

Planning Production Systems Resilience by Linking Supply Chain Operational Factors

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ABSTRACT

A mathematical model is proposed to plan production system resilience in a supply chain to overcome production related disruptions using appropriate operational factors at optimum cost. The research considers internally generated disruption risks due to supply, quality management, and plant reliability failures; and externally generated disruption risks from natural calamities. The production system of a supply chain has several options to utilize controllable operational factors to inhibit or mitigate the risks it faces. The operational factors are planned to mitigate the natural calamity disruptions and to inhibit the internally generated risks to create resilience. Since supply chain outcomes may be considered to be the net effect of complex interactions among several operational factors and resources, appropriate linkage of the operational factors is the key to select the right option(s) to create system resilience to contain risks and disruptions. Each operational factor can influence more than one supply chain outcome or relevant risk; on the other hand, containment of each risk may need contributions from several operational factors. Selection of the suitable controllable operational factors would be the most viable option for resilience creation. The analysis of the model outcomes establishes the effectiveness of the proposed model based procedure in creating production system resilience within an optimum cost using controllable operational factors. The operational factors used are: supplier flexibility; plant capacity flexibility; designating suppliers by a quality metric based evaluation procedure to have ensured quality inputs; quality metrics based plant capability determination and allocating production to capable plants to have ensured quality products. A numerical example illustrates the applicability of the model.

Key words: *risk resilience models, desired and current risk readiness measures, controllable operational factors, input management risks, manufacturing and quality management risks, multi-objective models.*

1. INTRODUCTION

Production systems of supply chains (SCs) are exposed to various risks and disasters that impact their capacity and capability to fulfill market requirements. These risks and

disasters may arise internally due to operational failures, such as supply failures, production quality failures, plant breakdowns (Tummala and Schoenherr, 2011), or externally as a result of low probability, high impact natural calamities and terrorist attacks (Simchi-Levi et al.2014). Considering several instances of natural disasters and the impact of the risks they pose to business systems (Park et al., 2013; Qiang and Nagurney, 2012), as well as instances of terrorist activities over the last several years (Keller et al., 2010), it is imperative that SCs create resilient production systems for their sustainability and future growth prospects.

The SC risk management (SCRM) literature defines resilience as the strategy or ability of a SC or a system to overcome disruptions or vulnerabilities and return to its original, or to a new, more desirable state of operations (Tang, 2006; Christopher and Peck, 2004; Rice and Canniato, 2003; Sheffi and Rice, 2005). Resilience has also been described as a function of a SC's competitive position and responsiveness to market. Since resilience is a part of the strategic initiative (Sheffi and Rice, 2005), it may be defined as a measure, or a metric, that reflects SC's ability to withstand or overcome disruptions and to return to its original, or an equivalent state to operate in a suitable mode in the changed state without experiencing failure. A workable measure of resilience may be in the form of the ratio of the target system output (affected by foreseeable and uncertain disruptions and aided by flexibility or redundancy options) to the desired or target output. Such a metric is workable because it provides the SC managers with an estimated resilience level for the current operations, and pinpoints the operational factors where SC should exercise control to inhibit or mitigate the disasters. It would also provide a clear picture of the options to include flexibility for improving resilience measures.

The present research proposes a resilience model for the production system of a SC following the above definitions. Since disruption risks are considered to be much higher than the operational risks (Tang, 2006), the system resilience creation should focus on both the risks and disruptions. To devise measures for inhibiting risks or

mitigating disruptions the SC should first identify the risks (Chopra and Sodhi, 2004). Production system risks and disruptions may arise from inputs, manufacturing, and quality system management. Supply chains are dependent on suppliers for their inputs, and as such they are exposed to several supply management-related risks (Swink and Zsidisin, 2006). Sheffi (2005) emphasizes the importance of a sound supply relationship to the resilience of a business. In order to obtain reliable input supply performance in terms of quality, quantity, and lead time with required flexibility, the SC may institute a supplier affiliation procedure based on a quality system metric, and create partnering relationship with a select pool of suppliers (Das, 2011).

Production system risks and disruptions may also be caused by manufacturing management, which involves such disruption factors as machine breakdowns and quality system failures. Supply chains need to develop manufacturing system resilience by including the required flexibility and quality management system to be able to handle such risks (Kleindorfer and Saad, 2005; Sheffi and Rice, 2005; Ponomarov and Holcomb, 2009). Considering the vital role of manufacturing in ensuring product quality in the market, the production system of a SC needs to critically examine the quality management system (QMS)-related disruption risks, and plan appropriate QMS measures to avoid product recalls, media attention, drastically falling share values (Hendriks and Singhal, 2005a), and other serious consequences.

An effective SC management should identify various risks and foreseeable disasters for each component of the production system; estimate their impacts on the overall business; explore possible inhibiting and mitigating steps using controllable operational factors; define and estimate resilience measures, and initiate appropriate strategies for improving the SC's resilience level. The present research attempts to formulate a resilience model for production systems by systematically identifying the relevant risks, disruptions, and associated operational factors that may inhibit or mitigate the risks. The study then proposes a bi-objective SC planning model to enable SC managers to assess the risk impacts on their business performance at various resilience levels, and select suitable controllable operational factors to improve the risk and disruption resilience. Compared to model based SC resilience research in the extant literature (e.g., Simchi-Levi, et al., 2014; Soni, et al., 2014; Munoz and Dunbar, 2015; Cardoso, et al., 2015) that are focused on the formulation and evaluation of the resilience index only, this research is unique in the sense that it not only defines resilience measures, but also identifies suitable controllable SC operational factors in a SC planning model to create a resilient production system. The contribution of the paper to the literature is to present a model-based approach to the development of a metric to get a handle on 'resilience' and incorporate it in the decision making framework of the supply chain.

The paper is organized as follows. Section 2 reviews the relevant literature. Section 3 formulates the resilience model and the bi-objective SC planning model. Section 4 illustrates the applicability of the model through a numerical example, and section 5 presents the conclusions and discussions.

2. LITERATURE REVIEW

Two streams of research that form the basis of this paper are: a) SC risk management that provides systematic guidelines for identification of risks and disruptions and their impacts, and methods for containment or mitigation by creating system resilience; b) the concept of SC resilience and its creation, measures, factors, and drivers, antecedents for resilience, and production systems resilience as part of it.

Before reviewing the literature on the above basis, the concepts of SC risk, disruptions, disturbances, vulnerability and resilience are discussed briefly to clarify the terms to be used subsequently. The SC risks considered in this research are taken as the failure of SC operations due to inefficient coordination and planning of supply and demand situations; and the disruptions of SC operations that may arise due to natural calamities, strikes, and similar events (Kleindorfer and Saad, 2006). In a similar manner, Wagner and Bode (2006) considered risk as the negative deviation from the expected value of a certain performance measure, resulting in negative consequences for the focal firm. SC disruptions are defined as the events that disrupt the flow of goods or services in the chain (Craighead et al., 2007), and that can have severe negative effects on the financial, market and operational performance of the firm (Hendriks and Singhal, 2005a). Disturbances and disruptions are often used interchangeably (Christopher and Lee, 2004). However, in this research disturbances are considered as disruption events, such as glitches, errors, and failure events. Vulnerability, or susceptibility, is a SC characteristic due to which the chain incurs losses as a result of disruptions (Wagner and Bode, 2006). SC resilience, as defined earlier, is the strategy or ability of a SC or a system to overcome disruptions or vulnerabilities and return to its original, or to a new, more desirable state of operations (Tang, 2006; Christopher and Peck, 2004; Rice and Canniato, 2003; Sheffi and Rice, 2005). A similar definition following Saurabh et al. (2015) is the ability of a firm to be alerted to, adapt to, and quickly respond to changes brought on by a SC disruption.

2.1. SC Risk Management

The SC operational risks arise when the SC operations fail due to inefficient coordination and planning of supply and demand situations. The SC disruption risks arise from natural calamities, strikes, and similar events (Knemeyer et al., 2009). The management of operational risks depends on such factors as effective forecasting, production and distribution planning, and information processing. The planning and management of such factors are well covered in the literature (Fahimnia et al., 2013). In the current business environment operational risks have become complex due to the globalized supply sourcing, disruptions caused by uncertain economic cycles, consumer demand, and the various manmade and natural disasters (Tang, 2006). So it is important that a SC adopt a systematic risk management approach to improve its performance. Based on the literature, the key elements for SC risk management (SCRM) include a) risk identification, b) risk assessment, c) risk mitigation, and d) responsiveness to risk incidents, where risk incidents can be operational risks or catastrophic risks (Sodhi et al., 2012). Another factor which is frequently mentioned is the organizational and personal learning including knowledge transfer (Wu and Blackhurst, 2009) as

an extension for mitigation and containment of risk. In the operational perspective, SC risks may be identified as supply, operational, process, demand, control, environmental, and security risks (Manuj and Mentzer, 2008; Tang and Tomlin, 2008; Christopher and Peck, 2004). The risk assessment (the second step in the SCRM) may be performed by considering the likelihood of potential risk events and their consequences on the resources/SC operations (Knemeyer et al., 2009). It may also be assessed as the negative effects of disruption or risk events (Tang and Tomlin, 2008). The literature also covers risk assessment empirically by considering the effects of economic glitches (defined as the mismatch of supply and demand situations) on stock prices and operating performance indices such as return on assets or sales (Hendriks and Singhal, 2005b). The next element is the risk mitigation, which may be achieved by keeping inventory (Schmitt and Sing, 2012; Dong and Tomlin, 2012), creating redundancy of resources (Sheffi, 2005), creating flexibility, such as supply flexibility to mitigate supply disruptions, and production capacity flexibility to mitigate production disruptions (Chopra and Sodhi, 2004; Dong and Tomlin, 2012; Juttner and Maklan, 2011; Sheffi, 2005). Disruptions can also be mitigated by buying insurance (Dong and Tomlin, 2012). Other mitigation steps include intra- and inter-firm collaborations, awareness of the employees, and agility of the organization in addition to the engineering or other resource based options (Scholten et al., 2014). Mitigation steps may extend to include quick response to disruptions (the last step). Collaboration with suppliers and partners helps in taking measures to withstand, and to prevent the damaging impact of the disruption events. Collaborative supports from various SC partners are vital for production system to mitigate the after effect. Agility to quickly respond to potential disruption events or after effect of disruptions is the organizational ability. According to Scholten et al. (2014), creating a task force to provide leadership in mitigation steps, providing training, and risk awareness is found to be very effective in emergency management process to recover from natural calamities and similar disasters. Such steps should be equally effective in mitigating and recovering from SC disruption events (Scholten et al. 2014). SC organization may refer to the well-documented FEMA as well as ECHACP (2013) guidelines to manage disasters and disruptions through advance planning.

