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RISK MANAGEMENT OF COMPLEX SUPPLY CHAINS PART 3: TECHNOLOGIES FOR SUPPLY CHAIN RISK MANAGEMENT

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RISK MANAGEMENT OF COMPLEX SUPPLY CHAINS PART 3:

TECHNOLOGIES FOR SUPPLY CHAIN RISK MANAGEMENT

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EXECUTIVE SUMMARY

Supply chains in the current age are complex networks as the result of globalization, outsourcing and lean initiatives. Globalization increases the complexity of the traditional supply chain yielding more nodes, longer links, greater connection among the links, and more collaboration among the nodes. Outsourcing provides the benefit of economies of scale but at the same time weakens the direct relationship between buyers and suppliers or shippers and carriers. Lean initiatives such as just-in-time practice promote supply chain efficiency as they reduce inventory buffers, which are critical to help a supply chain to sustain and recover when facing disruption risks.

In this complex environment, we hypothesize that the efforts from a single company in the context of a network is far from enough to cover it from many risks, especially those passed down from other companies, or those from risk reactions of a competitor company. The traditional mitigation approaches are limited in those areas. Risk management of complex supply chain networks is thus important and urgently needed, especially when the past decade has witnessed an ever-increasing number of disasters and disruptions to business.

A framework of supply chain risks should be developed to cover all possible types of risks to help companies systematically identify the potential risks. Under an environment of imbedded risks, the network of supply chains should be studied to understand the propagation of such risks. Finally, the technologies to manage supply chain risks should be reviewed in order to determine the state of progress. The three topics are addressed in a series of three white papers conducted by a research consortium of TLIAP, IHPC and SIMTech, which is supported by A*Star to study the implication of risks for a complex supply chain network.

This white paper is one of the series addressing the framework of supply chain risks and complex system. The paper elaborates the need and role of technologies in supply chain risk management. It then focuses on review the various technologies which are necessary for risk tracking and identification, risk analysis and modeling, risk mitigation and monitoring etc. The paper also briefly discusses on the innovation of technology in managing the risks in complex supply chains.

1. THE CHALLENGES AND NEEDS FOR TECHNOLOGIES IN SUPPLY CHAIN RISK MANAGEMENT

As companies are adopting globalization and outsourcing strategies for the purpose of reducing cost and gain competitive advantages, more and more companies from multiple locations with the capabilities of design, material supply, production, assembling, logistics services, and broking services are involved in supply chains. This means that the supply chains are growing in scale, connectivity and range. At the same time, companies have introduced more lean supply chain practices, which reduce the number of suppliers and consolidate production and distribution to focused factories and logistics centers. While this helps in cutting costs, it also incurs vulnerabilities especially when unexpected event occurs. In addition, with the implementation of various supply chain management technologies and applications, many manual processes and transactions become automatic, and more organizations and systems are connected across the supply chains. This implies that the impact of risks could be propagated across the supply chains, and the complexities of supply chains and also the related risks are increasing. Furthermore, we can see that technologies in the world are changing rapidly, and the technological changes bring in challenges and opportunities to supply chain risk management (SCRM). It becomes a necessity to review the status, clarify the need, and identify the gaps of technologies for SCRM, and hence to enable innovative research and practical technology development for SCRM.

1.1 THE VULNERABILITY AND RISKS OF SUPPLY CHAINS

The global market is characterized by turbulence and uncertainty, and the vulnerability of supply chains to disturbance or disruption has increased. There are a number of reasons why today's supply chains are more vulnerable (Christopher 2011; Wagner and Neshat, 2010). 1) Disasters have increased in number and in intensity during the last decades. Natural disasters such as droughts, floods, windstorms, hurricanes, earthquakes or tsunamis strike more often and have a more economic impact (Munich Re, 2006). 2) With the globalization of supply chain, the motivation for offshore sourcing and manufacturing is cost reduction. However long and complex global supply chains are usually slow to respond to change and the definition of cost should not just be limited to the costs of purchasing and manufacturing. 3) While the challenge in today's business environment is how best to combine "lean" practices with an 'agile' response, many companies still focus on efficiency rather than effectiveness. More focused factories and centralized distribution, for example, many faster moving consumer goods manufacturers aim to serve the whole of the western European market through a few distribution centers. 4) Global outsourcing brings with a number of risks, not least being the potential loss of control. Disruptions in supply can often be attributed to the failure of one of the links and nodes in the chain and, by definition, the more complex the supply network the more links there are and hence the greater risk of failure. 5) Reduction of the supplier base: a dramatic reduction in the number of suppliers from which a company procures materials, components, and services. In some cases, this has been extended to 'single sourcing', which is with high risk.

There are many types of supply chain risks which include operational and disruption risks. They can be further cataloged as supply risk, demand risk, process risk, control risk, and environment risk (Christopher 2011). Supply risk refers to risks caused by focused supplier, global sourcing and long supply chain. Demand could be risky due to the volatile demand and the "bullwhip" effect in supply chains. Process risk refers to the risk related with process resilient and bottlenecks. Control risk refers to the disturbances and distortions caused by internal control, such as decision on order quantity, batch size and policies can cause "chaos" effects. Environmental risk refers to external events and disruptions. And supply chain risk can be calculated by a general formula as Supply Chain Risk = Probability of Disruption * Impact.

1.2 THE CHALLENGES AND NEEDS FOR TECHNOLOGIES IN SCRM

With the turbulences in global economy, increasing complexities of supply chains, and the rapid changes in technologies, there are many challenges on the technologies for SCRM.

