Risk Mitigation and Disaster Readiness in a Global Supply Chain: An Integrated Strategic Model

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Abstract

A strategic planning model for mitigating several of the supply and production management-related risks faced by a Global Supply Chain (GSC) that involves multiple suppliers, plants, and distribution centers (DC) in a multiproduct-based business process. Supply risks are prevented by integrating a pool of approved, high quality and profit-loss-sharing partner-type suppliers in the supply chain (SC) using critical-to-quality (CTQ) and critical-to-business (CTB) factors within the model. The model ensures the allocation of production to plants that are approved using CTQ and CTB factors, defined by GSC, to mitigate the risks that stem from quality and safety-related product failures. The model also creates provisions for disaster readiness by providing inventories at select global locations to ensure capability in an affected market through the non-affected ones. Finally the paper describes a step-by-step procedure to solve the model using an example problem.

Keywords: Global Supply Chain, Risk Mitigation, Disaster Readiness, CTQ and CTB Factors, Supplier Affiliation Process, Plant Approval Process

1. Introduction

Most of the progressive and growing companies of this decade are either globally operated, or trying to go global in response to the current market challenges. This is because, even if a business is not operating globally, it still faces global competition at its doorstep. There are several other compelling reasons to globalize, such as cutting manufacturing costs, and proximity to emerging and high growth markets (Xu and Noziak , 2009); low labor costs, access to raw materials, the regulatory environment, and operating conditions (Sounderpandian *et al.*, 2008); and obtaining solutions to complex product or service requirements from the global sources of expertise (Harland *et al.*, 2003). While globalization may offer the above benefits, it also creates several risks that, if not handled effectively, may prove severely disruptive to a business.

Risks associated with global business processes have been widely covered in the recent literature. Zsidisin (2003) used a case study to explore the supply risks that result from supplier capacity limitations, including the potential occurrence of incidents such as natural or manmade disasters and their effect on the inbound supply. Harland *et al.* (2003) discussed the risks arising from complex and dynamic supply networks, arguing that due to several supplier expectations, including technological collaboration, design participation and product complexity management, the function of supply networks has become messy and ineffective—a fact that ultimately elevates network risk. Tang's (2006) comprehensive SC risk management review explained SC risks in terms of operational and disaster risks. Based on the review of several quantitative models from the literature, Tang's presentation provided a broad-based guideline for managing operational risks through appropriate supply, demand, product and information management approaches. To manage disaster risks, Tang suggested including a robust operational strategy—the creation of enough efficiency and resiliency to provide an SC with the ability to withstand disaster risks. Goh *et al.* (2007) proposed a single product-based stochastic optimization approach for managing global SC risks that spring from exchange rates, transfer prices, export/import tariffs, and uncertainties in operational business parameters through the opening and closing of plants and shipment quantity decisions to markets from the plants.

Based on the responses of 760 German executives, Wagner and Bode (2006) concluded that a firm's characteristics—such as dependence on a single customer or a single supplier, degree of single sourcing and reliance on global supply sources—were relevant to SC risks. Xu and Nozick (2009) considered supplier capability disruptions to be a risk of the SC process, and proposed a model for supplier selection that would assist global companies in making a decision between taking a trade-off based on the cost and risks of selecting suppliers in various categories, or taking the option contracts. Based on empirical research conducted among Chinese migrant workers, Jiang *et al.* (2008) studied the operations-related risk that arose from employee job dissatisfaction due to low pay and poor working conditions—influenced by alternative job availability as well as indifference to educational level and worker experience during employment. Wilson (2007) studied the GSC business disruptions that could arise from transportation, and Wu *et al.* (2007) proposed a network-based approach analyzing disruption propagation in the SC using Petri-nets. Wu *et al.*'s study would help SC managers develop a plan for managing SC risks based on the propagation dynamics and timing—as obtained from analysis. Burlingame and Pinerio (2007) addressed the risks that stemmed from food items as a result of quality and safety failures at the primary user's end.

Sarathi (2006) recommended redundancy creation at every SC link as a counter measure to disaster mitigation. Creating redundant resources at each link may seem expensive, but it could be justified when risk potentials grow high. Sheffi and Rice (2005) recommended creating either redundancy or flexibility in the SC as a mitigation approach. According to the authors, redundancy was more expensive because it involved adding more safety stock, a higher number of suppliers and adding more slack capacity. Creating flexibility was considered a better and more cost effective option. In an extended comprehensive study, Tomlin (2005) considered six flexibility options for creating counter measures. Each of the six options—acquiring business interruptions insurance, adding inventories, multiple supplier sourcing, increased production, alternate route to market and demand management—was considered separately as well as in combination with others as countermeasures in the analysis.

Based on an analysis of the various approaches and countermeasures proposed in the literature for effectively managing the catastrophic incidents such as hurricanes or terrorist attacks, Knemeyer *et al.* (2009) presented a comprehensive list that included, 1) assuming the risks or not taking any measure for small risks, 2) buying insurance to offset potential losses, 3) reducing dependence on key locations, 4) investing in key locations to minimize consequences, and 5) moving key locations to safe places. Hsu and Wallace (2007) proposed an enterprise information highway-based subject infrastructure SC integration model for monitoring and controlling SC network flow. The authors proposed the digitization of information on facilities and individual subjects of movement that would provide real-time monitoring and control of materials in movement. This highway-based information integration model would enable SCs to take prompt action in case of disasters or other types of risks.