SC risk management (SCRM) and SC vulnerability (SCV) are often mentioned in SC resilience related discussions. Juttner and Maklan (2011) studied the relationship among these three concepts using data from three case studies considering the global financial crisis as demand risk event (demand decreased by 20% to 30% globally) that affected the companies in question. The reported research findings show positive impact of SCRM steps such as risk sharing, hedging risks through redundant resources, and SC risk knowledge management on four SC resilience capabilities (flexibilities, velocity, visibility, and collaboration). The findings also pointed out the positive impact of the four SC resilience capabilities on SCV factors. These SC resilience capabilities are also very much relevant to production system resilience. Kleindorfer and Saad (2005) suggested to increase the capacity of SC participants to absorb and sustain more risks without serious negative impacts. A system must have very high quality process

management with a self-auditing option for such capacity increases. To achieve capacity increase organizations may adopt ISO 9000, OSHA safety standards type reporting and self-auditing options to mitigate disruption risks. Kleindorfer and Saad (2005) recommended coordination, cooperation, and collaboration both cross functionally and with the firms of the SC to practice and implement disruption mitigation management. In addition, the study emphasized installation of flexibility and mobility of resources to reduce the risks and increase the speed of the response. Based on the literature, Gunasekharan et al. (2011) mentioned supply chain integration as one of the enablers and quality as one of the key influencing factors for SME resilience. The study suggested that SMEs should adopt quality assurance, quality control, and continuous improvement to remain competitive.

Christopher and Peck (2004) mentioned that SC should be designed by considering certain features that, if implemented in the chain, would improve the SC resilience. The features include SC understanding (consideration of bottlenecks such as port capacity, key suppliers); supply base (more than one supplier for each item, whether suppliers should have risk mitigation and risk monitoring strategy); SC design strategy considering redundancy vs. efficiency; strategic disposition of additional capacity; and SC collaboration. SC operational risks arise due to variations in the flow of goods across the chain to balance the supply and demand (Juttner et al., 2003). Such variations come from suppliers' performance, production process including quality management, and customer process (Chen et al., 2013).

2.2. SC Resilience

SC management needs to evaluate the chain's vulnerabilities in order to build resilience by developing specific capabilities to deal with disruptions caused by such vulnerabilities (Fiksel et al., 2015). There are six major vulnerabilities to be considered:

1. Turbulence: changes in the business environment that are beyond the SC's control, such as shifts in customer demand, geopolitical disruptions, natural disasters and pandemics;
2. Deliberate threats: sabotage, terrorism, labor strikes;
3. External pressures that create constraints or barriers, such as innovations, regulatory shifts, and cultural attitudes;
4. Resource limits: potential to constrain a company's capacity;
5. Sensitivity and complexity of production processes;
6. The degree of connectivity to have cooperation with outside functions.

To overcome the vulnerabilities several capabilities have been identified, such as flexibility in sourcing, manufacturing, and order fulfillment; production capacity, efficiency, visibility, adaptability with demand situation; and internal and external collaborations (Fiksel et al., 2015). Most of these capabilities are also applicable in creating production system resilience. Similar vulnerabilities and their counter-measures to establish SC resilience have been well covered in several review studies including Hohenstein et al. (2015) who provided a list of proactive and reactive strategies for SC resilience. Proactive strategies include readiness elements to contain disruptions, such as the use of inventory and safety stocks to buffer against disruptions;

predefined plans for contingency and collaboration with suppliers, customers and employees; human resource development to include employee training and education, promotion of a risk sensitive culture and mindset, and hiring employees that are experienced in crisis management; provision of redundancy to create production slack; multiple sourcing and multiple production locations; visibility for early warning communication, real time information sharing and financial monitoring. These proactive strategies are similar to the proactive steps recommended by Knemeyer et al. (2009).

Reactive strategies listed in Hohenstein et al. (2015) that are related to response, recovery, and growth elements are: communication, information sharing; collaboration, coordination and cooperation with external and internal SC functions; flexibility for backup supplier, easy supply switching, flexible distribution channels, flexible production capacity; human resource management and redundancy similar to the proactive planning mentioned before.

In the current global economy SCs and their functions are exposed to various vulnerabilities. But a company can substantially increase its resilience by improving its ability to detect and respond to disruptions quickly. Disruptions may be detected from the SC event monitoring and mapping; from severity alerts for natural calamities issued by weather monitoring organizations; by tracking the news; by monitoring the supply base for supply disruptions; and by monitoring the social media. The ability to respond quickly may be achieved through data driven approaches (Sheffi, 2015). A firm's recognition and awareness of the potential disruptions and how it analyzes and learns from prior disruptions may be considered as a precursor to developing resilience to SC disruptions (Bode et al., 2011). Other antecedents to develop resilience to SC disruptions are a firm's resource configurations and its risk management infrastructure (Saurabh et al., 2015). Resource configuration is the ability of a firm to reconfigure, realign and reorganize the resources to face the external environment and/or disruption events. Risk management infrastructure is the structure or readiness of the resources to be used in managing SC risk. A similar study of antecedents of resilience for SME's by Demmer et al. (2011) addressed the entire facets of a business towards resilience creation. Recommendation of the research includes continuous improvement strategies, using cross functional teams for improvement projects to ensure knowledge sharing, incorporation of environmental scanning to earn new knowledge and information, emphasizing value added solutions for customers, externalizing innovation through partnering, outsourcing and collaboration, emphasizing the importance of business process optimization by applying lean manufacturing, quality management principles and investment in new technologies.

A resilient supply management is a crucial factor in the overall SC resilience structure. The literature includes model based approaches to create a resilient supply management by optimal selection, allocation of supply quantity, and protection of suppliers to obtain supplies in disruption events. Protection of suppliers involves prepositioning of emergency inventory of parts procured from protected suppliers (Sawik, 2013). The literature also prescribes strategies to reduce and mitigate the impact of supply disruption risks by keeping buffer inventories and creating

resource flexibility at suitable SC network locations considering the response time, and inventory carrying cost to improve SC resilience (Schmitt and Singh, 2012). Klibi and Martel (2012) proposed a model based approach for designing resilient supply networks by considering random customer orders, location of supply depots, disruption of depot capacity, location and investment in new depots, response to the customer delivery schedule and transportation planning. Such an approach is applicable when a firm can anticipate disruption events and their effect. In similar studies Carvalho et al. (2012) and Petit et al. (2010) argued that SC resilience may be reached by finding a balance between capabilities and vulnerabilities of an organization. Strong capabilities through collaboration, flexibility, and visibility may contribute to create resilience through the management of interrelated operations between multiple tiers of suppliers and customers. Tang and Tomlin (2008) proposed flexible supply models via multiple suppliers and via flexible supply contracts to take proactive measures for avoiding supply risks. These flexibilities may also be used to mitigate the risks. Tang and Tomlin (2008) also proposed flexible process models via flexible manufacturing resources and production postponement to mitigate and inhibit process risks. Such flexibility models will improve production system resilience.

Building resilience in the overall SC process or at any echelon or function helps to reduce and/or overcome disruptions (Tang, 2006; Wagner and Bode, 2006). Such resilience in advance of a disaster creates readiness to withstand it, and to take effective measures for mitigation (Das and Lashkari, 2015; Ponomarov and Holcomb, 2009). It is also important to appreciate that it would be too late for the SCs or their functions to develop preventive measures once disruption happens (Tomasini and van Wassenhove, 2009); creating resilience ahead of time is the only option to overcome or contain disruptions.

Soni et al. (2014) identified SC resilience enablers such as agility, collaboration, risk and information sharing, trust, visibility risk management, adaptive capability and structure of the SC, and studied the interdependence of the enablers by using a diagraph based approach. Their modeling approach transforms the interdependencies in the diagraph into a matrix, and based on the values of the enablers from expert opinions estimates the resilience index considering the summation of interdependencies among the enablers. It can also compare the resilience indices of two firms. Despite the fact that the evaluated or estimated outcomes can give an idea on resiliency index, it is very difficult to estimate such an index practically. But the elements of the enablers used by Soni et al. (2014) are very much applicable for production system resilience creation, especially for collaboration with suppliers and network partners to create flexibility and agility to respond to disruption events. Similarly, the establishment of a risk management culture and relevant training is a part of readiness to manage the after effects of a disaster event for quick recovery and mitigation. Simchi-Levi et al. (2014) presented a disaster risk management model that identifies risks, estimates the risk impacts, and the time to recover (TTR) from effects. TTR has been mentioned as the risk exposure index. TTR considers historical data of the particular node of the SC to estimate the recovery time. Such risk impact and time to recover may very well be applied to production system risk management also. In a

similar approach Munoz and Dunbar (2015) proposed an operational SC resilience metric and used simulation to analyze a hypothetical manufacturing SC to show the applicability of the approach to build the resilience metric. In the simulation, the customers (retailers) had the standing orders and had the option to satisfy their orders elsewhere when the SC under consideration could not fulfill their orders. Disturbances were inflicted to disrupt the order fill rate. Standing orders considered show post disruption recovery. A standing order of fixed quantity and frequency determined the volume and cycle time of each order to be delivered by the manufacturer to the retailer. Simulation was run for several periods where three periods were considered in one cycle. The percentage fill rate was the outcome of the runs with deterministic, pre-defined disruptions. The recovery period after each disruption was recorded, as were the performance loss and the profile length as a function of recovery time to reach a stable performance, or the original level. Based on the correlation analysis among these factors they concluded that multiple tier based performance analysis using a similar approach can provide a clear idea of how disruptions propagate. Based on the analysis, it is clear that such a model is of theoretical interest only, and is not suitable to use in a practical situation to provide managerial insights. Cardoso et al. (2015) proposed a multi-product multi-period closed loop SC network design and planning model to maximize economic performance and resilience towards disruptions. The main objective of the research is to decide which network characteristics a SC designer should consider to obtain higher economic performance and resilience indicators. They considered resilience in terms of eleven indicators; four (node complexity, flow complexity, density and flow criticality) are network indicators which are based on the number of network elements; four are network centralization indicators that are based on intensity of the flows around each node to decide the centrality; and three (the expected net present value, expected customer service level and investment) are operational indicators. To understand and evaluate the network resilience, Cardoso, et al. (2015) applied disruptions with a given probability to different SC echelons and the demand uncertainty was modeled using a scenario tree. As is evident the evaluation of resilience performance is complex which may be used for comparing the SC performance; however, it is not suitable for designing a resilient SC system.