First, globalization and its consequences are permanent and likely to have a greater impact over time. This growing globalization reduces both the depth and breadth of visibility and traceability achievable. The lack of visibility and traceability increases the risks of not being able to detect and remediate intentional and unintentional compromise which may be introduced through a variety of means, including counterfeit materials or malicious software (Boyens, 2012).

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Secondly, complex supply chain networks (SCNs) are formed by the interconnection of highly interactive subsystems at different levels, whose spatial and temporal characteristics make them significantly heterogeneous. As the SCNs are more-interconnected, non-linear, inter-dependent, global, complex and stochastic in nature, these "risky" characteristics of the SCNs present greater challenges in strategizing risk-mitigation measures during disruption events. The optimal management and execution of such systems must deal not only with issues related to unpredictability and uncertainty, but also with the non-linear interactions between the subsystems, and the overall system stability and optimality during abnormal and disruptive events. These increases in scale, connectivity, range and systems make managing the complex dynamics in supply chains, such as bullwhip effect and speculative behaviors, more difficult.

Thirdly, supply chain managers have to make decisions in more complex circumstances - with rapidly changing conditions, uncertain goals, system dynamics, shortage of information sharing, tight deadlines, numerous constraints, diversified stakeholders, difficult relations with other organizations, political considerations, inherent uncertainty, varied opinions, limited resources and a whole range of other complications. And this means the traditional and standard techniques of analysis and decision-making can be simplistic to deal with all the complexities of the problems (Waters, D., 2011).

In addition, nature disaster, terrorist attack, labor strike and major traffic chaos can all be the cause for supply chain disruption (Berger et al. 2004, Christopher and Lee, 2004; Poirier et al. 2007; Tang, 2006b). In volatile scenarios, the recovery from the disruptions is made more complex by the unintended consequences of localized optimal strategies in one supply chain may impact others in a supply chain network.

Furthermore, traditional approaches have limitations on modeling and managing complex dynamical behaviors and emergent phenomena in supply chains - but they often happen anyway, producing errors and undesired behavior that can bring the supply chain system crashing down. The scenario for SCRM is becoming more complex and challenge and it is difficult well-handled by traditional risk management approach. New approaches to design, engineer, manage and control complex systems are urgently needed. This produces a demand from industry to apply complex systems to SCRM to build systems that are scalable, robust, and adaptive.

These challenges in SCNs request for new technologies in risk tracking and identification, data analysis and assessment, risk modeling, risk planning and mitigation etc. to enable the management of risks in a more complex scenario and in non-traditional ways.

Table 1: Main issues discussed over the years by co-citation analysis (Tang et al. 2011)

T1 (1995–1999)	T2 (2000–2004)	T3 (2005–2009)
Performance	Innovation	Management
Successes	Industry	Systems
Power	Logistics	Model
Entry	EDI	Performance
Strategies	Model	Networks
Order	Management	Information
Quantity discount	Information	Product
Inventory	Organizations	Integration
Management	Interface	Design
Coordination	Perceptions	Products

As shown in Table-1, Tang et al. reviewed more than 200 research papers on SCRM and identified that research on SCRM had experienced a few stages. Stage 1 (1995-1999) mainly is on organization performance, material flow, inventory and coordination risks etc. Stage 2 (2000-2005) mainly is on innovation, interfacing, perceptions, and Staged 3 is more on system performance, networks, information and integration. We can see that the trends on SCRM is more on managing complexity, propagation, integration and networking scenario with increasing scale and connectivity of the supply chains. New technologies for SCRM based on system complexities are more needed by industry for the purpose of preparing their supply chain for unforeseen crises better and improving the future of their supply chain security, and making their supply chain more sustainable and flexibility.

1.3 THE ROLES OF TECHNOLOGIES FOR SCRM

In general, a risk management project will include the phases of risk identification, risk analysis and assessment, responding to risks, monitoring and evaluation (Figure 1). Supply chain risk management is a continuous improvement process with iteration of the above steps. Risk identification is the process of determining events which, if they occurred, could affect project objectives positively or negatively. Risk analysis is the process of evaluating and prioritizing risks, essentially with respect to their characteristics like probability and impact. Risk responding includes planning (contingency planning) and execution processes which aim to coordinate, choose, prioritize and execute actions which can reduce global risk exposure with least cost. Risk monitoring and control is the on-going process of “implementing risk response plans, tracking identified risks, monitoring residual risks, identifying new risks, and evaluating risk process effectiveness throughout the project”.

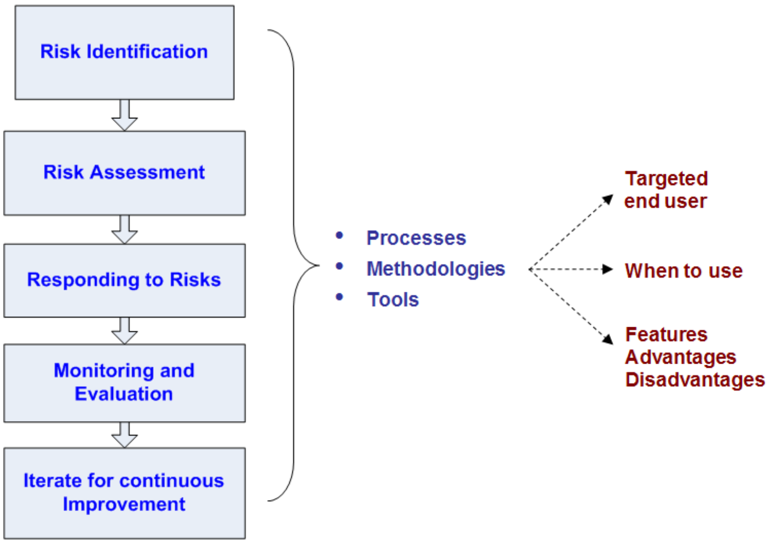

Figure-1: A general SCRM process framework (R. de Souza, M. Goh and F.W. Meng, 2007)

The role of technologies in SCRM is actually to enable and improve the planning and execution of the above phases as follows in our view:

1) Supply chain (risk) tracking, risk identification and alter
2) Data analysis and risk assessment
3) Risk modeling and mitigation
4) Supply chain contingency planning
5) Supply chain risk monitoring and control

The objective of this study is to review the technologies related to the above roles and identify the technology gaps for effective SCRM, and hence support innovative and practical R&D in the domain. To share our views and to stimulate discussion about future technologies on SCRM is also one objective.