Based on the literature, it is evident that a GSC would be able to mitigate most of the risks and disasters identified if it is able to do three things: plan a robust supply management to obtain quality input at the right time, in the right quantity and at the right price; design a quality-aligned production system to obtain the right quality and quantity of products at the shipment point; and create emergency inventories at selected globally-located DCs for providing quick supplies to a disaster affected market. To create a robust supply and production management system that will be effective across global operations, a GSC should adopt an appropriate quality management system (QMS) and integrate it into the decision model at the strategic level. In a GSC process, products from a manufacturing plant (MP) may be distributed to retailers at diverse geographical locations. Similarly, a supplier plant (SP) may supply inputs to several MPs. As such, it is crucial that the GSC plan a strategic level decision process to restrict supply disruption risks, product non-availability risks and the product recall risks prompted by quality and safety failures at each point of its global operation. To facilitate integration in the strategic model, the proposed QMS may consider CTQ and CTB-based performance metrics defined with respect to quality, safety, environmental, community responsibility, partnering and other crucial business factors for vital operation points relevant to the SPs and MPs. Based on the performance of the SPs with respect to CTQ and CTB attributes, the QMS may affiliate a pool of high quality partner suppliers (*HQS*) and of acceptable quality suppliers (*AQS*) for creating the required flexibility and ensuring the right input quality, quantity and price. A similar procedure may be applied for approving MPs operated globally by the GSC or the network partners to ensure shipment quality and quantity requirements of each market. In the next step, a scenario-based analysis may be framed for creating disaster readiness inventory (DRI) at selected geographical regions. This inventory can then be made available to the disaster-affected markets using central planning to reduce the effect of disaster on business. To make this disaster readiness planning effective, the GSC should also integrate DRI planning at the strategic level. The QMS and DRI-integrated GSC strategic decision process would be able to globally assign the inputs to *HQS* partners, allocate production to quality approved plants, create DRI and distribute it to the locations from where disaster affected areas can be supplied. In the event that *HQS* cannot fulfill input requirements, the GSC would assign inputs to *AQS* and production to approved MPs operated by network partners if the GSC MPs are unable to fulfill the requirements. For GSCs that involve complex multi-country-based retailers, multiple products and multilayered globally-located suppliers, the proposed approach should be able to provide a robust supply and production management and disaster readiness for most of the risks and vulnerabilities identified in the literature.

In the current, complex global market situations, SC managers are facing the challenge of staying ready to address the uncertainties, risks and disasters that their business may encounter on any given day. While the literature is quite rich when it comes to covering risks and proposing innovative recommendations, there is no study that comprehensively addresses the vital GSC problems, or that provides practicable solutions capable of mitigating most of the risks and vulnerabilities. The objective of this research is to develop a suitable QMS and an appropriate DRI, then integrate them into a strategic GSC planning model to obtain a robust supply, quality-aligned production management and the desired emergency supply inventories for disaster affected locations—allowing a GSC to mitigate most of the risks and disasters they can anticipate.

The contributions of this research that distinguish it from the similar studies include:

a) The proposition of a CTQ and CTB factors metrics-based QMS for affiliating SPs at different quality levels based on their performances;

b) The application of a similar CTQ and CTB-based QMS for approving MPs operated by the GSC and the network partners based on their performances;

c) The integration of a QMS-based supplier affiliation and plant approval process, with DRI in the strategic, mixed integer programming (MIP) GSC planning model to create a robust supply management, a quality aligned production system, and inventories at select globally-located DCs for mitigating anticipated disasters and risks. The robust supply management ensures that production inputs with the right quality, quantity and price are assigned to *HQS*. It also creates built-in supply flexibility for assigning inputs to the pool of *AQS* in case the *HQS* fails to supply. The quality-aligned production system assures shipment of quality products to retailers through the allocation of production to the approved plants. In addition to supply and production management decisions, the model also provides a complete GSC solution by allocating production to plants, plants to DCs and DCs to retailers in a way that maximizes the overall GSC profit.

d) The development of a solution procedure for resolving the complexity of the proposed strategic MIP GSC planning model.

This paper is organized as follows. Section 2 describes the methodology for affiliating SPs and approving MPs operated by the GSC and the network partners. Section 3 develops the IP-based models/constraints for affiliating SPs, approving MPs and estimating the DRI. The integrated strategic MIP model is also presented in Section 3. Section 4 describes the proposed solution methodology and illustrates the applicability of the model, as well as the solution methodology, with a numerical example. Section 5 concludes and discusses.

2. The QMS-Based Methodology for Affiliating SPs and Approving MPs

GSCs should use quality-based criteria to affiliate their suppliers and approve MPs operated by them as well as by network-based partners. The quality-based criteria proposed here averts business risks and/or mitigates manmade or natural disasters by integrating CTQ and CTB factors relevant to the GSC using multidimensional performance metrics of several critical quality and business attributes. By implementing these criteria, a GSC will ensure the input quality and shipment quality of products, thereby mitigating the effects of the risks and disasters that may arise from supply and production management failures or disruptions, such as product recalls prompted by product quality and safety failures; vulnerability to competition resulting from the low performance of specific, general quality factors; brand and company image deterioration due to a quality failure and the media coverage of that failure.

Here are some examples of how CTQ-based quality attributes and the relevant performance metrics applied to the approval and affiliation process might be defined:

1) ISO 9000 certification: a plant may be given a quality score of 10 if it has been certified/ recertified within the last three years, a score of 7 to 8 if it has been certified/recertified within the previous 3 to 5 years, a score of 5 to 6 if the plant is ready for a certification audit within the next year, a score of 2 to 4 if it is ready for a certification audit within next 3 years, and a score of 0 otherwise.
2) Scrap/rejection rates: the average quality score may be defined as (-2)*(highest scrap rate)/2%.
3) Retailer complaints: average retailer complaints per month during the past year can be defined as CC, with the quality score for retailer complaints being (-2)*(CC/3).

The GSC management may consider several other CTQ attributes, such as *Baldrige award winner, Baldrige award applicant, 6-sigma quality system,* and *lean manufacturing system follower*.

The risks that can be mitigated using CTB factors for affiliating SPs and approving MPs operated by a GSC or its network partners include: non-competitive product cost, employee safety related-disasters, community safety-related disasters, major plant breakdowns, supply/delivery failures, employee-created sabotage/disruptions, and natural disasters.
Here are some examples of how to define CTB-based critical attributes and the relevant performance metrics that may be applied in the approval and affiliation process:

1) Maintenance system performance: if OEEL is the lowest OEE (overall equipment effectiveness), considering all the plants in a factory, then the quality score value is OEEL*5/0.8.
2) Inventory turns: if the total inventory turns equal 6 to 9, the score is 1, with a score of 3 for inventory turns from 9 to 12, and a score of 5 for inventory turns of 24 or more. A score of 0 would be applied for inventory turns below 6.
3) Safety performance: if the number of reported lost-time accidents is RL, then the safety-related quality score is (-RL*2).