The above review establishes SC resilience as the prime consideration in SC literature, which underlines the importance of supply, production /conversion process, and quality systems related disruption management in the creation of resilience. There are model based approaches in supply resilience, and supply and capacity flexibility creation to contain business risks. A select number of research works (such as Soni et al., 2014, or Munoz and Dunbar, 2015) that may be used to estimate a resilience index are of theoretical interest only. These approaches are not practically applicable due to their complexity. In addition, the metrics defined in these papers are limited in their utility, as they do not provide clear ideas for a trade-off based approach that a business manager needs to decide the resource investments for improving resilience while considering the budgetary constraints. The model based research in Simchi-Levi, et al. (2014) identifies the risks, estimates the risk impacts, and the time to recover. It is

mainly a diagnostic tool which is not suitable to be incorporated in the SC planning process to develop resilient systems. It may also be noted that the model based research of Cardoso, et al. (2015) is suitable for comparing SCs only. As such there is an apparent need for a comprehensive model that would measure the resilience level of the overall production and SC system, facilitate the evaluation of SC's position, and initiate plans to achieve the desired resilience level. This study will contribute to partially close that gap by including a bi-objective model that provides several trade-off options for improving profits as well as the resilience.

3. MODEL DEVELOPMENT

3.1. Problem Statement

We assume a SC that produces products P in plants J using inputs I supplied by suppliers and then distributes them in a set of markets L . Over the past years the SC has faced several internal and external disruptions in its production systems that have affected the overall SC performance. Internal failures/disruptions had been due to plant breakdowns, input shortages, input quality failures, and finished products quality failures. External disruptions included the effect of natural calamities. Among the external disruptions the SC management is concerned with are potential terrorist attacks on the community or state resources, or on its own resources, that may disrupt the production system operations. Based on its own experience and a history of disruption effects on other businesses, the SC management has decided to create and enhance the resilience of its production systems to minimize disruptions and to continue the business operations without interruptions.

The SC planned to use the following controllable operational factors to weather away, prevent and/or mitigate the potential risks and disasters. An operational factor is one which is related to the SC operations for fulfilling the customer demand in terms of quality, quantity and delivery schedule. Such factors include the overall SC process control, and planning of the SC functions including supply, production, quality management, inventory control and management, and other factors as applicable for effective SC operations.

The factors are:

- a) Preventive and condition-based maintenance policy: To prevent unplanned plant downtime and to minimize product shortages due to plant breakdowns. This step is a part of operational contingencies recommended in Kleindorfer and Saad (2005)
- b) Quality metrics-based supply management system following Das (2011): To prevent input shortages and input quality failures. This supply management system facilitates the designation of suppliers as *acceptable* and *high quality* supplier pools based on the performance score of the suppliers with respect to the quality metrics. The designated supply pools provide supply flexibility, establish collaborative partnering relationships with the SC. The high-quality suppliers ensure the quality of the inputs, as well as the quantity and the delivery. A similar supply management approach has been recommended in several research work (Sawik, 2013; Christopher and Peck, 2004; Kleindorfer and Saad, 2004; Chopra and Sodhi, 2004).

c) Quality metrics-based plant capability determination was identified as the operational factor to minimize quality failure of finished products. This step has been included based on Das and Lashkari (2015).

The natural calamities that may affect the SC are floods, cyclones, tornados, heavy snow falls, and earthquakes. To mitigate the potential impact of a calamity, a scenario-based analysis has been planned to estimate plant availability losses due to the calamity using historical data from the SC's own plants, or from other plants that have been affected by such calamities. For each calamity, five scenarios are considered: no impact; low impact; moderate impact; strong impact, and severe impact. The objective of the present research is to develop a mathematical model of the SC operations that links the above operational factors to maximize the risk resilience with respect to production disruptions, and to improve the overall SC profit level.

3.2. Notation

Indices

- P : set of products ($p \in P$)
- I : set of inputs ($i \in I$)
- S : set of suppliers ($s \in S$)
- L : set of markets ($l \in L$)
- J : set of plants ($j \in J$) operated by the SC
- J' : set of partner plants ($j' \in J'$)
- J'' : pool of plants ($j'' \in J''$) that supply products to other markets, but can provide extra capacity to the SC to compensate for any emergency capacity shortages¹
- M : set of maintenance policies ($m \in M$)
- $c=1,2,3,\dots$, natural calamity types
- S' : set of scenarios ($s' \in S'$)
- O : set of mitigation options ($o \in O$)

Parameters

- A_j^m : Availability of plant j under maintenance policy m
- AQ_{is} : = 1 when supplier s is designated as an acceptable quality (AQ) supplier of input i ; = 0 otherwise
- CAN_{pj} : supply capacity of partner plant j' to manufacture product p when needed
- CAP_{pj} : production capacity of plant j to manufacture product p
- CM_{pj} : per unit cost of manufacturing product p at plant j
- CN_{pj} : per unit cost of procuring product p from partner plant j'
- $CPN_{pj''}$: supply capacity of SC's pooled plant j'' to manufacture product p when needed
- $CPS_{pj''}$: per unit cost of procuring product p from SC's pooled plant j''
- CV_{is} : capacity of supplier s to supply input i
- CI_{is} : per unit cost of input i from supplier s
- D_{pl} : demand for product p in market l
- EPC_{jc} : effective % loss time at plant j due to calamity c
- FI_{is} : fixed cost of procuring input from supplier s
- FM_{pj} : fixed cost of manufacturing product p at plant j
- FNC_{jco} : fixed cost of installing option o for mitigating the effects of natural calamity c at plant j

- $FN_{pj'}$: fixed cost of procuring product p from partner plant j'
- $FPN_{pj''}$: fixed cost of procuring product p from SC's pooled plant j''
- FP_s : probability of scenario s'
- HQ_{is} : = 1 when supplier s is designated as a high quality (HQ) supplier of input i ; = 0 otherwise
- IP_{pj} : % shortage of product p due to short supply, delayed supply, or inferior quality inputs at plant j
- IQM_{is} : per-order fixed cost of monitoring quality of input i from supplier s
- MNC_{jm} : annual maintenance cost for plant j under maintenance policy m
- MTC_{jco} : cost to mitigate the effect of natural calamity c on loss time of plant j under option o
- NC_{jco} : maximum possible % mitigation of the effect of calamity c under option o at plant j
- NS_{jcs} : % of plant time that may be affected by calamity c at plant j under scenario s'
- PSI : average % shortage of input supply from AQ suppliers due to quality problems, short supply, delays, and no supply, based on past records
- INR_{pj} : obtainable % of capacity for plant j to produce product p after adjusting for the effects of internal risks
- EXR_{pj} : obtainable % of capacity for plant j to produce product p after adjusting for the effects of external risks
- QPC_{pj} : quality monitoring cost of product p at plant j
- QA_{pj} : =1 if plant j is approved as a quality capable plant for product p ; =0 otherwise
- v_{pl} : per unit price of product p in market l
- ρ_{pi} : per unit usage rate of input i for product p

Decision variables

- MNT_{jco} : mitigation effect of option o on calamity c at plant j , in % desired level
- mp_{jm} : =1, if plant j follows maintenance policy m ; = 0 otherwise
- PSR_{pj} : production system resilience for plant j to manufacture product p
- $pn_{pj''}$: =1, if product p is obtained from SC's pool plant j'' ; = 0 otherwise
- rs_{jco} : =1, if option o is chosen to mitigate natural calamity c at plant j ; = 0 otherwise
- u_{pj} : =1, if plant j is slated to manufacture product p ; = 0 otherwise
- un_{pj} : =1, if partner plant j' is selected for obtaining product p ; = 0 otherwise
- $up_{pj''}$: =1, if SC's pooled plant j'' is selected to provide extra units of product p ; = 0 otherwise
- v_{is} : =1, if supplier s is assigned to provide input i ; =0 otherwise
- $xn_{pj'}$: number of units of product p procured from partner plant j'
- $xpn_{pj''}$: number of units of product p procured from SC's pool plant j''
- x_{pj} : total number of units of product p manufactured at plant j
- xe_{pj} : effective number of units of product p manufactured at plant j after adjusting for capacity losses due to maintenance and input shortages

¹ To designate the plant pool, the SC assigns each market to a set of its own plants to fulfill product demands. When some of the plants are affected by disruptions, the remaining plants

in combined form will act as a pool to provide extra capacity to the affected plants.

- xs_{pj} : overall short supply of product p from plant j due to external and internal reasons
- xIs_{pj} : short supply of product p from plant j due to input shortages or quality problems
- y_{pl} : demand for product p in market l
- ys_{pl} : short supply of product p in market l
- z_{is} : number of units of input i supplied by suppliers
- za_{is} : number of units of input i supplied by AQ suppliers
- zh_{is} : number of units of input i supplied by HQ suppliers

3.3. Measure of Risk Resilience

Following the definition of resilience discussed before, a system is considered resilient if it can overcome the disruptions and go back to the original, or a better, state of operations, after being impacted by disruptions. The resilience may be achieved if the disruptions/disturbances that impact the system are inhibited or mitigated partially or completely, by the relevant controllable operational factors, and if the system is supported by flexibility or redundancy options for its recovery in case the operational factors contribute only partial or negligible levels of inhibition or mitigation. An organization may achieve partial resilience if the effect of the operational factors and supports from the flexibility options cannot take the system back to the original state to obtain the same output.

Based on the above definition, the production system resilience, PRY , may be defined in equation (1):

$$PRY = \left\{ \sum_{p \in P} \left(\sum_{j \in J} CAP_{pj} INR_{pj} EXR_{pj} + \sum_{j' \in J'} CAN_{pj'} un_{pj'} \right) + \sum_{j'' \in J''} CPN_{pj''} pn_{pj''} \right\} / \left(\sum_{p \in P} \sum_{j \in J} CAP_{pj} \right) \quad (1)$$

The first term in the numerator of equation (1) represents the overall production system capacity impacted by internally developed risks (through the factor INR_{pj}) and externally generated disruptions (through the factor EXR_{pj}). The second term represents the amount of the flexible capacity available through network-based partner plants, and the third term represents the flexible capacity available through the SC's pool plants. The denominator in equation (1) is the overall production system capacity. The factors INR_{pj} and EXR_{pj} are defined in equations (2) and (3), respectively:

$$INR_{pj} = (1 - IP_{pj})(1 - QP_{pj}) \sum_{m \in M} A_j^m \quad \forall p, j \quad (2)$$

$$EXR_{pj} = (1 - \sum_{c \in C} EPC_{jc}) \quad \forall p, j \quad (3)$$

Equation (2) expresses the overall percentage effect on plant capacity as the combined effects of the supply management failure (through the term $1 - IP_{pj}$), the quality management failure (through the term $1 - QP_{pj}$), and the maintenance policy (through availability A_j^m). Equation (3) represents the estimated combined effects of all the potential calamities on the operation time of a plant for each product manufactured in that plant.

