probability and Impact Assessment.* Presented at the International Conference on Production Research (ICPR), July 28-August 1, 2013**,** Iguazu Falls, Brazil.
10. Amundson, J., **Brown, A**., Shuaib, M., Badurdeen, F., & Goldsby, T., (2013). *Bayesian Methodology for Supply Chain Risk Analysis: Concept and Case Studies*. Presented at the Industrial and Systems Engineering Research Conference (ISERC), May 18-22, 2013, San Juan, Puerto Rico.
11. Badurdeen, F., **A. Brown**, R. Gregory, H. Fu, M. Schroeder, D. Sekulic, L. Vincent, & G. A. Luhan, (2013). *Reframing Interdisciplinary Approaches to Systems Thinking for Sustainability*. Proc. International Symposium on Sustainable Systems & Technologies (ISSST), May 15 – 17, 2013, Cincinnati, OH USA.
12. **Brown, A**., & Badurdeen, F., (2011). *Optimization of queuing theory wait time through multi-skilled worker assignments*. Presented at the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Dec. 6-9, 2011. ***Conference paper award, honorable mention**

<u>Conference Presentations with Refereed Abstracts</u>

1. Aydin, R., **Brown, A.** & Badurdeen, F., (2017). *Total Lifecycle Product Design Optimization*, Submitted for the International Congress on Sustainability Science and Engineering (ICOSSE '17), October 2-4, 2017, Barcelona, Spain.
2. Amundson, J., Badurdeen, F., & **Brown, A.,** (2015). *Quantitative modeling to assess total life-cycle risk implications across the supply chain for sustainable manufacturing decision making*. Presented at the International Congress on Sustainability Science and Engineering (ICOSSE), Balatonfured, Hungary, May 26-29, 2015.
3. Badurdeen, F., **A. Brown**, J. Amundson, & S. Roberts, (2013). *Manufacturing Sustainability Evaluation through Sustainable Value Stream Mapping (Sus-VSM): Approach and Case Study*. Presented at the International Congress on Sustainability Science and Engineering (ICOSSE), August 11-15, 2013, Cincinnati, OH.
4. Badurdeen, F., Gregory, R., Luhan, G., Schroder, M., Sekulic, D., Vincent, L., **Brown, A.** & Fu, H., (2013). *Systems Thinking for Sustainability: Experiences from Developing and Teaching a Multi-*

disciplinary Course. Presented at the Kentucky Innovations Conference, May 16-17, 2013, Lexington, KY, USA.

<u>Posters</u>

1. **Brown, A.,** & Badurdeen, F., (2017). *Resilience Assessment in the Context of a Laser Printer Supply Chain: Comparison of Two Supplier Segmentation Methods.* Presented at the University of Kentucky Mechanical Engineering Student Research Showcase, Lexington, KY. ***Outstanding student poster award**
2. **Brown, A.,** & Badurdeen, F., (2017). *Resilience Assessment in the Context of a Laser Printer Supply Chain: Comparison of Two Supplier Segmentation Methods.* Presented at the University of Kentucky Gatton College of Business and Economics 7th Annual Supply Chain Forum: Managing Risks in the Supply Chain
3. **Brown, A.,** & Badurdeen, F., (2016). *Supplier Relationship Management as a Tool for Increased Supply Chain Resiliency and Sustainability.* Presented at the Tracy Farmer Institute for Sustainability and the Environment (TFISE) 5th Annual Sustainability Forum, Lexington, KY.
4. **Brown, A.,** & Badurdeen, F., (2016). *Supplier Relationship Management as a Tool for Increased Supply Chain Resiliency and Sustainability.* Presented at the Institute for Sustainable Manufacturing 5th International Forum on Sustainable Manufacturing, Lexington, KY.
5. **Brown, A,** & Badurden, F., (2016). *Supplier Segmentation for Increased Resilience: Development of an Agent-Based Simulation to Examine Trade-offs between Supply Chain Resilience and Normal Operating Cost.* Presented at the University of Kentucky Mechanical Engineering Graduate Student Research Showcase, Lexington, KY.
6. **Brown, A.**, & Badurdeen, F., (2015). *Assessing Effects of Supplier Relationship Management Strategies on Supply Chain Resiliency, Efficiency, and Sustainability Performance Trade-Offs*. Presented at International Congress on Sustainability Science and Engineering (ICOSSE), Balatonfured, Hungary.
7. **Brown, A.**, & Badurdeen, F., (2013). *A Queuing Model for Systems with Rework and Process Downtime: Waste Reduction for Improved Sustainability*. Presented at the Tracy Farmer Institute for Sustainability and the Environment (TFISE) 3rd Annual Research Showcase, Lexington, KY.
8. **Brown, A.**, & Badurdeen, F., (2013). *A Queuing Model for Systems with Rework and Process Downtime: Waste Reduction for Improved*

Sustainability. Presented at the Institute for Sustainable Manufacturing 3rd International Forum on Sustainable Manufacturing, Lexington, KY. ***Student poster award, 2nd place**

Professional Memberships and Community Activities

Council of Supply Chain Management Professionals (CSCMP)

Institute of Industrial and Systems Engineers (IISE)

Toastmasters International