Depending on the importance imparted to the factors, a GSC may also consider several other CTB attributes, such as: *employee turnaround*; *supplier reliability* and *ISO 14000 certification.* The CTQ and CTB attributes listed above are by no means exhaustive, and the GSC management should identify the attributes specific to their business, and design the performance metrics accordingly. The attributes, as well as the performance metrics, for affiliating SPs may be different from those used in the MP approval process. Once the attributes have been identified and the metrics are defined, the GSC's Quality Management Department (QM) can decide on an acceptable score value for each CTQ and CTB attribute, based on the importance they would like to impart to each attribute. In the next step, the QM sets the threshold limits for the acceptable total quality-score values required for their supplier affiliation process, as well as their plant approval process. Based on the output of the affiliation and approval model, production will be allocated only to the approved quality plants (*AQP*s) and input orders will be allocated only to the affiliated or acceptable quality suppliers (*AQS*s). It is possible to identify high-quality suppliers (*HQS*s) among the *AQS*s by looking for very high quality-score values.

A GSC may also identify partnership attributes, by defining performance metrics and threshold values following the same procedure as the affiliation process to select partner suppliers (PRs). Examples of typical partnership attributes and metrics include:

1) Flexible supply capacity: agrees to accommodate changes in the component order quantity at any time using a contract price; metric can be 10 if they agree, 0 otherwise.
2) Ownership of a design and development department: agrees to participate in the component design based on a contract; metric can be 5 if they agree, 0 otherwise.
3) Established lean six sigma follower: agrees to implement cost cutting measures based on supply contract; metric can be 5 if they agree, 0 otherwise.

Using a structured survey tool/informal feedback procedure from the *HQS*s on their agreement and attitude towards long term business prospects, a GSC may select profit-loss sharing partner suppliers (*PRS*) from several countries. The GSC management may procure from *AQS*s using spot buying rate, using short term contract from *HQS* and long term profit and loss sharing contract for *PRS*.

3. The Integrated Strategic GSC Planning Model (ISGPM)

This section includes the problem statement, the affiliation model for SPs, the approval model for MPs, the disaster readiness provision, and the formulation of ISGPM.

3.1 Problem Statement

Here we describe the business process problem of a GSC that manufactures a set of products P, in a set of plants I, located in a set of countries C, using inputs R, supplied by globally located suppliers S. The product p ($p \in P$) is transported from plant i ($i \in I$) to DC j ($j \in J$), located at diverse geographical locations, and distributed from there to retailer k ($k \in K$) in country c ($c \in C$). DCs are located near the retailer locations to ensure quick response to the retailers at a reasonable overall cost. The SC planning pursued by the company includes: 1) supply risk mitigation (SRM) strategy, by creating a robust supply management served by three types of suppliers—*AQS*, *HQS* and *PRS*; 2) product recall risk mitigation (PRM) strategy, by integrating a QMS in the supply and production management to ensure CTQ and CTB factors at the supply points for inputs and product shipment points; and 3) natural or man-made disaster mitigation (NDM) strategy, by using inventory and networking with several other similarly engaged businesses. These steps are included in the strategic level to ensure they are effectively applied to all the entities in the GSC.

The model's objectives are to mitigate the risks associated with the supply, product delivery, product recall, and to provide disaster readiness to ensure allocation of inputs to the right supplier, production to quality approved plants, transportation of products to DCs and distribution and delivery of required quantities of products to retailers according to the retailer expectations of lead time, cost and quality, while maximizing the profits.

3.2 Affiliation Model for the SPs

The terms *supplier* and *SP* refer to supplier plants in this paper. The supplier affiliation model using the CTQ and CTB-based attributes, described in the last subsection, is presented in this section. The indices, parameters and variables are described in the Appendix.

Objective function: **maximize** $SPLR= \sum_{r\in R}\sum_{s\in S}\sum_{c\in C} (l_{rsc} + q_{rsc} + g_{rsc})$ (1)

s.t.

$$AF_{rsc}QA \le \sum_{q\in Q} QS_{rscq} \qquad \forall r,s,c \qquad (2)$$

$$AB_{rsc}BA \le \sum_{a\in A} BS_{rsca} \qquad \forall r,s,c \qquad (3)$$

$$AF_{rsc} \le AB_{rsc} \qquad \forall r,s,c \qquad (4)$$

$$q'_{rsc}QH \le \sum_{q\in Q} QS_{rscq} \qquad \forall r,s,c \qquad (5)$$

$$q'_{rsc} \le AF_{rsc} \qquad \forall r,s,c \qquad (6)$$

$$AF_{rsc} - q'_{rsc} = l_{rsc} \qquad \forall r,s,c \qquad (7)$$

$$g_{rsc}TP \le \sum_{d\in D} PS_{rscd} \qquad \forall r,s,c \qquad (8)$$

$$g_{rsc} \le q'_{rsc} \qquad \forall r,s,c \qquad (9)$$

$$q'_{rsc} - g_{rsc} = q_{rsc} \qquad \forall r,s,c$$

(9.1)

$$(AF_{rsc}, AB_{rsc}, l_{rsc}, q'_{rsc}, q_{rsc}, g_{rsc}) \in \{0,1\} \quad \forall r,s,c \qquad (10)$$

The objective function in Equation (1) maximizes the number of *AQS*, *HQS* and *PRS* partners based on the cumulative performance of SPs with respect to the CTQ and CTB attribute metrics. This objective function will not be needed if supplier affiliation is solved with overall strategic GSC planning model. Constraints (2) and (3) affiliate suppliers based on their metric scores for CTQ and CTB attributes, and the relevant threshold values set by a GSC's QM. Constraint (4) affiliates suppliers that qualify for both the CTQ and CTB attribute metrics. Constraint (5) selects HQSs based on the cumulative metric scores for CTQ attributes. Constraint (6) ensures the affiliation of suppliers before they are qualified to be HQS. Constraint (7) identifies pools of *AQS* and *HQS* in a distinct way from the entire set of affiliated suppliers. Constraint (8) identifies suppliers that may be considered for *PRS*s, based on their partnership attribute scores and the relevant threshold value set by the GSC management. Constraint (9) ensures that a *PRS* is selected from a pool of *HQS*s only. Constraint (9.1) distinctly identifies the *HQS* and *PRS* pools. Constraint (10) imposes integrality.