As may be observed in equations (1), the first part includes the practical actionable items by the SC management with respect to the controllable operational factors to overcome the internal and external risk impacts on the plant capacity. Since the risk impacts on the plant capacity are uncertain, flexibility options in the second and third parts of the equation are incorporated as standby, in

case the SC cannot contain the risk impacts completely through its own operational measures. The strategy of a SC should be to obtain the highest possible overall performance of its resources by effectively deploying its operational factors, and rely on support from flexibility options only to supplement any resource shortages. These options are incorporated into the decision making process in the mathematical model to be chosen when necessary. As such, we employ the first part of equation (1), as presented in equation (4) below, as the metric in evaluating the production system resilience status (PSR_{pj}) for each product-plant combination. The SC, however, is still considering PRY as the overall risk resilience for the production system.

$$PSR_{pj} = (CAP_{pj} INR_{pj} EXR_{pj}) / (CAP_{pj}) = INR_{pj} EXR_{pj} \quad \forall p, j \quad (4)$$

It may be mentioned here that the model estimates EXR_{pj} in equation (3) based on the effect of the natural calamities on plant capacity using a scenario based analysis. This process is explained in the next section.

3.4. Natural Calamity Effects

It is noted that the probability of the occurrence of a natural calamity is influenced by:

- a) plant location with respect to i) earth quake zones, ii) flood prone areas/state/country, iii) cyclone prone areas/state/country, iv) tornado prone areas/state/country;
- b) the number of floods per year based on the last 10-year history due to heavy rain falls, river overflows, etc.;
- c) the frequency of transportation stoppages due to heavy snow falls in the last 10 years;
- d) the number of droughts during the last 10 years.

The natural calamities considered are $c=1$: floods; $c=2$: cyclones; $c=3$: tornados; $c=4$: heavy snow falls; and $c=5$: earth quakes. For each calamity, we assume five scenarios in terms of its impact:

- $s'=1$: no impact
- $s'=2$: low impact
- $s'=3$: moderate impact
- $s'=4$: strong impact, and
- $s'=5$: severe impact.

The loss of plant time due to the occurrence of a calamity under each scenario may be estimated based on past historical data for the duration of the calamity and recovery with respect to each plant considering the location and other susceptibility factors. If NS_{jcs} is the percentage of time lost at plant j due to calamity c under scenario s' , and FP_s is the probability that scenario s' prevails, then EPC_{jc} , the percentage of time lost at plant j due to the natural calamity, will be evaluated in constraint (30). To mitigate the after effect of a natural calamity a plant may select one or more of the following options:

$o=1$: Providing training to the employees to take timely steps on self-rescue, rescue of fellow employees, protecting properties, informing state, national and international rescue teams (where applicable and possible), and aid and protection agencies.

$o=2$: Keeping the lowest possible inventory of each material in the plants located in high calamity risk zones.

$o=3$: Creating inventories of inputs, products, and spare parts in the safer locations considering location factors and relevant scenarios.

$o=4$: Preplanning on pooling options to obtain products, inputs, and resources from plants in safer locations within the SC network. Planning should also include the transfer of products from unsafe plants to safe, pooled plants. This may also include creating safety stocks.

$o=5$: Forming a taskforce consisting of experts, managers, and representatives from line functions to quickly make the plant suitable for production. Detailed preplanning based on structured checklists to estimate resource requirements, predictable work steps, limitations, external support requirements, etc.

$o=6$: Creating partnering relationship with other SC plants and facilities at safer zones (Knemeyer et al., 2009).

The maximum possible mitigation effects that each of the above options may provide for a given calamity at a plant may be estimated by following resource literature such as Pre-disaster Mitigation Act 2009 (Ford, 2011). As discussed before, detailed practical guidance for advance planning as well mitigation steps for overcoming disruptions are available on FEMA website and ECHACP (2013).

3.5. The Model

The objective functions are defined as follows:

Objective 1: maximize $MR = \sum_{p \in P} \sum_{j \in J} PSR_{pj}$ (5)

Where MR is the overall production system resilience metric based on the definition of production system resilience in equation (4) for each product–plant combination.

Objective 2: maximize $Profits = \text{Gross Revenue } GR - \text{Total Cost } TC$ (6)

where

$$GR = \sum_{l \in L} \sum_{p \in P} (y_{pl} - y_{s_{pl}}) v_{pl}$$
 (7)

$TC = \text{production cost (PRC)} + \text{plant maintenance cost (PMC)} + \text{natural calamity and terrorist attack readiness cost (NTC)} + \text{input cost (INC)} + \text{QSC quality system cost (QSC)}$ (8)

$$PRC = \sum_{j \in J} \sum_{p \in P} x_{pj} CM_{pj} + \sum_{j \in J} \sum_{p \in P} u_{pj} FM_{pj} +$$
 (9)

$$\sum_{j' \in J'} \sum_{p \in P} x_{nj'} CN_{pj'} + \sum_{j' \in J'} \sum_{p \in P} un_{pj'} FN_{pj'} + \sum_{p \in P} \sum_{j'' \in J''} xp_{nj''} CPS_{pj''} + \sum_{j'' \in J''} \sum_{p \in P} up_{pj''} FPN_{pj''}$$

$$PMC = \sum_{j \in J} \sum_m mp_{jm} MNC_{jm}$$
 (10)

$$NTC = \sum_{o \in O} \sum_{j \in J} \sum_{c \in C} MNT_{jco} MTC_{jco} + \sum_{o \in O} \sum_{j \in J} \sum_{c \in C} rs_{jco} FNC_{jco}$$
 (11)

$$INC = \sum_{i \in I} \sum_{s \in S} (z_{is} CI_{is} + v_{is} FI_{is})$$
 (12)

$$QSC = \sum_{j \in J} \sum_{p \in P} QPC_{pj} x_{pj}$$
 (13)

$$+ \sum_{i \in I} \sum_{s \in S} IQM_{is} (AQ_{is} + HQ_{is})$$

The constraints are as follows:

$$y_{pl} = D_{pl} \quad \forall p, l$$
 (14)

$$\sum_{l \in L} y_{pl} = \sum_{j \in J} x_{pj} \quad \forall p$$
 (15)

$$x_{pj} = x_{pj} - x_{s_{pj}} \quad \forall p, j$$
 (16)

$$\sum_{i \in I} y_{is} = \sum_{j \in J} x_{sj} - \sum_{j' \in J'} x_{nj'} - \sum_{j'' \in J''} xp_{nj''} \quad \forall p$$
 (17)

$$x_{pj} \leq u_{pj} CAP_{pj} \quad \forall p, j$$
 (18)

$$u_{pj} \leq QA_{pj} \quad \forall p, j$$
 (19)

$$x_{nj'} \leq un_{pj'} CAN_{pj'} \quad \forall p, j'$$
 (20)

$$xp_{nj''} \leq up_{pj''} CPN_{pj''} \quad \forall p, j''$$
 (21)

$$x_{s_{pj}} = CAP_{pj} (1 - PSR_{pj}) \quad \forall p, j$$
 (22)

$$\sum_{s \in S} z_{is} = \sum_{j \in J} \sum_{p \in P} \rho_{pi} x_{pj} \quad \forall i$$
 (23)

$$z_{is} = za_{is} + zh_{is} \quad \forall i, s$$
 (24)

$$za_{is} \leq AQ_{is} CV_{is} \quad \forall i, s$$
 (25)

$$zh_{is} \leq HQ_{is} CV_{is} \quad \forall i, s$$
 (26)

$$PSI \sum_{s \in S} za_{is} = \sum_{p \in P} \rho_{pi} \sum_{j \in J} x_{sj} \quad \forall i$$
 (27)

$$x_{pj} \leq mp_{jm} A_j^m CAP_{pj} \quad \forall p, j, m$$
 (28)

$$\sum_{m \in M} mp_{jm} = 1 \quad \forall j$$
 (29)

$$EPC_{jc} = u_{pj} \sum_{s' \in S'} FP_{s'NS_{jcs'}} \quad \forall j, c$$
 (30)

$$MNT_{jco} \leq rs_{jco} NC_{jco} \quad \forall j, c, o$$
 (31)

$$\sum_{o \in O} MNT_{jco} \geq EPC_{jc} \quad \forall j, c$$
 (32)

$$IP_{pj} = x_{sj} / CAP_{pj} \quad \text{if } CAP_{pj} > 0;$$

$$IP_{pj} = 0, \quad \text{if } CAP_{pj} = 0 \quad \forall p, j$$
 (33)

$$u_{pj} \in \{0, 1\}, \forall p, j; un_{pj'} \in \{0, 1\}, \forall p, j'; mp_{jm} \in \{0, 1\}, \forall j, m; rs_{jco} \in \{0, 1\}, \forall j, c, o$$
 (34)

Objective 1 in equation (5) maximizes the resilience metric MR for the overall SC production system. Objective 2 in equation (6) maximizes the $Profits$, defined as the difference between Gross Revenue (GR) and Total Cost (TC). GR , defined in equation (7), is earned by selling the effective amounts of products to the market at the market price. The effective amount of a product is the amount needed to comply with market demand after adjusting for the product short supply, if any. Total Cost (TC) is defined in equation (8) in terms of its components. The production cost, PRC , is defined in equation (9), and consists of the variable and set up cost of production at SC's own plants, the procurement and fixed costs of product acquisition from the partner plants (NTPs), and the similar costs for product acquisition from the SC pooled plants. The next component of TC , defined in equation (10), computes the plant maintenance cost (PMC) based on the maintenance policy pursued by the plant. Equation (11), the third component of TC computes the natural calamity and terrorist attack readiness cost (NTC) by considering the various options involving resources and operational factors to be applied to mitigate the disasters. Equation (12) computes the input cost

(*INC*) by considering the variable and fixed cost of ordering the inputs from suppliers. The last component of *TC*, the quality system cost (*QSC*) in equation (13), computes the cost of monitoring production quality at the plants and the quality monitoring and tracking cost of the suppliers.