The structure of the paper is as follows. Section 1 analyses the challenge, need and role of the technologies for SCRM and clarify the objective of the investigation. Section 2 reviews the technologies for SCRM; Section 3 identifies some gaps in the technologies for SCRM. Section 4 concludes.

2. REVIEW OF TECHNOLOGIES FOR SCRM

Relating to the roles discussed, the technologies for SCRM mainly include supply chain risk tracking and tracing technologies, quantified optimization and simulation technologies for supply chain risk modeling and mitigation, complex systems technology, supply chain contingency planning, and supply chain risk data mining technologies.

2.1 TRACKING & TRACING TECHNOLOGY FOR SC VISIBILITY AND RISK IDENTIFICATION

Visibility allows supply chains to be transparent and minimizes the need for inventory and capacity buffers. The visibility is important to build confidences in the SCNs, which normally is weakened when end-to-end pipeline is long and the visibility in the pipeline is poor. To restore supply chain confidence and break the risk spiral, we must address the two basic elements of supply chain confidence: visibility and control (Christopher and Lee, 2004).

SCRM involves the identification and management of risks among supply chain members including suppliers, manufacturers, distributors, intermediaries, third-party service providers, and customers. It relates to all risk elements involved in sourcing, procurement, production, logistics, transportation and order fulfillment, product services, and finance services etc.

Tracking and tracing technologies, provide the technological capabilities of closed-loop tracking, process automation, and supply chain visibility yield three specific risk management capabilities: increased monitoring capacity, increased response speed, and higher decision-making quality. The tracking and tracing technologies such as Radio Frequency Identification (RFID) and Geographic Positioning System (GPS) are the import enabling technologies for logistics supply chain visibility and tracking (He *et al.*, 2009). Other technologies also permit the tracking and tracing of goods and people, e.g., video surveillance, barcode, GSM, Bluetooth, and are extensively used by enforcement agencies and industries.

Especially, RFID, as a relatively new development in supply chain management, holds great promise for managing supply disruptions and for containing their harmful ripple effects (Tajima M., 2011). RFID is an automatic identification technology that identifies specific items and gathers data on them without human intervention or data entry (Wyld, 2006). Item identification occurs when a reader scans an RFID tag that is tuned to the same frequency as that of the reader. Fundamentally, RFID technology can be summarized by the following characteristics: (a) RFID is wireless. This eliminates product positioning which is associated with barcode scanning. (b) it provides unique identification to an object, and it has a high data capacity than barcode; (c) it traces and tracks objects, and can provide a supply chain wide and real-time visibility of items. Each of these fundamental characteristics leads to an advantage over the existing bar code technology and allows RFID to possess three distinct capabilities: (i) advanced process automation, (ii) closed-loop tracking, and (iii) supply chain visibility (Tajima, 2007).

Although the application of tracking and tracing technologies specific to the area of risk management has not yet been well-explored, the potential for the technologies to enable the visibilities and robustness of the supply chains are observed (Shi et al. 2012).

Typical supply chain risk management consists four phases as shown in Figure 1. For risk tracking and identification, Helferich (2002) indicated that supply chain disruptions could occur from interruptions in production facilities, supplier networks, transportation networks, communication infrastructure, and utility services. It is necessary to make use of the technology which can track and trace the risks along the whole supply chain and to communication the information in the supply chain network, and RFID is the most suitable technology for supply chain risk tracking based on its fundamental features. However, there are quite some challenges in the technology domain of RFID application for handling supply chain risk issues.

First is the privacy issue on applying RFID in supply chain. In RFID systems, each tag contains a unique identifier that is used by the reader to identify the tag. If the unique identifier is transmitted in clear, an adversary can eavesdrop on the wireless channel to identify and track the tag, thereby violating its privacy (Juels, 2006). Such a violation becomes more serious when the tag reveals further information or when background information is available that enables the adversary to link the tag identifier to the identity of the tag's owner (Li, He and Chiew, 2009). Secondly, while RFID is useful for inventory and material handling processes, as soon as the RFID-tagged goods leave the warehouses or factories, one often lose track of them until the next loading docks. In between the sending and receiving points, there is often no tracking of the cargo which may be at risk of missing, off-loading and delay especially if the cargo is critical or perishable. The positioning system such as GPS is usually used to track the vehicle. In SCRM, in order to track and trace cargo seamlessly, it is necessary to provide integrated solution architecture for seamless, global wide, track and trace system for logistics supply chain using an integrated RFID and positioning system technologies (He, Tan, Lee and Li, 2009). Thirdly, the tracking, tracing and identification of risks in supply chains needs to be communicated and shared in a standardized and affordable network. In today's supply chain management, facilitating the use of RFID technology in global supply chains has become a challenge (Li & He 2009). One potential solution is the EPCglobal network which is a platform to pass EPC numbers and leverage on the Internet to access large amount of associated information that can be shared among authorized users. EPCglobal is considered to be the next generation of automatic product identification system to facilitate object track & trace in real time throughout a supply chain (Tan, 2005), and one important purpose of the EPCglobal network is to improve the security in supply chains (He et al. 2009). Questions of concerns include whether a received item is valid, whether an RFID reader is authorized to read its information, and how to keep the information secure among partners in the EPCglobal network. To address these challenges, hundreds of papers have been published in research literature on solving various security or privacy issues. Many international organizations such as Customs Trade Partnership against Terrorism (C-TPAT), Container Security Initiative, and Auto-ID Center are formed to address security issues in various industries (Auto-ID Centre at St. Gallen, 2006). However, for the research for protecting RFID information in global supply chains, there are many issues to resolve before we can achieve a fully collaborative system (Sheu et al., 2006). In particular, there is a lack of unified RFID track & trace scheme to provide authenticity, integrity, privacy and accuracy for syndicated applications in EPCglobal-enabled supply chain networks.