3.3 MP Approval Model

As previously described, a GSC may use CTQ and CTB attributes that are similar to the supplier affiliation process for factory approval. The simplified model for factory approval is presented below:

$$ap_{ic}PQ \le \sum_{q\in Q} QP_{icq} \qquad \forall i,c \qquad (11)$$

$$ab_{ic}PB \le \sum_{a\in A} BP_{ica} \qquad \forall i,c \qquad (12)$$

$$ap_{ic} \leq ab_{ic} \qquad \forall i, c \qquad (13)$$

$$(ap_{ic}, ab_{ic}) \in \{0,1\} \qquad \forall i, c \qquad (14)$$

Constraints (11) and (12) check the manufacturing plants (GSC or network partner-operated) for compliance with CTQ and CTB requirements using the cumulative score values and the relevant threshold limits. Constraint (13) ensures that an approved plant complies with both the CTQ and CTB requirements set by the QM. Constraint (14) imposes integrality.

3.4 Disaster Readiness Provision

Suppose that, in a year, there will be some type of disruption, such as natural calamities, terrorist attacks, employee created problems, huge transportation accidents, severe productivity problems due to plant breakdowns, or other production problems. If we assume, in general, that at least one type of disaster happened during the last decade, the probability of business disruption due to these events can be from 0 to 10 % per year. A scenario-based analysis may then be carried out to create disaster readiness inventory provisions for products and inputs. The following four scenarios are assumed:

- Increasing trend in terrorist threats
- Unstable financial indices
- Prediction of natural calamities
- Miscellaneous (such as employee created problems, transportation delays due to border congestion, transportation accidents, or a big plant breakdown)

These scenarios are common for a GSC in any market. For each scenario the probability of disaster in the market and its effect on product demand is assumed to be different. Practically speaking, each geographical location will have a different disaster probability, resulting in different effects on product demand. A GSC should plan provisions for extra inventory only in selected DCs, considering the fact that if the GSC has this product in safe condition during a disaster in any country or market location, it can supply the product to disaster-affected markets, whether global or local, using a centralized planning option. Such a centralized planning would stretch over a period of at least one year, so it may become a part of the strategic planning.

The DCs selected to create inventory should exist in a comparatively safe location in terms of the anticipated disasters. We assumed a disaster likelihood metric on a scale of 0 to 10 for each disaster type at each DC. The cumulative metric values (CMV) based on the entire set of disaster types for a DC indicates the comparative position of the DC in terms of disaster safety. If, for example, we consider 4 disaster types on the assumed scale of 0 to 10, then, for practical reasons, the CMV for a set of DCs are assumed to be 10, 11, 12, 13,….40 ; and the DC that has the minimum CMV is the safest one. The following model would be integrated into the strategic model to create a disaster recovery inventory (DRI) model:

$$IDP_{pkc} = \sum_{o \in O} PD^{o}_{pkc} DF^{o}_{pkc} \qquad \forall p, k, c \qquad (15)$$

$$ID_{pkc} = IDP_{pkc} D_{pkc} \qquad \forall p, k, c \qquad (16)$$

$$\sum_{j=1}^{J} DR_{jc} = 1 \qquad \forall c \qquad (17)$$

$$DI_{jc} \leq M \cdot DR_{jc} \quad \min j \in J \qquad \forall c \tag{18}$$

$$DRI_{pjc} = DR_{jc} \sum_{k \in K} ID_{pkc} \qquad \forall p, j, c \tag{19}$$

$$DRjc \in \{0,1\} \qquad \forall j,c \tag{20}$$

Constraint (15) computes the extra units of the product as a percentage of the average product demand needed for a retailer location based on the probability-of-disaster scenarios and the anticipated percentage increase in demand for the given scenarios. Constraint (16) estimates the product demand increase based on the annual forecasted demand and the estimated percentage increase from scenario-based analysis. Constraint (17) creates the provision of DRI at only one DC in a country. Constraint (18) selects the safest DC within a country considering the CMV for each DC. Constraint (19) determines the inventory of each product type for the selected safe global locations. Constraint (20) imposes integrality.

3.5 The ISGPM

The strategic GSC model that integrates the CTQ and CTB metrics-based QMS, and the disaster readiness provision, is presented here.

Strategic Global Supply Chain Model
Objective Function: **maximize** *Profit PV* (21)

PV= Revenue (*REV*)- Production cost(*PRC*)-Distribution cost(*DRT*)- Input cost (*INC*) - Quality System Cost (*QSC*)-Disaster readiness cost (*DRC*) (22)

where:

$$REV = \sum_{c \in C} EX_c \sum_{p \in P} \sum_{k \in K} V_{pkc} \sum_{j \in J} Y_{pjkc} \tag{23}$$

$$PRC = \sum_{c \in C} EX_c \left[\sum_{p \in P} \sum_{i \in I} C_{pic} \sum_{j \in J} \sum_{c' \in C} X_{picjc'} + \sum_{i \in I} FP_{ic} u_{ic}) \right] \tag{24}$$

$$DRT = \sum_{c \in C} EX_c \{ \sum_{p \in P} \sum_{j \in J} \sum_{k \in K} Y_{pjkc} CD_{pjkc} + \sum_{j \in J} FD_{jc} w_{jc} \} \tag{25}$$

$$INC = \sum_{c \in C} EX_c \sum_{r \in R} \sum_{s \in S} \left[\sum_{i \in I} \sum_{c' \in C} Z_{rscic'} CI_{rscic'} + FS_{rsc} (q_{rsc} + g_{rsc} + l_{rsc}) \right] \tag{26}$$

$$QSC = \sum_{r \in R} \sum_{s \in S} \sum_{c \in C} \sum_{i \in I} \sum_{c' \in C} Z3_{rscic'} CI_{rscic} .IC + \sum_{s \in S} \sum_{c \in C} QM_{sc} \sum_{r \in R} (g_{rsc} + q_{rsc} + l_{rsc}) + \sum_{i \in I} \sum_{c \in C} QAS_{ic} u_{ic} \tag{27}$$

$$DRC = \sum_{c \in C} EX_c \, h. \sum_{p \in P} \sum_{k \in K} V_{pkc} ID_{pkc} D_{pkc} \tag{28}$$