Constraint (14) balances the number of units of a product shipped to a market against the demand for that product. Constraint (15) balances the total number of units of a product shipped to all the markets against the total production of that product at all the plants. Equation (16) computes the effective production quantity of a product considering production losses due to input shortages and quality failures. Equation (17) computes the total short supply of a product in all the markets considering the losses due to production and supply management disruptions after adjusting for any extra units procured from the partner plants and the SC pooled plants. Constraint (18) limits the production quantity obtainable from the SC's own plant based on its capacity. Constraint (19) allocates production to quality-capable plants only. Constraints (20) and (21) limit the production quantities obtainable from the partner plants and the SC's pooled plants based on their respective capacities. Constraint (22) estimates the overall production loss of a product based on the plant capacity and the production system resilience factor for the plant-product combination. Equation (23) estimates the requirements of each input for all the products manufactured in the plants. Equation (24) balances the amount of an input needed against what is supplied by the AQ and HQ suppliers. Constraints (25) and (26) limit the input quantities supplied by the AQ and HQ suppliers in terms of their capacities.

Equation (27) estimates production losses due to supply management disruptions (input quality, short supply, no supply, and delayed supply) based on the past history of the average percentage of input loss for the quantity supplied by the AQ suppliers. Constraint (28) limits the production quantity of a product at a plant based on the plant availability, the maintenance policy in force at the plant, and the plant capacity. Constraint (29) ensures that only one maintenance policy is adopted by a plant. Equation (30) estimates the percentage of plant capacity loss due to a natural calamity considering the various scenarios (see section 3.4. Natural Calamity Effects above) and the past history of losses from occurrences of such a calamity. Equation (30) also ensures that plant capacity losses due to natural calamity are computed only for the plants that are slated for production. Constraint (31) ensures that the mitigation effect achieved at a plant does not exceed the maximum mitigation effect possible for a given calamity type. Constraint (32) ensures that the effect of the application of the various mitigation options is large enough to at least overcome the loss suffered by the plant due to the calamity. Constraint (33) computes the percentage of product shortages due to supply management losses. Constraint (34) imposes integrality.

4. A NUMERICAL EXAMPLE

To illustrate the applicability of the model and the overall approach we consider the yearly planning case of a hypothetical SC that produces 16 products in its 9 plants to satisfy customer demands in 7 market areas. For the past few years the SC has been experiencing poor business performance due to various types of production system

disruptions, such as input/supply quality failures, input shortages or no supply of inputs, and frequent plant breakdowns. In addition, production could not be run for days altogether in some years due to natural calamities, such as heavy snowfalls, power supply outages due to storms and hurricanes, and floods. Based on the recommendations of a consultant, the SC decided to enhance the resilience of its production system to contain the disruptions through a systematic model-based decision process outlined in this research.

4.1. Model Input Data

In addition to its own production plants for the planned markets, the SC also has access to a pool of 8 plants that produce similar products for other market areas, but that have spare capacity to support the current market areas in case of product shortages. Further, the SC has partnering relations with 5 manufacturers that produce similar products, and that have agreed to make their spare capacities available. The products from these 'pool plants' or 'partner plants' are quality-assured. The SC follows a quality metrics-based plant capability determination that uses several critical-to-quality (CTQ) and critical-to-business (CTB) attributes as outlined in Das (2011). Examples of some CTQs considered are: process capability, rejection/scrap rate, overall equipment effectiveness (OEE), average number of accidents per month causing time losses, and ISO 9001 certifications. Examples of some CTBs are average yearly hours of quality, safety, and lean-based trainings per employee; inventory turns; employee turnover; percentage absenteeism, and the number of labor disputes per year. Table 1 presents the plant capacity and quality capability status of all the product-plant combinations. See the Appendix for all the tables. For example, the capacity of plant 1 to manufacture products 1 is 4,150 units, but the plant is not quality capable for product 1 ($QA=0$); however, plant 2 is quality capable for this product ($QA=1$) and has a production capacity of 3,794 units.

The supply capacity of the SC's pool plants and partner plants are presented in Table 2. For example, pool plant 2 has the capacity to supply up to 1,069 units of product 3, while partner plant 2 has the capacity to supply up to 1,906 units of the same product. Table 3 displays product demands in various markets. For instance, the demand for product 1 in market 1 is 3,900 units.

The SC needs a total of 24 types of inputs to manufacture its 16 products, and each product needs from 5 to 12 inputs for its assembly process. The SC procures these inputs through its suppliers. Recently the SC quality management system (QMS) has evaluated the supplier pool based on the CTQ and CTB attribute metrics outlined in Das (2011), and designated 18 suppliers as HQ and AQ suppliers on the basis of their overall performance score on the CTQ and CTB attribute scales, and the threshold limits set for the score by the QMS. The CTQ and CTB attributes are similar to the ones described above for quality capability determination of production plants.

The HQ suppliers emerging out of this rigorous screening procedure are quality-assured suppliers with no history of short or delayed supply. Inputs supplied by the HQ suppliers are accepted without any receiving inspection. However, the AQ suppliers have a history of rejected items, short and/or delayed supplies, and thus a percentage of the

inputs supplied by them are inspected. Based on their previous history, an average of 1% of the inputs supplied by the AQ suppliers result in either scraps, rejected products, or products returned by customers. Products manufactured using these inputs may be considered scraps resulting in short supplies to market.

Table 4 presents the supplier affiliation information for each input based on the methodology described above. According to Table 4, for input 1, for instance, suppliers 1, 5, 8, 9, 11, and 15 are evaluated as HQ suppliers and the remaining 12 suppliers are identified as AQ suppliers. The input usage data for the products are displayed in Table 5. For example, one unit of product 1 uses one unit each of the inputs 1, 5, 8, 10, 12, 16, 23, and 24.

The SC production plants follow either a breakdown maintenance plan (BM), a preventive plan (PM), or a condition-based plan (CBM). Based on the plant maintenance record, Table 6 displays the availability and the average annual maintenance cost data for the plants operated by the SC.

The SC estimates the potential effects of five types of natural calamity (floods, cyclones, tornados, heavy snow falls, and earthquakes) on the plant capacity using a scenario based analysis. Typical capacity losses at plant 1 due to natural calamities under the five different scenarios as well as the probabilities of the occurrence of the scenarios are shown in Table 7. For example, at plant 1 under scenario 3, the natural calamity 1 (flood) may cause a capacity loss of 0.005 (i.e., $\frac{1}{2}$ of one percent), and the probability of this scenario is 10%. Although it is understood that the generation of such data is difficult, we assume that similar data may be estimated based on the historical data on the effect of similar calamities on some other plants in other regions of the globe.

The five scenarios assumed are: no impact, low impact (0.25 to 1 day of production loss at the plant per year), moderate impact (1.25 to 4 days of loss per year), strong impact (10 to 15 days of loss per year), and severe impact (20 or more days of loss per year).

Based on historical data on disaster effects and mitigation options adopted by industries and government agencies, the SC assumes six mitigation options (as discussed in Section 3.4) along with their maximum possible mitigation effects achievable. Table 8 displays typical data on the estimated mitigation effects of each option that are assumed in this study, along with the fixed and variable costs of adopting and implementing the options. To illustrate, the maximum possible mitigation effect of option 1 (“providing training to the employees to take timely steps on self-rescue, rescue of fellow employees, protecting properties, informing

state, national and international rescue teams (where applicable and possible), aid and protection agencies”) when calamity 1 (flood) hits is 0.12, the fixed cost of implementing the option is \$4,908 (over the planning period of the project), and the variable cost per percentage mitigation is \$1,141.

In addition to the above input data, we also assume randomly generated data for product prices, input costs, fixed and variable costs of manufacturing, and various quality system costs in order to solve the model which have not been presented here.

4.2. Model Solution

To solve the proposed bi-objective non-linear model LINGO 14 solver was used on a Dell PC (Latitude series computer, 4 GB RAM, Intel Core i7 2620 M CPU). The model involved a total of 6,013 variables including 561 nonlinear and 1,307 integer variables, and 4,103 constraints. We obtained most of the solutions within one to two hours on average.

Table 9 presents the Pareto optimal solutions for Objective 2 (the overall profits) vs. Objective 1, as well as the corresponding revenue and total cost for each solution. The solutions are also displayed in Figure 1 and identified as S1, S2... S11. As column 4 in Table 9 indicates, the revenues corresponding to the solutions are constant. This is because the model constraint (17) manages the total shortages resulting from various failures by taking supplies from the partner and pool plants if the shortage amount does not exceed their combined capacities.

Pareto optimal Solution 10 generates the highest overall performance resilience metric (referred to as *MR* henceforth) value of 132.67 and the lowest profits of \$ 9.50 million. It also generates revenues of \$17.40 M and incurs total costs of \$7.9 M. As the model attempts to increase the profits, the *MR* values gradually decrease from 132.67 to 128.0 for solution 2, which corresponds to the maximum profits of \$11.54 M, as can be seen in Table 9. Thus for solutions 2 to 10, the *MR* values vary in the range of 128.0 to 132.67, the profits vary in the range of \$11.54 M to \$9.50 M, and the total costs vary in the range of \$5.86 M to \$7.9 M. It may be noted here that the *MR* values may fall below 128.0, and the profits may exceed \$11.54M, but the corresponding solutions will not be able to fulfill the market demands given the current conditions under which the SC operates. Similarly, the *MR* values cannot exceed 132.67 given the fact that the plant availability cannot be made 100% and the potential failure probability for a natural calamity cannot be zero.

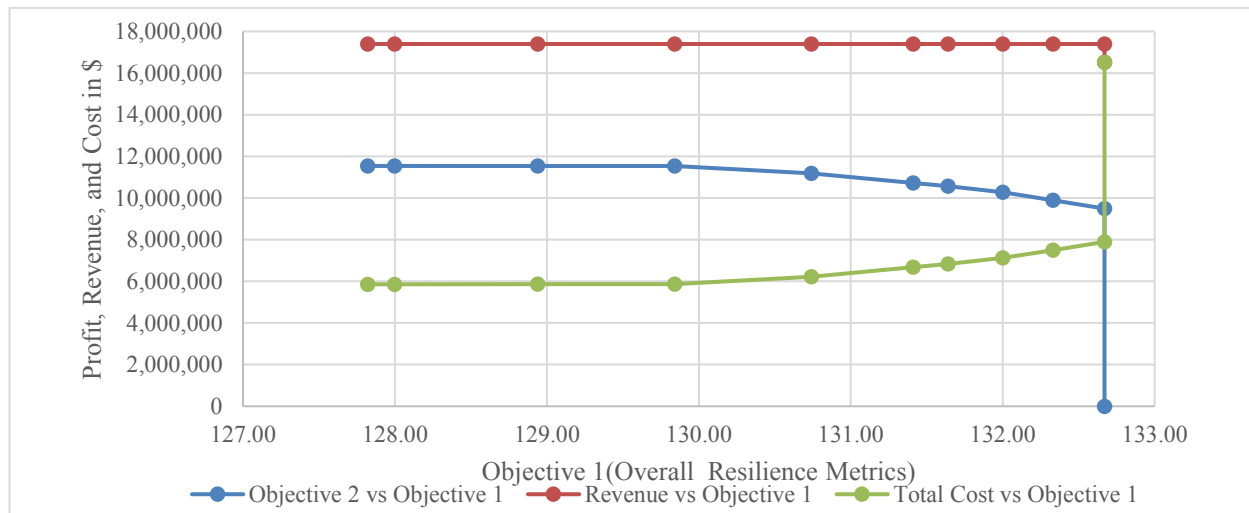


Figure 1. Pareto Optimal Solutions

Table 10 shows the typical model output for production system resilience metric (PSR , see equation (4)) for some product-plant combinations for solutions 2 and 10 of Table 9. For example, considering solution 2, the PSR value for product 1 produced in plant 1 is 0, i.e., $PSR_{11} = 0$; and the PSR value for product 1 produced in plant 2 is $PSR_{12} = 0.947011$, that is, this combination has the capability of containing 94.7% of the risks. The reason we have $PSR_{11} = 0$ is that the model has not assigned product 1 to plant 1 as it is not quality capable to produce this product (See Table 1).