There are many other approaches for supply chain risk identification. Some of them identify risks based on analyze the processes of the supply chain. Bodendorf and Zimmermann (2005) proposed a proactive risk identification approach based on analyzing of supply chain events and activities. Gaudenzi et al. (2006) apply AHP method for supply chain risk identification. Neiger (2008) et al discussed on supply chain risk identification based on value-focused process engineering approach. There are also a number of works on risk identification based on analyzing of source of the risks by linking to at least some supply chain elements and their flows (Juttner et al. 2003; Chopra and Sodhi, 2004; Cucchiella and Gastaldi, 2006; Norrman and Jansson, 2004; Wu et al., 2006). These approaches are more on risk identification and are not on risk tracking and tracing.

2.2 ANALYTICAL OPTIMIZATION TECHNOLOGIES FOR SCR ANALYSIS AND ASSESSMENT

Modern supply chains can be affected seriously during supply chain disruptions and firms may suffer detrimental effects (Wagner, 2010). In line with the frequently cited business wisdom ‘‘You can’t manage what you don’t measure’’, supply chain managers need support in quantified optimization technologies for risk modeling and mitigation. They need to calculate the supply chain risk exposure of a firm and as a consequence determine the effectiveness of SCRM measures. Most of the quantified models focus on external disruptions risks: the supply and outsourcing risks, the demand (delivery) risks, and also quite some risk models are built for the whole supply chain.

For supply risk modeling, Zsidisin et. al. (2003, 2004) presented a factorial risk method to measure supply risk related to products in a supply chain by weighting equal importance for the risk factors identified. AHP based methods for quantifying the risk for suppliers for inbound supply chain operations are proposed by Finnman (2002). Berger et al. (2004) presented a decision-tree based optimization model for supplier selection with risk consideration. Levary (2007) studied a foreign supplier's supply-risk ranking model. Kirkwood et al.(2005) presented a supplier selection model based on cost, quality, responsiveness, strategic issue and operating constraint and Agrell et al. (2004) studied incentive conflicts and coordinating contracts model for outsourcing.

Another hot topic for quantified optimization models is demand disruptions and demand related distribution risks. Kouvelis and Rosenblatt (2002) demonstrated the pervasive effects of financing, tariffs and taxation on shaping the manufacturing and distribution network of global firms. Tang (2006a) elaborated a postponement model for mitigating distribution risks. Nagurney et al. (2005) presented an equilibrium modeling to counter supply and demand risk. Wu (2006) presented an optimization model for optimal operating policy on risk analysis of supply chain enterprises. Sounderpandian et al. (2008) Robust economic order quantity (EOQ) model for managing delivery risks. Fang and Whinston, (2007) studied option contracts and capacity management for enabling price discrimination under demand uncertainty.

Ding (et al 2007) worked on the integration of production and financial hedging decisions by a two-stage stochastic model.

There are also quite a number of quantified models available for managing risks of the whole supply chain. Nagurney, Cruz and Matsypura (2003) developed a model for the modeling, analysis and computation of solutions to global supply chain risks. Goh, Lim, and Meng (2007) developed a model, based on the Moreau – Yosida regularization, to optimize the trade-off between profit and risk for a multi-stage global supply chain network. You et al. (2008) proposed a two-stage linear stochastic programming approach for multi-period planning that takes into account the production and inventory levels, transportation modes, times of shipments and customer service levels of a global multi-product chemical supply chain under demand and freight rate uncertainty. Wagner (2010) proposes a method to quantify vulnerability using the permanent of an adjacency matrix based on graph theory at the economics, industry, and supply chain levels. However, the dynamic characteristics of supply chain vulnerability over time and the consequences therein need further research. Xia and Chen (2011) propose a decision-making model based on the internal triggering and interactive mechanisms in an SC risk system, which takes into account operational process cycle (OPC) and product life cycle (PLC). Tapiero (2005) provides a decision analysis justification for the VaR approach based on ex-post disappointment decision making arguments. It shows that the VaR approach is justified by a disappointment criterion. It also provides its applications to inventory management by quantifying the risk exposure. Chuan et al. (2010) use the VaR method to measure and analyse the fruit market price risk. They show that a Normal distribution is not the optimal distribution model to be applied when assessing fruit market risk as different fruits have different degrees of market risk. VaR currently applied to SCRM is still based on directly measuring the risk in terms of the loss from a structural perspective (Zhang et al., 2012)

As reviewed, publications on analytical research on SCRM increased greatly since 2004. The interests are not only from academic researchers but also from industry practitioners. This indicates a growing awareness of optimization technologies for SCRM in industry, but still there is a lacking of quantitative models for specific risk modeling and analysis needs for SCRM, for example, no much research is on quantitative methods for the disruption risk in terms of a disruption recovery model from a business continuity perspective.