$$Y_{pjkc} = D_{pkc} a_{jkc} \qquad \forall p, j, k, c \qquad (29)$$

$$\sum_{j \in J} \sum_{c' \in C} X_{picjc'} \leq PC_{pic} u_{ic} \qquad \forall p, i, c \qquad (30)$$

$$u_{ic} \leq ap_{ic} \qquad \forall p, i, c \qquad (31)$$

$$\sum_{i \in I} \sum_{c \in C} X_{picjc'} \leq WC_{pjc'} w_{jc'} \qquad \forall p, j, c' \qquad (32)$$

$$\sum_{k \in K} Y_{pjkc'} \leq \sum_{i \in I} \sum_{c \in C} X_{picjc'} \qquad \forall p, j, c' \qquad (33)$$

$$a_{jkc} \leq w_{jc} \qquad \forall j, k, c \qquad (34)$$

$$\sum_{c'' \in C} \sum_{s \in S} Z_{rsc''ic'} = \sum_{p \in P} \rho_{rp} \sum_{j \in J} \sum_{c \in C} X_{pic'jc} \qquad \forall r, i, c' \qquad (35)$$

$$\sum_{i \in I} \sum_{c' \in C} Z1_{rscic'} \leq SQ_{rsc} g_{rsc} \qquad \forall r, s, c \qquad (36)$$

$$\sum_{i \in I} \sum_{c' \in C} Z2_{rscic'} \leq SQ_{rsc} q_{rsc} \qquad \forall r, s, c \qquad (37)$$

$$\sum_{i \in I} \sum_{c' \in C} Z3_{rscic'} \leq SQ_{rsc} l_{rsc} \qquad \forall r, s, c \qquad (38)$$

$$Z_{rscic'} = Z1_{rscic'} + Z1_{rscic'} + Z3_{rscic'} \qquad \forall r, s, c, i, c' \qquad (39)$$

$$\sum_{i \in I} \sum_{c' \in C} Z_{rscic'} - SQ_{rsc}(g_{rsc} + q_{rsc}) \leq (1 - qg_{rsc})BN \qquad \forall r, s, c \qquad (40)$$

$$-SQ_{rsc}(q_{rsc} + g_{rsc}) + \sum_{i \in I} \sum_{c' \in C} (Z1_{rscic'} + Z2_{rscic'})\} \leq qg_{rsc} BN \qquad \forall r, s, c \qquad (41)$$

$$l_{rsc} \leq (1 - qg_{rsc}) \qquad \forall r, s, c \qquad (42)$$

$$a_{jkc}, w_{jc} \in \{0,1\}, \forall j, k, c; \; qg_{rsc}, u_{ic} \in \{0,1\}, \forall r, i, c \qquad (43)$$

The objective function in equation (21) maximizes profits. Equation (22) computes profits by considering the revenue earned and various GSC costs. According to Equation (23), revenue *REV* is earned by supplying products to the retailer at the market price. Equation (24) computes *PRC*, the production cost by considering the estimated production cost for a product and the fixed cost of opening a plant. The distribution cost, *DRT,* in Equation (25) computes the cost of distributing the products from the DCs to the retailers. Equation (26) computes the input cost, *INC,* based on the cost of inputs and the fixed cost of placing input orders to the suppliers. The quality system cost, *QSC,* in Equation (27) includes an inspection cost computed as a percentage of the cost of the items supplied by *AQS*s, and a QMS cost for the approval and quality monitoring relevant to *AQS*, *HQS* and *PRS*. The final Equation (28) of the objective function is the disaster readiness cost, *DRC*, which computes an inventory carrying cost for the inventory provision created for disaster readiness. Equation (29) distributes products to the retailers from DCs that are allocated to the retailers. Constraint (30) limits the production quantity of the plants to their capacity. Constraint (31) ensures that only the quality approved plants open for production. Constraint (32) ensures the transportation of products to DCs according to their capacity.

Constraint (33) ensures the fulfillment of retailer requirements by the quantity produced. Constraint (34) ensures that a DC is opened before it is assigned to the retailers. Equation (35) determines the input requirements for the production quantity. Equations (36) to (38) limit the input supply by *PRS*s, *HQS*s and *AQS*s based on their capacity. Constraint (39) computes the total quantity supplied by the suppliers. Constraints (40) to (42) work in a combined way to ensure that *AQS*s are not allocated input supply when PRSs and HQSs have sufficient capacity to fulfill the entire demand of a plant in a country. These three equations also establish that if *PRS*s and HQSs combined cannot fulfill the entire requirements of a plant's input, AQSs are allocated an input supply after exhausting the entire capacity of the *PRS*s and *HQS*s. Constraint (43) imposes integrality. In this model l_{rsc}, q_{rsc}, g_{rsc}, ap_{ic} and ID_{pkc} are inputs if the models for affiliation of SPs, approval of MPs and DRI are solved separately.

4. Numerical Example

This numerical example involves 5 products produced in 5 MPs, operated by the GSC and its network partners, using 6 inputs supplied by 7 SPs, transported to 3 DCs after production, and marketed, finally, through 8 retailers, with each MP, SP, retailer and DC located in 5 different countries. The input data include: metric values for the 15 CTQ, 10 CTB and 7 partnering attributes; set threshold values for CTQ, CTB and partnering; SP capacities for inputs, MP capacities for production and DC capacities for warehousing; and the costs of procurement, production, transportation, distribution, inspection, quality monitoring and inventory.

The first author's experience in global operations and interaction with global companies suggests that, other than generating basis data for the QMS-based attributes and metrics, most of this data is practically available to any globally operated company. While the model's solution provides several SC management decisions, we will focus mainly on the typical inputs and relevant decisions for quality integration and risk management.

We first solved the ***Integrated Strategic GSC Planning Model*** (**ISGPM**, Sec. 3.5) for the example problem using the commercial solver LINGO 9 on an Intel Core 2, 2.0 GB RAM, 2GHZ processor PC. The problem involved a total of 25,452 variables, including 1,410 integer (0/1) variables, and 9,329 constraints. It took approximately 400 minutes to obtain a global optimal solution.