The overall performance resilience metric value in objective 1 provides information on the resilience status of the entire production system but it does not guide the managers to the limitations or action points. As such, understanding the PSR_{pj} values for product-plant combinations is important for decision making on resilience improvement. For example, the reasons why $PSR_{11} = 0$ or $PSR_{32} = 0$, could be traced back to quality capability of plants 1 and 2 using the PSR_{pj} solution for product-plant combinations only. As another example, we discuss the reasons why the PSR_{pj} values for solution 10 in Table 10 are the same in each column; or why the $PSR_{1,10}$ and PSR_{33} values differ between solutions 2 and 10? To explain, we consider the model equation (4) for the definition of PSR_{pj} and equations (2) and (3) for the definitions of its components. For solution 10 the model selected each of the best values for INR_{pj} and EXR_{pj} .

Typical model output presented in Tables 11-14 would also help to provide an answer. Table 11 describes the typical model output for external risks effects EXR_{pj} and internal risks effect INR_{pj} on PSR_{pj} values. For solutions 2 and 10 external risk effects EXR_{pj} are the same. It may also be observed in Table 10 that for a given plant j the PSR_{pj} values for solution 10 are the same for the entire set of products p , except when the product is not produced in the plant (i.e., $PSR_{pj} = 0$). This is because the effect of natural calamity is product independent (See constraints 30-32). For example, the external risk effect for product 1-plant 1 combination is $EXR_{11} = 0.00$; and for product 2-plant 1 we have $EXR_{21} = 0.976$. That is, the effects of external calamities are to reduce the plant capacity to 97.6% of its normal value, for this particular combination.

The results for the internal risk effects on resilience metrics of solutions 2 and 10 are similarly displayed in Table

11. For example, in solution 2, for product 3-plant 3 combination, $INR_{33} = 0.757$. That is, for this product-plant combination, the effects of internal disruptions are to reduce plant 3's available time to 75.7% of its normal value. The effects of INR_{pj} on risk resilience metrics for product-plant combinations have been defined in equation (2) as a function of production losses due to supply management (IP_{pj}) and quality management (IQ_{pj}) failures in addition to production losses due to maintenance policy A_j^m .

For solution 10, the model assigned only 850 units of each of the inputs 1,3,7,9,14,17, 20,22 and 23 to AQ suppliers 3,4,4,1,10,10,13,2, and 10, respectively, as may be seen in Table 12. These inputs are assigned to AQ suppliers since HQ suppliers could not accommodate these quantities. The model assigned the remaining inputs to HQ suppliers to improve the INR_{pj} values to maximize objective 1, despite the fact that the average cost of inputs from HQ suppliers are higher than that of AQ suppliers. For example, the highest cost for input 1 from AQ supplier 17 is \$9.0 per unit, compared to the lowest cost of \$13.39 from HQ supplier 15. By this strategy of assigning as much of the input amounts as possible to HQ suppliers, the model ends up with only 25 units of production shortage for product 16 at plant 10 as may be observed in Table 13. As such, in solution 10, $IP_{pj} = 0$ for each product-plant combination except for $IP_{16,10}$ which is equal to $25/5621 = 0.0044$, as computed in model constraint (33) and shown in Table 14. Thus, the model improved the INR_{pj} values for solution 10 but increased the total cost (TC) due to the use of inputs from HQ suppliers. Also, the solution made $QP_{pj} = 0$ because the model assigned production only to the quality capable plants following constraint (18) and (19).

Table 12 presents typical input procurements from AQ and HQ suppliers for solution 2. For example, the model procured the entire requirements of input 1 (i.e., 142,820 units) from AQ supplier 3. In fact, in solution 2 all the input requirements are procured from AQ suppliers only. For solution 2, the model objective is to maximize MR after achieving the profit target of \$11.54M. As such, and as expected, solution 2 attempted to assign as much inputs as possible to AQ suppliers to achieve the profit requirements and then to maximize the MR . To achieve the profit target, procuring cheaper inputs is an obvious step. However, the

inputs from AQ suppliers ($z_{a_{is}}$) generated production losses (x_{spj}) (computed in equation (22), and shown in Table 13) that in turn result in percentage production losses (IP_{pj}) for some product-plant combinations due to supply management failures, as shown Table 14. For example, we observe in Table 13 that, in solution2, a shortage of 1191 units of product 3 has been generated in plant 3 due to input quality failures. This production shortage is equal to $1191/6250 = 0.190$, or 19% of the capacity of plant 3 to produce product 3, which is the value of IP_{33} in Table 14, as computed in equation (33).

With the exception of few select values (for example $INR_{1,10}$; $INR_{5,10}$; $INR_{3,3}$) the INR_{pj} values in solution 2 as shown in Table 12 are essentially the same as in solution 10. This is because, the model selected the option of making quality failure cost $QP_{pj} = 0$ for all solutions by assigning production to quality capable plants. Now, the PSR_{pj} for solutions 2 and 10 may be verified from the model output in Table 12. For example, for solution 10,

$$\begin{aligned} PSR_{11} &= EXR_{11} * INR_{11} = 0 \\ PSR_{21} &= EXR_{21} * INR_{21} = 0.9763 * 0.97 = 0.947011 \\ PSR_{31} &= EXR_{31} * INR_{31} = 0.9763 * 0.97 = 0.947011 \end{aligned}$$

Similarly, for solution 2,

$$\begin{aligned} PSR_{11} &= 0.0 \\ PSR_{21} &= 0.9763 * 0.97 = 0.947011 \\ PSR_{31} &= 0.9763 * 0.97 = 0.947011 \\ PSR_{33} &= 0.9763 * 0.756908 = 0.7389692 \text{ (see Tables 11, and 10)} \end{aligned}$$

Table 15 provides the managerial insights for deciding flexibility creation based on the costs and expected revenue. As shown in the Table, there is a production loss of 3,751 units in solution 10. However, the model decision is to procure 3,096 units from the partner plants, and 655 units from the pool plants, for a total of 3,751 units, to manage the shortfalls. In solution 2, the production losses are 5,146 units, and the model decision is to procure 3,967 units from the partner plants, and 1,179 units from the pool plants, for a total of 5,146 units, to cover the losses. The production losses had the potential to generate revenue losses of \$1,304,988 and \$1,789, 982 in solutions 10 and 2, respectively. By spending only \$494,125 (in solution 10) and \$685,604 (in solution 2), the model decision enabled the SC to avert the potential revenue loss amounts. A question that may arise is, why there are production shortages in solution 10, which corresponds to the maximum overall resilience metric value. The reasons are: 1) machine availability cannot be made 100%; 2) the probability of natural calamity cannot be eliminated; 3) the model had to take some inputs from AQ suppliers since HQ suppliers could not accommodate all the requirements (see Table 13). By providing support to AQ suppliers to improve their quality, the SC can transform AQ suppliers to HQ status which enhances the MR value.

The next question is, why the total cost (TC) for solution 10 is so high as to make such a large difference in gross profits. The main reason is the input cost (\$4.93 M in solution 10, compared to \$2.75M in solution 2) due to the fact that in solution 10 the decision is to procure the maximum possible inputs from HQ suppliers which are more expensive than AQ suppliers.

The above analysis of the model solutions establishes the effectiveness of the model in integrating resilience

measures with the SC decision making process to investigate the details of failure effects, controllable factors, and flexibility options to enable SC managers in taking suitable decisions for achieving performance targets from a set of Pareto optimal solutions.

4.3. Examining the effect of natural calamity on production planning decisions

Table 16 summarizes the results of a study in which the typical effects of the natural calamities on the performance of the plants are studied under different conditions, and their impact on the overall SC performance is examined in terms of the resilience index (MR), profits and the total cost as they pertain to Solution 10 in Table 9, as a typical example which emphasizes the maximization of the resilience index (MR). The study will provide the SC managers with insights into the impacts of natural calamity variations on the SC performance.

The data given in Table 7, are the calamity effects on a typical plant (plant 1 for example), and are considered as the base case. Instance 1 in Table 16 is generated by multiplying the base case data by a randomly generated multiplier using U (0.75, 1.5), and solving the model as before. As a result, the MR value and the profits decrease slightly, whereas the total cost increases slightly. Since the range for the randomly generated multiplier includes decreases (1:00 to 0.75) as well as increases (1.01-1.5), the overall effects do not differ significantly from the base case.

Instance 2 is similarly generated by multiplying the base case data by a randomly generated multiplier using U (1.25, 1.75). Thus, in this case the natural calamities have a larger effect on the performance of plant 1. As is shown in Table 16, we observe a decrease in the MR value (from 132.67 to 131.03), a decrease in profits (from \$9.49M to \$9.42M) and a slight increase in the total cost (from \$7.90M to \$7.98). This is expected because an increase in calamity effects should negatively affect the resilience index and the profits which in turn will increase the cost.

In the third case, the base case data are generated in a similar manner, but the multiplier is chosen randomly using U (0.5, 0.75). Thus, in this case the natural calamities have a smaller effect on the performance of plant 1. As expected, there is an increase in the resilience index (from 132.67 to 134.06), an increase in profits (from \$9.49M to \$9.56M), and a slight decrease in the total cost (from \$7.90M to \$7.84M). This seems logical as a decrease in calamity effects should have a positive effect on the resilience performance and the profits.