2.3 SIMULATION TECHNOLOGIES FOR SCR ANALYSIS AND ASSESSMENT

Simulation is a powerful tool for analyzing, designing, and operating complex supply chains. It enables one to test hypotheses without having to carry them out, potentially saving you thousands, even millions of dollars. This makes simulation technology very useful for managing disruption risks in supply chain, since quite some of these disruptions are with low probability but high negative impacts.

Discrete-event simulation (DES) has been the mainstay of the Operational Research (OR) simulation community for over 40 years. In DES, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system (Robinson, 2004). Many mechanisms and models have been proposed for carrying out discrete-event simulation; among them are the event-based, activity-based, and process-based approaches (Pidd, 1998).

The arrival of agent-based simulation (ABS) in the early 1990s promised to offer something novel, interesting, and potentially highly applicable to OR. Agent-based modeling is a technique that simulates complex systems from the bottom-up in order to capture their emergent properties. It characterizes a system by allowing individual agents to perform a set of behavior rules which leads to interactions between agents and between agents and their environment. This method of simulation is "founded on the notion that the whole of many systems or organization is greater than the simple sum of their constituent parts" (North, 2007). ABS allows people to model their real-world systems of interest in ways that were either not possible or not readily accommodated using traditional modeling techniques, such as DES (Siebers et al., 2010). In addition, agent-based models can be run repeatedly – even millions of times – to capture rare but large events that result from unlikely synergies between supply chain risk factors. Such low-frequency, high impact events constitute the so-called "long tail" of the risk distribution. In the past, traditional methods to estimate risk failed to capture the real statistics of long tails. Or the estimates have been inaccurate because of the law of small numbers, that is, the tendency of draw broad conclusions from a tiny number of events.

However, there is still relatively little evidence that ABS is much used in the OR community, there being few publications relating to its use in OR and OR-related simulation journals, comparing with that in journals from disciplines such as Computer Science, the Social Sciences, and Economics (Siebers et al., 2010). We may attribute this to the wide availability and experience of the OR community with DES software. However, we see the situation as very likely changing in the future as the number of people developing 'agent-type' models grows, for since the OR community would be called upon to address new kinds of problems that have not been adequately addressed by DES (Siebers et al., 2010).

The simulation technologies have been applied in supply chain management include agent based (Datta, 2007; Chen, 2007), discrete event (Schmitt and Sigh 2009), timed Petri net based simulation (Tuncel, 2010), and Monte Carlo (Schmitt, 2009; Wu, 2008) simulation.

Discrete Event Simulation and Monte Carlo simulation models are the mostly used for supply chain modeling currently. Tako et al. (2012) suggested that DES has been used more frequently to model supply chains, with the exception of the bullwhip effect, which is mostly modeled using SD. Chong et al. (2004) designed a distributed simulation test bed enabling detailed supply chain simulation to study a customer-demand driven semiconductor supply chain. Snyder and Shen (2006) used DES models to contrast supply uncertainty and demand uncertainty in optimal system design. Schmitt et al. (2011) confirmed this result analytically and show that for risk-averse firms, risk diversification generally dominates risk pooling, indicating that risk should be spread and shared across the supply chain. Deleris and Erhun (2005) also used simulation in examining supply chain disruptions. Their Monte Carlo model requires entire branches of a supply chain to be non-functional if a disruption occurs at any stage in the branch. Schmitt and Singh (2009) used a combination of Monte Carlo and discrete-event simulation to model downtime due to disruptions, and they allow the rest of the supply chain to function if a single stage is down (at least for as long as material is available to do so). Schmitt and Singh (2012) quantitatively analyzed disruption risk for a multi-echelon supply chain through simulation. The disruption risk is measured by the amplification of the disruption using "weeks of recovery".

ABS has become a more frequently used technology in supply chain (risk) research. Swaminathan et al (1998) designed agent based simulation models for supply chain, which enable rapid development of customized decision support tools that could certainly include risk management. Li, low and Kumar (2003) developed a multi-agent system based supply chain/logistics coordination systems with focusing on agent interactions in a fourth party logistics scenario. Thadakamalla (2004) developed an agent-based model to show how various supply-chain network topologies fare under attack. The model, built in Netlogo, was originally developed to analyze military supply chain vulnerability to terrorist or military attacks. Li et al. (2008) considered a multi-location inventory system with several retailers who share one supplier. The model, using Anylogic software, considers demand lead-time, replenishment lead-time, and transshipment lead-time. Jirong et al. (2008) proposed a 4-level multi-agent system model for supply chain inventory with a decision-making model for every enterprise agent in the supply chain. Their results confirmed that the information sharing strategy effectively decreases the variation amplitudes of inventory of each enterprise in the supply chain. Krishnamurthy et al. (2008) developed a new inventory control technique for large-scale supply chains, which considered stochastic transport delays, manufacturing times, and repair times and probabilistic characterization of part repair success. Sirivunnabood and Kumara (2009) used an agent based simulation model to determine appropriate risk mitigation strategies for a supply chain network under supplier risks. The model was implemented by the Java Agent Development (JADE) platform.

As reviewed, ABS has the advantage to generalize the impact of disruptions on supply chain networks, provide analysis on risk events occurring instantaneously or events leading up to a supply chain problem. It also can be used to analyze effectiveness of risk mitigation strategies with focus on recovery of the supply chain performances. However, although some supply chain ABS simulations for supply chain/logistics have been done, but almost none have modeled actual organizations and supply chains with sufficient detail to adequately compare alternative policies with practical applications.

2.4 COMPLEX SYSTEMS TECHNOLOGIES FOR SCRM

A complex system is a system composed of interconnected parts that as a whole exhibit one or more properties and emergent behaviors not obvious from the properties of the individual parts (Joslyn, 2000; Mitchell, 2006). Complex Systems are mainly bottom-up approaches that attempt to understand how local changes in the number of individuals and at the micro-level can have emergent behaviors at the macro level.