Considering that the computational requirements of the integrated model are very high (which would be even higher for a real world business case), we resorted to solving the model in two steps, taking advantage of the model structure. We solved ***the Affiliation Model for the SPs*** (Sec. 3.2)***, the Approval Model for the MPs*** (Sec. 3.3)**,** and ***the Disaster Readiness Provision Model*** (Sec. 3.4) in the first step, then integrated the results of these models in the remaining part of the ISGPM solution process. There were no qualitative differences between the results obtained from the stepwise and the integrated models. For this two-step process, LINGO 9 took 2 and 3 minutes, respectively, to provide the global optimal solutions.

Input Data. Table 1 presents typical cumulative/total CTQ, CTB and partnering metric (see Sec. 2 for definitions) scores that have been computed based on each of the 15 CTQ, 10 CTB, and 7 partnering-based attribute metrics assumed and defined for the SPs operating in diverse geographical locations. For example, SP 1 in country 2 could obtain total CTQ, CTB and partnering metric scores of 62, 47, and 30, respectively.

Table 1 Typical CTQ, CTB, and Partnering Metric Scores for Supplying Input 1 by SPs

Supplier plants (SPs)	Total CTQ metrics score					Total CTB metrics score					Total Partnering metrics score				
	by SP types in countries					by SP type in countries					by SP type in countries				
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
1	0	62	36	0	36	0	47	46	0	38	0	30	20	0	30
2	0	0	67	0	50	0	0	44	0	47	0	0	32	0	35
3	0	0	52	41	35	0	0	34	28	45	0	0	35	29	40
4	0	62	53	0	0	0	39	42	0	0	0	27	29	0	0
5	44	51	65	0	58	45	45	31	0	25	42	36	43	0	21
6	47	0	0	41	42	40	0	0	35	31	24	0	0	24	21
7	55	64	0	60	50	48	36	0	30	46	41	32	0	39	25
Threshold Value QA :40, QH : 55						Threshold Value BA: 35					Threshold Value TP: 35				

Table 2 presents the cumulative/total CTQ and CTB metric scores, computed by considering each of the 15 CTQ and 12 CTB attribute metrics defined for the GSC-operated plants 1, 2, and 3, in addition to network partner-operated plants 4 and 5 at the global locations. For example, MP 1 in country 1 obtained total CTQ and CTB metric scores of 44 and 37, respectively.

Table 3 displays the typical anticipated fraction increase ion demand and the probability of demand increase (PD) under four different scenarios (see Sec. 3.4) for retailers 1 and 2, as relevant to product 1, in order to address the extra product demand due to probable disasters. For example, retailer 1 operating in country 1, can expect a 10% increase in demand (demand increase fraction, DF = 0.10) with a probability of 7% (PD= 0.07), under scenario 1.

Table 2 CTQ and CTB Metric Scores for the MPs

Manufacturing Plant (MPs)	Total CTQ metrics score					Total CTB metrics score				
	by MPs in countries					by MPs in countries				
	1	2	3	4	5	1	2	3	4	5
1	44	63	51	58	0	37	50	49	42	0
2	57	58	0	0	64	49	39	0	0	39
3	58	65	62	47	44	45	43	35	39	43
4*	61	0	52	44	0	39	0	40	36	0
5*	0	0	42	62	55	0	0	37	45	42
* network partners	Threshold Value PQ :45					Threshold Value PB:38				

Table 3 Typical Demand Increase Estimation Data

Retailers	Scenarios	Probability of Demand Increase, PD, and Increase in Demand as a fraction of average demand, DF, under Different Scenarios in Countries									
		1		2		3		4		5	
		PD	DF	PD	DF	PD	DF	PD	DF	PD	DF
1	1	0.07	0.10	0.03	0.05	0.04	0.11	0.02	0.12	0.04	0.07
	2	0.09	0.15	0.05	0.10	0.10	0.07	0.06	0.06	0.07	0.05
	3	0.07	0.08	0.08	0.05	0.06	0.08	0.07	0.11	0.06	0.15
	4	0.06	0.12	0.10	0.11	0.01	0.05	0.05	0.07	0.04	0.08
2	1	0.03	0.11	0.04	0.14	0.05	0.07	0.09	0.09	0.09	0.06
	2	0.05	0.11	0.02	0.11	0.02	0.10	0.03	0.06	0.02	0.15
	3	0.09	0.11	0.04	0.05	0.04	0.14	0.09	0.11	0.08	0.08
	4	0.04	0.08	0.05	0.11	0.02	0.12	0.03	0.15	0.07	0.07

Table 4 Model Decision on Supplier Plant (SP) Affiliation for Inputs (R1, R2…R6)

Suppliers	SPs affiliated at *AQS*, *HQS*, and *PRS* levels for inputs (R1,…, R6) in various countries														
	1			2			3			4			5		
	AQS	*HQS*	*PRS*	*AQS*	*HQS*	*PRS*	*AQS*	*HQS*	*PRS*	*AQS*	*HQS*	*PRS*	*AQS*	*HQS*	*PRS*
SP1			R3	R3	R1, R4	R6	R4	R6					R6		
SP2							R2	R1	R5				R1, R2	R4, R6	
SP3							R2, R5	R4		R2, R6	R3	R4			R4
SP4			R3, R5, R6	R3, R5, R6	R1, R2	R1	R6								
SP5	R1, R3, R6	R2, R5	R1, R6	R1, R6	R4	R3	R6	R2					R6	R4	R3
SP6	R1, R2,R3									R1	R2		R6	R3	R5
SP7	R2		R1	R6	R1, R3					R4, R6	R3	R2	R1, R3	R2	

Table 4 presents the crucial model decisions regarding the affiliation of SPs at *AQS*, *HQS*, and *PRS* levels (see Sec. 2) for supplying specific inputs based on the scores obtained for the metrics defined for CTQ, CTB, and partnering attributes (Table 1). For example, SP1 in country 2 could be affiliated at *HQS* level for inputs 1 and 4 (R1, R4, highlighted), but it could also be affiliated at *PRS* level for input 6 (R6, highlighted) and at *AQS* level for input 3 (R3, highlighted). Let us explore the model decision for input 1(R1), for which we have the CTQ, CTB and total partnering metric scores in Table 1. Based on

Table 1, the total CTQ score for SP1 in country 2 is 62, which is greater than QH=55 (the *HQS* threshold limit); the CTB score for is 47, which is greater than BA=35 (the CTB threshold limit); and the total partnering metric score is 30, which is less than TP=35 (the partnering threshold limit). As such, input 1 (R1) for SP1 in country 2 could be affiliated at the *HQS* level, but not at the *PRS* level. A similar explanation of the affiliation of SPs for various inputs in each country may be given. The ISGPM has integrated this decision in Table 4 for subsequent decisions applied to the assignment of inputs to SPs (presented in Table 6) as a way to assure input quality and prevent product recall risks. This is the first and most crucial step of the ISGPM in risk mitigation, considering a complex supply management process for a GSC operation.