5. CONCLUSION

The research introduced a production system risk resilience measure (PRY) and integrated it into the SC decision making process through a bi-objective SC production planning model. The model includes the workable part of PRY as one of its objectives by defining it as the production risk resilience metric to enable the SC managers to monitor the resilience status and pinpoint the measures to be taken to improve the production system resilience status. The remaining part of PRY is integrated in the model to support SCs to bounce back when an achievable resilience status cannot fulfill market requirements. The model considers the interrelationship among controllable

operational factors, various cost impacts, and resilience metric to optimize the overall production system resilience status (objective function 1) and the overall profits (objective function 2) while fulfilling the market demand effectively. The model provides the SC managers with a range of Pareto optimal solutions and a what-if analysis framework to examine trade-offs in the decision making process to achieve the business objectives. The model includes the option of focusing on each product separately with respect to quantity realization, quality, and supply management to initiate steps for maximizing profits while creating a desired resilience status. The scope of the future research is to explore the applicability of the model in a real world business context.

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Appendix- Tables

Table 1: Production capacity and quality capability status for plants

Product	Parameters	Production Capacity in Units and Quality Capability Status (QA) of Plants										
		1	2	3	4	5	6	7	8	9	10	11
1	Capacity	4150	3794	3255	4286	3163	3948	3290	3514	3265	4000	4800
	QA	0	1	1	1	1	1	1	1	1	1	0
2	Capacity	3666	4147	3595	3858	4261	4013	4554	4227	3796	4210	4680
	QA	1	1	0	1	1	1	1	1	1	0	1
3	Capacity	5457	6170	6250	5403	6407	6024	5856	5997	5984	6200	6450
	QA	1	0	1	1	1	1	1	1	1	1	0
4	Capacity	2793	3138	3555	32443	2842	3895	3059	3475	3703	3802	3800
	QA	1	1	1	0	1	1	1	1	1	0	1
5	Capacity	4012	3501	4094	3572	3741	0	3926	4122	3581	4122	4321
	QA	1	1	1	1	1	0	1	1	1	1	0
6	Capacity	6922	6445	6883	6568	6840	5957	6486	6292	3000	7250	6850
	QA	1	1	1	1	0	1	1	1	1	1	0
7	Capacity	3213	3881	4300	2000	4142	3661	3977	4067	3161	4500	4750
	QA	1	1	1	1	1	1	1	0	1	1	0
8	Capacity	6511	6876	7226	6928	7270	6599	6825	7470	4000	6900	7500
	QA	1	1	0	1	1	1	1	1	1	0	1
9	Capacity	4628	4801	4336	4800	4105	4647	3975	4887	4110	5100	5655
	QA	1	0	1	1	0	1	1	1	1	1	0
10	Capacity	0	5341	5353	5005	5057	5554	5154	5575	5700	6500	6010
	QA	0	1	1	1	1	0	1	1	1	0	1
11	Capacity	4530	3246	3354	3778	3392	3997	3500	3814	3493	4900	4985
	QA	1	1	1	1	1	0	1	1	1	1	1
12	Capacity	0	5023	4507	4418	5022	5088	4893	4550	4221	5144	5950
	QA	0	1	1	1	1	1	0	1	1	1	0
13	Capacity	4796	4898	4344	4322	4790	3919	4416	4019	4714	5000	4600
	QA	1	1	1	0	0	1	1	1	1	1	1
14	Capacity	3714	0	3710	4048	3140	3182	3598	3709	3963	4142	5210
	QA	1	0	1	1	0	1	1	1	1	1	0
15	Capacity	3650	3555	4185	4118	3869	3727	4132	3906	4275	4300	4231
	QA	0	1	1	1	1	0	1	1	1	1	1
16	Capacity	5245	5531	5010	5009	4581	5152	5450	5538	5152	5621	6500
	QA	1	1	0	1	1	1	1	1	1	1	0

Table 2: Product Supplying Capacity of Pooled and Partner Plants

Products	Product supplying capacity of Pooled Plants							
	1	2	3	4	5	6	7	8
1	872	845	691	677	894	671	737	957
2	968	817	862	732	663	864	709	778
3	1379	1069	1152	1264	1344	1228	1084	1247
4	772	695	848	695	702	581	758	825
5	1061	925	939	820	818	997	1062	837
6	1504	1378	1641	1234	1263	1577	1397	1351
7	698	690	868	913	773	729	820	794
8	1480	1686	1788	1405	1395	1712	1264	1448
9	973	1079	884	1030	846	949	838	957
10	906	1246	1003	1217	1134	1099	1007	1045
11	961	1014	916	998	934	1034	1074	806
12	1012	802	797	906	775	1000	999	789
13	1049	1107	1108	762	913	950	866	994
14	613	866	718	691	836	779	655	754

Products	Product supplying capacity of Pooled Plants							
	1	2	3	4	5	6	7	8
15	859	918	751	941	795	777	747	916
16	1325	1277	1258	1271	1121	1189	1037	1152
Products	Product Supplying capacity of Partner Plants							
	1	2	3	4	5			
1	1384	2076	1782	1514	1507			
2	1663	2011	2049	1461	1355			
3	1931	1906	2109	2105	2694			
4	1782	1113	1369	1704	1354			
5	1500	1926	1742	1223	1859			
6	2683	2563	2236	2331	2139			
7	1455	1754	1093	1084	1585			
8	1067	2476	3254	3277	2392			
9	1773	2272	1369	1317	1667			
10	2054	2268	2091	2379	1850			
11	1229	1640	2176	1795	1772			
12	1930	2199	1386	1813	2096			
13	2229	2087	2105	1964	2068			
14	1858	1420	1533	1899	1364			
15	1232	1266	1362	1559	1614			
16	2322	2247	1983	2295	1832			

Table 3: Demand for Products in the Market

Products	Demand for product in the Markets						
	1	2	3	4	5	6	7
1	3900	3422	4136	3931	3052	3301	3904
2	4289	3624	4025	3341	4359	3904	4048
3	5866	5648	5633	5357	5832	5806	5543
4	3469	2987	2702	3613	3442	2852	3627
5	3566	4137	4272	3506	3880	3797	4680
6	6644	5820	6914	6504	6205	6448	6121
7	3967	3703	3282	3923	3890	3432	3638
8	7343	6363	6792	7308	7157	6873	7003
9	4010	4568	4080	3984	4658	4102	4095
10	5087	5153	5488	4933	4566	5271	4465
11	3879	3552	4728	3545	3585	3534	3631
12	3942	4452	4931	4876	4002	3803	4955
13	4703	3985	3965	4034	4406	3943	4406
14	3848	3534	3892	3253	3207	3294	3445
15	4105	4224	3847	4040	3644	3490	3951
16	4878	4918	4898	4950	5449	4823	5178

Table 4: Typical affiliated HQ suppliers for the inputs

Input	HQ Supplier
1	1,5,8,9,11 and 15
2	1,2,3,6,13, and 17
3	2,5,6,8,14,16, and 18
4	1,5,9,12,17,and 18
5	3,4,5,10,15,16,17,and 18
6	2,5,6,9,10,14,16, and 18
7	8,9,10,11,12,13, and 16

Table 5: Input usage data for the products

Product	Input Usage (One Unit for Each Type)				
	1	2	3	4	5
1	1,5,8,10,12,16,23, and 24	7	1,2,5,8,15,18 and 22	13	4,5,7,10,15,18 and 24
2	1,3,11,16,18,19, and 23	8	4,9,13,15,17,19,20,and 21	14	6,8,11,12,15,22 and 24
3	2,4,10,13,18,20,23 and 24	9	2,5,8,10,13,18,20 and 21	15	5,10,11,12,13,22, and 24
4	2,6,7,10,14,16, and 19	10	2,5,8,14,18,21 and 24	16	1,3,7,9,14,17,20,22 and 23
5	1,5,9,11,16,19,21, and 24	11	1,3,7,9,14,17 and 20		
6	4,6,9,10,12,14,17, and 24	12	3,4,6,14,18,21, and 24		

Table 6: Plant maintenance data

Maintt. Policy		Availability and Average Annual Cost Data for the Plants										
		1	2	3	4	5	6	7	8	9	10	11
Break-down	Avail ability	0.78	0.80	0.77	0.81	0.79	0.77	0.78	0.80	0.76	0.78	0.76
	Cost /year	9,000	6,500	18,000	9,880	18,500	12,500	9,301	7,500	7,800	4,800	5,600
Preventive	Avail ability	0.86	0.88	0.86	0.88	0.85	0.87	0.89	0.86	0.88	0.87	0.86
	Cost /year	9,500	9,050	22,000	13,655	22,500	17,800	15,000	9,500	8,500	7,600	6,800
Condition-Based	Avail ability	0.97	0.97	0.935	0.955	0.975	0.96	0.97	0.98	0.96	0.97	0.95
	Cost /year	12,000	13,250	28,000	16,000	26,000	19,000	17,254	11,250	16,000	11,200	12,900

Table 7: Typical average effect of natural calamities on capacity of plant 1 under various scenarios

Natural Calamity	Percentage Effect of Calamities on Plant Capacity Under Various Scenarios				
	1	2	3	4	5
1	0	0.001	0.005	0.04	0.08
2	0	0.004	0.02	0.04	0.06
3	0	0	0.02	0.06	0.08
4	0	0	0.02	0.04	0.08
5	0	0	0.02	0.06	0.08
Probability of Scenario	0.35	0.5	0.1	0.045	0.005

Table 8: Typical data for disaster mitigation options

Calamity	Parameter	Maximum Mitigation Effects and Cost Data for Options					
		1	2	3	4	5	6
1	Mitigation Effect	0.12	0.13	0.14	0.12	0.11	0.15
	Fixed Cost (\$)	4,908	4,330	1,828	2,337	4,835	1,952
	Variable Cost per % Mitigation	1,141	1,564	1,477	1,838	1,105	1,157
2	Mitigation Effect	0.15	0.13	0.09	0.13	0.12	0.14
	Fixed Cost (\$)	3,319	2,512	2,729	3,904	1,583	4,031
	Variable Cost per % Mitigation	1,908	1,985	958	836	1,264	667

Table 9: Pareto optimal solutions for overall resilience performance metric and profits

Solution	Objective 1	Objective 2	Revenue	Total cost	Short	Model Objective
	Resilience Metric (MR)	Profit \$	\$		Supply units	for solution
1	127.82	11,539,809	17,397,200	5,857,391	0	Max Objective 2
2	128.00	11,539,809	17,397,200	5,857,391	0	Max Obj. 1 s.t. Obj. 2 ≥ \$11.54M
3	128.94	11,539,210	17,397,200	5,857,990	0	Max Obj. 2 s.t. Obj. 1 ≥ 128.94
4	129.84	11,533,310	17,397,200	5,863,890	0	Max Obj. 2 s.t. Obj. 1 ≥ 129.84
5	130.74	11,179,610	17,397,200	6,217,590	0	Max Obj. 2 s.t. Obj. 1 ≥ 130.74