The increasing interests in complex systems are being driven predominantly by new trends, challenges and demands in practical systems such as economy and supply chain systems. Industry needs to know how to design, manage, build and control systems as they increase in scale and connectivity. They want to be able to build systems that are scalable, robust, and adaptive by using properties such as self-organization, self-adaptation, and manage the disruptions happening in their systems. Complexity science is in a good position of bringing together deep scientific questions with application-driven goals across many interesting domains including supply chain risk management.

Complexity science involves a lot of techniques which can be technically divided into two main approaches: mathematical and simulation based. In the area of mathematics, arguably the largest contribution to the study of complex systems was the discovery of chaos in deterministic systems, a feature of certain dynamical systems that is strongly related to nonlinearity. Mathematical approaches need direct observation on the behaviors of the system given a set of parameters describing the working conditions and inputs for the system. However, exact analytical models are largely unviable. It is therefore more favorable to employ computer techniques to obtain a simulation which combine a partial analytical form with an appropriate learning model (e.g. neural network) to resemble the characteristics of the system. The simulation-based approach creates systematic computer simulations of the interactions within and between agents in a complex system and subsequently monitors (i.e., observe, measure) the emergent behaviors. Agent-based simulation is a tool for studying complex systems and has been discussed in last section.

In general, technologies under Complex Systems can be categorized into five main groups in terms of research topics and issues, namely, (1) evolution and adaptation, (2) game theory, (3) complex networks, (4) dynamic systems, and (5) scalability and stability. Some discussions of the technologies are given as follows:

(1) Evolution and Adoption Approaches for Complex Adaptive Systems: Components of a complex system are found to evolve, self-organize, and improve themselves in order to adapt with the changes of the environment. Such systems are commonly referred to as complex adaptive systems (CAS) (Holland, 2006). CAS interacts with its environment to learn from the process of emergence and adapts with the environmental changes via the constant feedback mechanism (Lansing, 2003). The concept of CAS is applicable to supply chains that constantly evolve in interactions and is constantly changing to gain competitive advantages over its' competitors. The study of CAS focuses on the evolution and adaptation properties. There are various different EA CAS optimization techniques: Genetic Algorithms (GA): (Holland, 1992; Dawkins 2006); Memetic Algorithms (MA): (Ong et al., 2004); Learning classifier systems (Holland, 1976) and Echo Modeling (Forrest and Jones, 1994).

(2) Game theory: It is the study of strategic decision making. More formally, it is "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers" (Myerson, 1991). Among various famous works in this field, Axelrod (1981) argued that Darwins evolutionary theory may not be able to explain the cooperation in organisms and proposed a probabilistic model to study the interactions between pairs of individuals. Gintis (2009) conducted extensive experimental study to prove that people often do not play the best move, even when the move is obvious. In game theory study, one of the challenges lies on modeling the rationale process of the agent within a system, which is still a very much open subject in psychology and social behaviors.

(3) Network Theory: Network Theory is one of the best developed areas of Complex Systems theory (Newman, 2010; Cohen and Havlin, 2010). Strogatz (2001) tried to characterize between different forms of networks by identifying their topology. Newman (2010) presented a wide range of topics, including the measurement and structure of networks, methods for analyzing network data, mathematical models of networks, and theories of dynamical processes taking place on networks. Cohen (2010) used a range of examples, from the stability of the internet to efficient methods of immunizing populations to explain the theoretical methods commonly used, and the way experimental results can be analyzed. Network theory enables companies to evaluate the risk of interconnected business systems such as supply chains. Quite some researches have recently focused on "scale-free networks" (Bonabeau, 2007).

(4) Dynamic Systems: Dynamic Systems is another well-developed area. In dynamic systems study, behaviors of the components over time are represented individually or collectively by simple mathematical time models which allow their interactions to be studied.

Dynamical systems are normally divided into continuous and discrete dynamics. The former are typically modeled using differential equations and allow us to observe emergent behaviors such as chaos and bifurcations behaviors (Strogatz. 1994. Barrat, 2008). The latter makes use of discrete time steps and serves as a tool for understanding emergent phenomena in the systems (May, 1976). In Dynamical Processes on Complex Networks, Barrat et al. (2008) presented a comprehensive explanation for the effects of complex connectivity patterns on dynamical phenomena. Strozzi et al. (2007) presented a classic beer game which represents an excellent example of system that can be easily modeled using simple mathematical equation but the emergent behaviors are enormous.

The reason to apply complex systems approaches on SCRM is to handle the challenges on managing the increasing complexities in scale, connectivity, range, system and risks in supply chains. While many research works have been carried on managing risks in single supply chain, supply chains are more complex today and risks may propagate cross the networks. It is a trend and a necessity to study comprehensive SCRM approaches in a more complex network scenario with Complex systems approaches.