The next crucial decision for risk mitigation that the model integrates for subsequent decisions is the quality-based plant approval, which considers the total CTQ and CTB metric scores of the MPs operated by the GSC and its network partners. Table 5 shows the approval decisions of MPs that are integrated in the ISGPM for subsequent decisions. For example, based on Table 5, MP 1 could only be approved for countries 2, 3 and 4 (Y, in yellow), but not for countries 1 and 5. To explain this decision, we notice in Table 2 that MP 1 has no operation in country 5, but in country 1, it has CTQ=44, which is less than 45, and CTB= 37, which is less than 38, the threshold limits. A similar explanation for each plant approval decision in Table 5 may be given.

Table 5 Model Output on Manufacturing Plant (MP) Approval

Manufacturing Plants (MPs)	**Plants in countries**				
	1	2	3	4	5
1		Y	Y	Y	
2	Y	Y			Y
3	Y	Y		Y	
4	Y		Y		
5				Y	Y

Based on the integration of SP affiliations (Table 4) and MP approvals (Table 5), the ISGPM ensures that the inputs are only assigned to the affiliated SPs, and the production is only allocated to the approved MPs.

Table 6 presents the model results, where SP affiliation and MP approval are combined to further the integration process. As an example, input 1 is assigned, by the ISGPM, to the *PRS*s and *HQS*s only, because they could cover the entire requirements of input 1. The fact that SP 7 in countries 1 and 2, and SP 1 in country 2 supplied the entire input 1 quantity to the MPs may be verified from Table 1 which displays the affiliation decisions. We may also verify further integration, where the ISGPM ensured a supply of quality inputs only to the approved plants, as shown in the last two columns of Table 6. It is noted that, input 1, supplied by SP 7 (countries 1 and 2), is allocated to MP3 (in countries 2 and 4) and MP5 (in countries 4 and 5), which are quality approved plants (see Table 5).

Table 6 Typical Model Decision-Assignment of Inputs to SPs Supplied to MPs

Inputs	SPs	Country	Affiliation	Assigned quantity	Supplied to MPs	Country
	7	1	PRS	9,000	3	2
	7	2	HQS	2445	3	4
	7	2	HQS	4500	5	4
	7	2	HQS	3079	5	5
1	1	2	HQS	3,200	2	1
	1	2	HQS	2800	2	2
	1	2	HQS	10405	2	5
	1	2	HQS	2500	3	2
	1	2	HQS	545	3	4

Table 7 presents further integration for a typical production allocation. Here for instance, product 1 is assigned to MPs 2, 3, and 5 in countries 5 and 4; and the units delivered to the DCs from the three plants are 1805, 3000, and 1500, respectively. The ISGPM ensured the allocation of production only to the approved plants, which may be verified using Table 5; as discussed earlier, ensuring the final product quality sent to shipment points is a way of mitigating product recall risks. Table 7 also presents the use of MP 5, which is a plant run by a network partner that provided flexibility to mitigate risks—from product non-availability to the market places when GSC plants cannot meet market requirements.

Table 7 Typical Production Allocation to Plants, and Units Transported to DCs

Product	Manufacturing plants (MPs)	country	Units of product transported to DCs
1	2	5	1805
	3	4	3000
	5	4	1500
2	2	5	3700
	3	2	3300
	5	5	2401

We considered four typical disaster likelihood metrics such as the threat of terrorist attacks, the volatility of financial indices, prediction of natural calamities, potential for man-made disasters (e.g., employee created problems, transportation accidents, prolonged plant break downs, etc). The metrics are evaluated on a scale of 1 to 10. The cumulative scores based on these disaster likelihood metrics obtained by the DCs are shown in Table 8. For example, the disaster likelihood metrics for DC 1 in countries 1,2, ,.., 5 are estimated to be {8,16,.., 23}. The ISGPM allocated DRI to safe DCs based on the cumulative scores in Table 8. Table 9 presents the creation of DRI at safe DCs. For example, for product 1 the model considered DC 1 to be 'safe' in countries 1,2 and 3, and allocated, respectively, 149, 89, and 163 units . It may also be observed in Table 9 that the model further allocated 160 units of DRI to DC2 in country 4, and another 182 units to DC 3 in county 5.

Table 8 Typical Cumulative Metrics for the Disaster Indices of Globally Located DCs

DCs	Cumulative Disaster metric score for the DCs in Countries				
	1	**2**	**3**	**4**	**5**
1	8	16	20	21	23
2	28	19	40	9	36
3	33	32	32	32	9

Table 9 Typical Model Output for Creating Disaster Recovery Inventory (DRI) Globally at Safe DCs

	DRI quantity in the selected safe DCs				
	DC1	DC1	DC1	DC2	DC3
	in countries				
Product	1	2	3	4	5
1	149	89	163	160	182
2	196	224	77	190	201
3	160	130	133	154	122
4	140	164	152	202	164
5	162	124	134	163	103

Based on the ISGPM output analysis, it is evident that the proposed model effectively mitigates the risks associated with product recall, supply management failures, product non-availability, and disasters. As discussed, the model integrated CTQ and CTB-based QMS for affiliating SPs to assure the input quality of production, and to approve MPs that ensure the shipment quality of products to mitigate product recall risks. The model created pools of *AQS*, *HQS* and *PRS*s enabling SC managers in their efforts to obtain the required flexibility and apply contract provisions that effectively prevent supply failure risks. Further, it created the provision of using MPs operated by network partners to obtain production that mitigates risks stemming from the non-availability of product to markets. Also illustrated was the creation of DRI at selected safe DCs in each country, so that GSCs may effectively manage product availability to disaster-affected geographical locations.