Solution	Objective 1	Objective 2	Revenue	Total cost	Short	Model Objective
	Resilience Metric (MR)	Profit \$	\$		Supply units	for solution
6	131.41	10,720,000	17,397,200	6,677,200	0	Max Obj. 1 s.t. Obj. 2 ≥ \$10.72M
7	131.64	10,562,430	17,397,200	6,834,770	0	Max Obj. 2 s.t. Obj. 1 ≥ 131.64
8	132.00	10,275,860	17,397,200	7,121,340	0	Max Obj. 2 s.t. Obj. 1 ≥ 132.0
9	132.33	9,900,000	17,397,200	7,497,200	0	Max Obj. 1 s.t. Obj. 2 ≥ \$9.9 M
10	132.67	9,496,903	17,397,200	7,900,297	0	Max Obj. 2 s.t. Obj. 1 ≥ 132.67
11	132.67	00	16,512,410	16,512,410	2,512	Max Objective 1

Table 10: Typical resilience metrics for product-plant combinations of solutions 2 and 10

Performance Resilience Metrics of Solution 2 for Each Product-Plant Combination											
Product	1	2	3	4	5	6	7	8	9	10	11
1	0	0.947011	0.912841	0.932367	0.951893	0.937248	0.947011	0.956774	0.937248	0.764881	0
2	0.947011	0.947011	0	0.932367	0.951893	0.937248	0.947011	0.956774	0.937248	0	0.763469
3	0.947011	0	0.738969	0.932367	0.951893	0.937248	0.947011	0.956774	0.937248	0.947011	0
4	0.947011	0.947011	0.912841	0	0.951893	0.937248	0.947011	0.956774	0.937248	0	0.76135
5	0.947011	0.947011	0.912841	0.932367	0.951893	0	0.947011	0.956774	0.937248	0.755165	0
Performance Resilience Metrics of Solution 10 for Each Product-Plant Combination											
Product	1	2	3	4	5	6	7	8	9	10	11
1	0	0.947011	0.912841	0.932367	0.951893	0.937248	0.947011	0.956774	0.937248	0.947011	0
2	0.947011	0.947011	0	0.932367	0.951893	0.937248	0.947011	0.956774	0.937248	0	0.927485
3	0.947011	0	0.912841	0.932367	0.951893	0.937248	0.947011	0.956774	0.937248	0.947011	0
4	0.947011	0.947011	0.912841	0	0.951893	0.937248	0.947011	0.956774	0.937248	0	0.927485
5	0.947011	0.947011	0.912841	0.932367	0.951893	0	0.947011	0.956774	0.937248	0.947011	0

Table 11: Typical internal and external risk effect on resilience metric values of Table 10

Product	Typical External Risk Effect (EXRp) on Resilience Metrics of Product-Plant Combinations for Solutions 2 and 10										
	1	2	3	4	5	6	7	8	9	10	11
1	0	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0
2	0.976	0.976	0	0.976	0.976	0.976	0.976	0.976	0.976	0	0.976
3	0.976	0	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0
4	0.976	0.976	0.976	0	0.976	0.976	0.976	0.976	0.976	0	0.976
5	0.976	0.976	0.976	0.976	0.976	0	0.976	0.976	0.976	0.976	0
Product	Typical Internal Risk Effect (INRp) on Resilience Metrics of Product-Plant Combinations for Solution 2										
	1	2	3	4	5	6	7	8	9	10	11
1	0	0.970	0.935	0.955	0.975	0.96	0.970	0.980	0.960	0.783	0
2	0.970	0.970	0	0.955	0.975	0.96	0.970	0.980	0.960	0	0.782
3	0.970	0	0.757	0.955	0.975	0.96	0.970	0.980	0.960	0.97	0
4	0.970	0.970	0.935	0	0.975	0.96	0.970	0.980	0.960	0	0.780
5	0.970	0.970	0.935	0.955	0.975	0	0.970	0.980	0.960	0.773	0
Product	Typical Internal Risk Effect (INRp) on Resilience Metrics of Product-Plant Combinations for Solution 10										
	1	2	3	4	5	6	7	8	9	10	11
1	0	0.970	0.935	0.955	0.975	0.960	0.970	0.980	0.960	0.970	0
2	0.970	0.970	0	0.955	0.975	0.960	0.970	0.980	0.960	0	0.95
3	0.970	0	0.935	0.955	0.975	0.960	0.970	0.980	0.960	0.970	0
4	0.970	0.970	0.935	0	0.975	0.960	0.970	0.980	0.960	0	0.95
5	0.970	0.970	0.935	0.955	0.975	0	0.970	0.980	0.960	0.970	0

Table 12: Model solution for input procurement from AQ and HQ suppliers

Typical Input Procurement from AQ Supplier in Solution 2								
Input	AQ suppliers		No. of units ($z_{a_{is}}$)		Inputs	AQ suppliers		No. of units ($z_{a_{is}}$)
1	3		142,820		5	13		200,530
2	7		178,320		6	1		122,780
3	4		120,100		7	1		113,690
4	4		193,590		8	4		140,414
No Inputs Procured from HQ Suppliers in Solution 2								
Input	AQ suppliers	No. of units ($z_{a_{is}}$)		Input	AQ suppliers	No. of units ($z_{a_{is}}$)		Input
Inputs Procured from AQ Suppliers in Solution 10 (Units)								
1	3	850		9	1	850		20
3	4	850		14	10	850		22
7	4	850		17	10	850		23

Note: all the remaining inputs procured from HQ suppliers in solution 10

Table 13: Model output for production losses due to input quality failures

Production losses due to input quality failures in solution 10								
Product	Plant	Production Loss (units)		Product	Plant	Production Loss (units)		Product
16	10	25						
Production Losses Due to Input Quality Failure in Solution 2								
1	10	769		7	4	775		13
2	11	828		8	11	1465		14
3	3	1191		9	3	885		15
4	11	681		10	9 and 11	1049		16
5	10	835		11	11	794		
6	7 and 10	1350		12	4	929		

Table 14: Model solution for % capacity shortage effect due to production losses related to input quality failures

% of Capacity Shortage Effect Due to Production Losses from Input Quality Failures in Solution 10								
Product	Plant	IP_{pj}		Product	Plant	IP_{pj}		Product
16	10	0.0044						
% of Capacity Shortage Effect Due to Production Losses from Input Quality Failures in Solution 2								
1	10	0.192		7	4	0.387		13
2	11	0.177		8	11	0.195		14
3	3	0.190		9	3	0.204		15
4	11	0.179		10	9 and 11	0.095 and 0.846		16
5	10	0.203		11	11	0.159		
6	7 and 10	0.179 and 0.025		12	4	0.210		

Table 15: Comparison of solutions 10 and 2 with respect to flexibility options, costs and revenue

Model output items	(Solution 10) Max Profits s.t. $MR \geq 132.67$	(Solution 2) Max MR, s.t. Profits $\geq \$ 11.54M$
Overall Resilience Metric MR	132.67	128.0
Gross Profit \$	9,496,903	11,539,809
Revenue Earned \$	17,397,200.	17,397,200
Total Cost	7,900,297	5,857,391
Production Cost	2,180,958	2,319,595
Input Cost	4,931,157	2,752,107
Quality System Cost	486,204	483,708
Maintenance Cost	182,854	182,854
Calamity Mitigation Option Cost	119,127	119,127
Overall Product Demand, Units	50,096	50,096

Model output items	(Solution 10) Max Profits.s.t.MR ≥ 132.67	(Solution 2) Max MR, s.t. Profits ≥\$ 11.54M
Products Sold, Units	50,096	50,096
Production Losses, Units	3,751	5,146
Flexibility creation and advantage cost \$	494,125	685,604
Potential Revenue Losses \$	1,304,988	1,789,982
Products From Partners Plants, Units	3,096	3,967
Products From Pool Plants, Units	655	1,179

Table 16: Typical effects of the natural calamities on plant 1 and the overall supply chain performance

Base Instance: Data From Table 7						Overall SC performance			
Natural Calamity	Percentage Effect of Calamities on Plant 1 Capacity Under Various Scenarios					Model objective for solution	MR	Profits	Total Cost
	1	2	3	4	5				
1	0	0.001	0.005	0.04	0.08	Maximize Objective 1	132.67	0	\$16.51M
2	0	0.004	0.02	0.04	0.06	Max Obj2 s.t. Obj1 ≥132.67 (Solution 10 in Table 9)	132.67	\$9.49M	\$7.90M
3	0	0	0.02	0.06	0.08				
4	0	0	0.02	0.04	0.08				
5	0	0	0.02	0.06	0.08				
Instance1: Base Instance % Effect * U (0.75,1.5)						Overall SC performance			
Natural Calamity	Percentage Effect of Calamities on Plant 1 Capacity Under Various Scenarios					Model objective for solution	MR	Profits	Total Cost
	1	2	3	4	5				
1	0	0.001	0.007	0.043	0.095	Maximize Objective 1	132.18	0	\$16.41M
2	0	0.003	0.018	0.045	0.079	Max Obj. 2 s.t. Obj. 1 ≥132.18	132.18	\$9.47M	\$7.92M
3	0	0	0.026	0.089	0.1				
4	0	0	0.015	0.059	0.08				
5	0	0	0.028	0.067	0.084				
Instance2: Base Instance % Effect * U (1.25,1.75)						Overall SC performance			
Natural Calamity	Percentage Effect of Calamities on Plant 1 Capacity Under Various Scenarios					Model objective for solution	MR	Profits	Total Cost
	1	2	3	4	5				
1	0	0.002	0.009	0.063	0.116	Maximize Objective 1	131.03	0	\$16.53M
2	0	0.007	0.032	0.066	0.103	Max Obj. 2 s.t. Obj. 1 ≥131.03	131.03	\$9.42M	\$7.98M
3	0	0	0.033	0.078	0.114				
4	0	0	0.028	0.053	0.102				
5	0	0	0.028	0.084	0.134				
Instance3: Base Instance % Effect * U(0.5,0.75)						Overall SC performance			
Natural Calamity	Percentage Effect of Calamities on Plant Capacity Under Various Scenarios					Model objective for solution	MR	Profits	Total Cost
	1	2	3	4	5				
1	0	0.001	0.003	0.018	0.033	Maximize Objective 1	134.06	0	\$16.56M
2	0	0.002	0.012	0.019	0.042	Max Obj. 2 s.t. Obj. 1 ≥\$134.06	134.06	\$9.56M	\$7.84
4	0	0	0.009	0.018	0.049				
5	0	0	0.012	0.036	0.046				
Probability of Scenario	0.35	0.5	0.1	0.045	0.005				