More and more people use complex systems approaches for supply chain risk analysis, modeling and mitigation although the number of research work is still limited. Naraharisetti (2009) divided risk management decisions into system representation, modeling and simulation, synthesis and design, planning and scheduling, as well as control and supervision. Bonabeau (2007) discussed on managing supply chain complexity risk and stated that the internal weakness of a system tend to reveal themselves in times of external turbulence and stress. Cachon (2003) discussed supply chain models at various levels of complexity, from the perspective of contract coordination and the risks of both supplier and receiver in the supply chain. Nagurney and Matsypura (2005) use system dynamics and network theory approaches to investigate global supply chain decision-making issues under risk and uncertainty. Datta et al (2007) propose the adaption of methods from the finance domain to risk management within supply chain. Kleindorfer (2006) studied handling supply chain risks by flexibility with building in system redundancy. Mitigation and contingency strategies are also discussed by several current authors (Sheffi, 2005; Tomlin 2006;), all of whom take various levels of approach with respect to modeling and analytics to make their arguments. Cruz et al. (2011) developed network equilibrium patterns to analysis and effect of social relationship on supply chain network. Giannakisa and Louisb (2011) developed a framework for the design of a multi-agent based decision support system for the management disruptions and mitigation of risks in manufacturing supply chains. Ashesh et al. (2011) developed a heuristic method like Co-evolutionary Particle Swarm Optimization based on Cauchy distribution for supply chain coordination. Behdani et al. (2012) developed agent-based model for mitigating supply disruption for a global chemical supply chain.

As reviewed, the applications of complex systems approaches in SCRM are increasing due to the complexities of supply chains and the related uncertainties. This is mainly because the traditional mathematical and simulation approaches cannot handle these complexities, and it is difficult for them to meet the industry needs of modeling and analyzing the complex supply chains and designing sustainable, robust, self-organizing and self-adaptive supply chains.

2.5 DATA MINING FOR SUPPLY CHAIN RISK MONITORING AND ANALYSIS

Information quantity is growing exponentially, and almost all of it is in digital form. In 2006, roughly 161 billion GB of new data were stored, and this will have increased by six-fold by 2010. The major drivers are cost reduction and replacement of paper-based practices with digital processes. Miniaturization and embedding software in “Things”, together with social media arenas, will further accelerate this trend. By 2020 it is expected that 200 times more data will be generated annually than in 2008 (Harstad, 2012).

Through the use of automated data mining techniques, businesses are discovering new trends and patterns of behavior that previously were unnoticed. Due to the increasing complexities and uncertainties in SCNs, it would be very difficult if we are not using more advanced data mining and analysis technologies.

In addition, for many companies, information across all enterprises and the departments is distributed, dynamic and disparate in nature (Julka, 2002). For this type of information to be useful the process of data mining and analytical methods must be applied. This is a process that combines tools and techniques from computational intelligence, optimization, machine learning, statistics, and data management to extract useful knowledge from data automatically (Srinivas and Harding 2008). Data mining and analytical methods also can be implemented in the forms of intelligent agents where intelligent agents are used to emulate enterprise entities (Julka, 2002).

Data analytical techniques used include stress testing (Shi, 2004); behavioral risk theory (Ellis, 2010); complexity analysis (Yang, 2010); structural self-interaction matrix and reachability matrix (Faisal, 2006); information entropy assessment (Li Y., 2010); economics models (Singh, 2010); Pareto analysis (Gunasekaran, 2001); analytical hierarchy process (AHP) analysis (Rabelo, 2007); failure mode, effects and criticality analysis (FMECA) technique (Tuncel, 2010); Bayesian models (Li X. a., 2007); and principle component analysis (Qiang, 2010).

Data mining is emerging in supply chain management. To handle supply chain risk raised due to nonstationary customer demand, Jiang and Sheng (2009) propose a reinforcement learning algorithm combined with case-base reasoning in a multi-agent supply chain system. (Chen, Tang et al. 2005) presented a clustering procedure for an order batching problem in a distribution center with a parallel-aisle layout based on a data mining technique of association rule mining. Piramuthu (2005) introduced an approach of incorporating data mining techniques into a dynamically configurable supply chain framework for better effectiveness with respect to comparable static supply chains. Oluwole (2008) applied data mining and analytics to aerospace manufacturing supply chain risk management. Wu et al. (2010) proposed a possibility multi-objective programming model for supplier selection taking risk factors into consideration. The model consists of three levels and uses simulated historical quantitative and qualitative data. Xiao et al. (2011) introduced an approach of integrating the fuzzy cognitive map and fuzzy soft set model for solving the supplier selection problem. This method considers both the dependencies among criteria and the uncertainties on decision making process. Song and Kusiak (2010) presented a data mining framework for discovering optimal modules in a delayed product differentiation scenario based on historical product sales data. Chung and Tseng (2012) proposed a new class of business intelligence systems using data mining. They conduct both qualitative and quantitative experiments to evaluate the performance of the BI system developed based on the proposed framework. The results indicate that the system achieved high accuracy and coverage related to rule quality, and produced interesting and informative rules with high support and confidence values.

So, data mining algorithms for SCRM are still emerging based on research and industry needs. For a productive SCRM data mining project, the first step is to gather more operations and risk data; and then locate the data critical to a business, refine it and prepare it for the data mining process. With the right data available, then we can choose data mining algorithms, and the choice of algorithm will depend upon the data gathered and the SCRM problem we try to solve.

3. DISCUSSIONS ON INNOVATION OF TECHNOLOGY FOR SCRM

As mentioned above, managing supply chain risks is a cross-functional effort between risk management, supply chain, IT, operations management, and complex systems technologies. A successful SCRM program will require the supply chain organizations to use the right technologies to assess and manage supply chain risks. This section we briefly discuss the technologies for risk management in complex supply chains.

3.1 SUPPLY CHAIN RISK TRACKING, IDENTIFICATION AND ALERT

In the area of supply chain (risk) tracking, tracing and monitoring, new technologies should be developed based on RFID and GPS technologies to provide privacy management, seamless information visibility and integration, so that the risk information can be captured, identified and shared in the SCNs. If both technologies can be effectively integrated, the result is not only seamless visibility, but also increased reliability of logistics, automatic exception reports, dynamic goods routing, and in-time exception report and risk identification. Hence this could reduce loss incurred by risks. Also there is a need to develop risk identification and management solutions for RFID based track & trace services in EPCglobal-enabled SCNs with authentication processrelated to the technologies (Li and He, 2009).