5. Conclusion

The proposed research introduced a new approach to the mitigation of the risks of product recall, supply management and production management using a CTQ and CTB integrated strategic MIP-based GSC decision process. The research defined the CTQ, CTB and partnering attributes and relevant metrics in a way that allowed the supplier affiliation and plant approval processes to be effectively integrated in the strategic level GSC decision process. The proposed model is suitable for resolving multi-dimensional CTQ, CTB and partnering-based metrics used to affiliate SPs and approve MPs in a tractable way that ensured input quality to production and product quality to markets. The research introduced an effective approach for planning disaster recovery readiness through the creation of DRI in comparatively safe, select geographical locations. The model created the provision for using pools of partners, HQS's and AQS's and taking inputs from AQS's in case partners or HQS's fail to supply.

To the best of our knowledge, this research is the first to propose a systematic and practicable approach for mitigating product recall risks, supply failure risks, production non-availability risks and a disaster recovery plan. The research also proposes a solution approach for addressing the model complexity when applied to real world problems.

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Appendix

Indices and parameters

a:	CTB attributes;
c, or c':	countries;
d:	PR attributes;
i:	plants;
j:	distribution centers (DC);
k:	retailers;
o:	scenarios;
p:	products;
q:	CTQ attributes;
r:	inputs;
s:	suppliers;

BP_{ica} : performance score for GSC plant i in country c with respect to CTB attribute a

BA : threshold limit for the total CTB performance scores to become an affiliated supplier

BS_{rsca} : CTB score value for supplier s in country c supplying input r, for attribute a

C_{pic} : per unit average cost of producing product p at plant i in country c

CD_{pjkc} : per unit distribution cost of product p from DC j to retailer k in country c

$CI_{rscic'}$: per unit cost of input r from supplier s in country c supplied to plant i in country c'

D_{pkc} : average demand for product p at retailer k in country c

DI_{jc} : cumulative score for disaster indices for DC j in country c

DF^{o}_{pkc} : fraction increase in demand for product p at retailer k in country c under scenario o

EX_{c} : exchange rate between country c and the country where the global company's corporate office is located

FD_{jc} : fixed cost of opening DC j in country c

FP_{ic} : fixed cost of setting up plant i for production in country c

FS_{rsc} : fixed cost of ordering input r by supplier s in country c

h : holding cost as a % of product price

IC : inspection cost as a percentage of the cost of the inputs

IC_{rsc} : per unit inspection cost of input r from supplier s in country c

ID_{pkc} : amount of demand increase for product p at retailer k in country c estimated over all disaster scenarios

IDP_{pkc} : percentage increase in average demand for product p at retailer k in country c estimated over all disaster scenarios

M : a large integer number

PC_{pic} : production capacity of plant i in country c to produce product p

PD^{o}_{pkc} : probability of demand increase for product p at retailer k in country c under scenario o

PS_{rscd} : performance score for supplier s in country c to supply input r with respect to partnering attribute d

PQ : CTQ attributes threshold limit set by QM for approving plants

PB : CTB attributes threshold limit set by QM for approving plants

QH : threshold limit for total CTQ performance scores to become an HQ supplier

QB : threshold limit for total CTB performance scores to become an HQ supplier

QA : threshold limit for total CTQ performance scores to become an affiliated supplier
QS_{rscq} : CTQ score value for supplier *s* in country *c* to supply input *r* with respect to attribute *q*
QM_{sc} : anual QMS cost for affiliating and quality monitoring for supplier *s* in country *c*
QAS_{ic} : annual QMS cost for plant *i* in country *c*
QP_{icq} : performance score for GSC plant *i* in country *c* with respect to CTQ attribute *q*
SQ_{rsc} : capacity of supplier *s* in country *c* to supply input *r*
TP: : threshold limit for partnering attribute score
V_{pkc} : per unit price of product *p* that retailer *k* in country *c* agrees to pay
$WC_{pjc'}$: capacity of DC *j* for product *p* in country *c*
ρ_{rp} : per unit usage rate of input *r* for producing product *p*
UR_{ric} : dummy variable for keeping track of input *r* received at plant *i* in country *c*
DRI_{pjc} : inventory of product *p* maintained at DC *j* in country *c* for disaster recovery
$X_{pic'jc}$: units of product *p* produced in plant *i* in country *c'* and transported to DC *j* in country *c*
Y_{pjkc} : units of product *p* distributed from DC *j* to retailer *k* in country *c*
$Z_{rscic'}$: units of input *r* supplied by supplier *s* in country *c* to plant *i* in country *c'*
$Z1_{rscic'}$: units of input *r* supplied by partner supplier *s* in country *c* to plant *i* in country *c'*
$Z2_{rscic'}$: units of input *r* supplied by HQS supplier *s* in country *c* to plant *i* in country *c'*
$Z3_{rscic'}$: units of input *r* supplied by AQS supplier *s* in country *c* to plant *i* in country *c'*

a_{jkc} : 1, if DC *j* is assigned to retailer *k* in country *c;* 0, otherwise
ab_{ic} : 1, if plant i in country *c* complies with the CTB threshold requirements; 0, otherwise
AB_{rsc} : 1, if supplier *s* in country c qualifies to supply input *r* based on CTB attributes; 0, otherwise
AF_{rsc} : 1, if supplier *s* in country *c*, is affiliated to supply input *r;* 0, otherwise
ap_{ic} : 1, if plant *i* in country *c* is approved based on CTQ and CTB attributes; 0, otherwise
DR_{jc} : 1, if DC *j* in country *c* is selected for keeping disaster recovery inventory; 0, otherwise
g_{rsc} : 1, if supplier *s* in country *c* qualifies to be a partner (*PRS*) to supply input *r*; 0, otherwise
l_{rsc} : 1, if supplier *s* in country *c* is qualified to be at *AQS* level to supply input *r;* 0, otherwise
q_{rsc} : auxiliary 0/1 variable to aid in segregating *PRS* (partner suppliers) from *HQS* (high quality suppliers)
qg_{rsc} : auxiliary 0/1 variable to aid in ensuring the allocation of no inputs to *AQS* but allocation to *PRS* and *HQS* when *PRS* and *HQS* have sufficient combined capacity
q'_{rsc} : 1, if supplier *s* in country *c* qualifies to be at HQS level to supply input *r*; 0, otherwise
u_{ic} : 1, if plant *i* is opened; 0, otherwise
w_{jc} : 1, if DC *j* in country *c* is opened; 0, otherwise