In addition, risk identification and categorization techniques need to be developed to use the data from detected risks as well as the configuration of the data-collection points to deliver tracking information. For instance, the locality of risks, i.e., their inverse tracking and forward tracing to reduce either the occurrence probability or the degree of severity of risk consequences.

Supply chain visualization technologies that display temporal, spatial and connectivity patterns will be useful for identifying and understanding the risks in complex supply chain networks. A graphical visualization platform mounted as a part of a decision-making dashboard in a supply chain control tower setting will allow senior management to have a clear overview of operations in a local / regional and inter-enterprise setting for their theatre of operations within their business region, especially, Asia-Pacific.

3.2 SUPPLY CHAIN ANALYSIS AND ASSESSMENT

As reviewed, most of the current supply chain analysis and modeling technologies are still based on the traditional approach and case studies for special supply chains, and some of these rely on material focused approach and not information or network focused approach, especially with those applied to industry. More information and network focused technologies on supply chain analysis, SCN modeling and simulation, rapid modeling and analysis, strategies for managing the risks in the SCNs would be better suit the emergent needs with increasing supply chain complexities.

As SCN decisions often require inputs from many actors and multiple perspectives, in order to discover the key patterns influencing the dynamics of an SCN, we should adopt a network-analytics perspective (Cook and Holder, 2007). This could better identify how and where the highly connected nodes in an SCN can help management in control towers gain early insight to issue such as demand congestion or modality hiccups, and as such buffer stock dispersion. Network theory and graph mining approaches are potential technology employed to analyze network structure and characteristics.

The review indicates a growing awareness of quantified modeling and simulation for supply chains, but there still is a lacking of quantitative models for specific risk modeling and analysis needs for SCRM. For example, little research is focused on quantitative methods for the risk in terms of a disruption recovery model from a business continuity perspective. Also there is a shortage of approach and platform which can provide the interface to facilitating of the developed models for different purposes of supply chain risk analysis.

3.3 SUPPLY CHAIN RISK MITIGATION TECHNOLOGY

There are three complementary strategies for mitigating risks: 1) assess the risk to make better informed decisions, such as purchasing an insurance policy to cover the risk, 2) spot vulnerabilities and fix them before catastrophic events occur, and 3) design out weakness through resilience (Bonabeau 2007). Researchers have had to reinvent them in the context of extremely complex, interconnected, cascade-prone systems.

Techniques need to be developed to quantify the disruption effects and mitigate the variability in a SCN to hasten the recovery from disruptions for better responsiveness to anomalies in a volatile market. These techniques add in an integrated dynamical perspective to mitigate supply chain variances. In addition, mitigation technologies should be applied to supply chain contingency planning where leading companies deal with this range of supply chain risks by holding reserves. Top manufacturers hold supply chain reserves that includes excess inventory, excess capacity and redundant suppliers (Chopra S. and Sodhi, M.S. 2004). The big challenge here: mitigate risk by intelligently positioning and sizing supply chain reserves without decreasing profits.

3.4 ROBUSTNESS STRATEGY FOR SUPPLY CHAIN SURVIVABILITY

To design and implement robustness strategy for supply chain survivability, complex systems attributes such as self-organization, self-adaption and self-repairing should be built into the supply chains.

Self-organizing and adaptive supply chains need to be designed to alter their structures and behaviors when the world around changes or when some of their constituent units fail. Resource pooling capability could be one strategy to improve self-organizing capabilities, such that it is easier to replace some failed parts in a supply chain; another strategy is to build the supply chain in modularity which allows for great flexibilities. In addition, sustainable topology of the supply chain network is also important for robustness design; and fourthly, to embed evolution and adaption capabilities in supply chain organizations, for example to include evolutionary and adaptive algorithms in supply chain planning.

3.5 DATA MINING FOR SUPPLY CHAIN RISK MONITORING AND ANALYSIS

The application of data mining in SCRM can be further developed on a few topics for risk monitoring and analysis. First, there could be a domain specific data analysis/mining to discover useful information/insights from tremendous amounts of data and sophisticated interactions with human experiences for supply chain risk management. Second, techniques for the problem of mining supply chain data sets which are not traditional i.i.d. (independent, identically distributed) could be developed. Finally, since the statistical validation of the association rules are often neglected (Lallich et al. 2007), research could be conducted in the validation of statistical hypothesis testing for supply chain risk analysis via association rule mining.

4. SUMMARY

This paper reviews the status and briefly discusses on the innovation of the technologies for SCRM.

First, we analyzed the challenges and needs in technologies for SCRM, especially the technologies to manage the complexities in SCNs. The paper further clarifies the importance and the role of the technologies in SCRM.

Second, we conducted a comprehensive literature review on technologies related to SCRM based on the roles of the technologies. We analyzed the current status, literatures and challenges of risk management technologies on complex supply chains under conditions of demand volatility and price pressure etc. The main technologies reviewed include Track & Trace Technologies for SC Visibility and Risk Identification, Analytical Optimization Technologies for SCRM, Simulation Technologies for SCRM, Complex Systems Technologies for SCRM and Data Mining Technologies for Supply Chain Risk Identification and Analysis.

Finally, based on the review, the paper briefly discussed the innovation of technologies for SCRM. Important potential technologies for future research are discussed, which include integrated and seamless EPCglobal tracking network based on RFID technologies, network theory and graph mining, rapid modeling and analysis of SC risks, and data mining for risk monitoring etc. New capabilities based on these technologies need to be developed and applied to reflect the dynamic and complex nature of supply chains and eventually to enable effective SCRM.

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