This paper describes the application of hierarchical holographic modeling (HHM) to supply chain risk management. Specifically, it seeks to present a structured and systematic hierarchical approach for identifying the potential risks in supply chain operations. To avoid the confusion of risk management in supply chain operations, this research adopts the ISO risk management framework, which provides general principles and guidelines for managing any form of risk in a systematic manner. The paper provides a conceptual framework to identify supply chain risks from multiple overlapping perspectives.

KEYWORDS: Risk management, Supply Chain Risk Management, System Approach, Hierarchical Holographic Modeling

INTRODUCTION

Managing risks in the supply chain networks is becoming increasingly challenging due to the complex and dynamic nature of modern environment, such as greater uncertainties in supply and demand, globalization of markets, and shorter product and technology life cycles. The increased use of outsourced manufacturing, distribution, and logistics results in complex international supply network relationships leading to ever increasing exposure to risks. The literature suggests that while technological advances and best practices in supply chain management can aid in mitigating supply chain risks, significant gap still exists in quantitative and qualitative analytical approaches addressing the supply chain risks from multiple perspectives (Christopher and Lee 2004; Tang 2006; Manuj and Mentzer 2008; Rao and Schoenherr 2011).

The aim of the research is to describe an application of hierarchical holographic modeling (HHM) to supply chain risk identification. While the field of SCRM has evolved alongside the parent field of SCM, very limited literature actually addresses the issue of risk identification in supply chains (Manuj and Mentzer 2008; Rao and Goldsby 2009; Kouvelis et al. 2006). Yet, identifying risks is the first step in developing a risk management process. Drawing on a holistic representation of complex systems and processes termed in hierarchical holographic modeling, this paper outlines a conceptual framework for analyzing supply chain. We conclude that exploiting the inherent synergy of HHM’s philosophy can provide an efficient, methodological, and practical foundation for supply chain risk identification.

The article is organized as follows. Section 2 provides a framework of supply chain risk management and risk identification in the view of the International Organization Standard (ISO). Section 3 introduces Hierarchical Holographic Modeling and its applications. Section 4 develops a framework for identifying supply chain risks illustrating HHM philosophy and method. Section 5 includes the closing remarks and proposes future research directions.
LITERATURE REVIEW

Numerous articles on risk and supply chain risk management have been published in the last 20 years. While the literature on managing risks is fairly well developed, research associated with identifying risks is still in an early stage (Zsidisin, 2003; Tang 2006; Rao and Goldsby 2009). The success of supply chain risk management depends on the effectiveness of the management framework providing the foundations and arrangements that will embed it throughout the organizations at all levels. The generic approach described in the International Organization Standard (ISO) provides the principles and guidelines for managing supply chain risk in a systematic, transparent and credible manner and within supply chain scope and context. The consistent processes within a comprehensive framework can help to ensure that the risks are managed effectively, efficiently and coherently across a supply chain.

According to the International Organization Standard (www.ISO.org), risk management is a systematic process of identifying and assessing organizational risks and taking action to protect an organization against them. It consists of coordinated activities to direct and control an organization with regard to risk. The task of a risk manager is to predict and enact measures to control or prevent losses within an organization. Organizational objectives are influenced by internal and external factors which create uncertainty in achieving those objectives. The effect of this uncertainty is the risk to the organization’s objectives.

To avoid confusion, the current research applies the systematic framework of ISO to further analyze supply chain risk management. ISO risk management framework, although focusing on one organization, can provide general principles and guidelines for managing any form of risk in a systematic manner. We extend the logic and spirit to whole supply chain consisting of multi-organizations. With the ISO perspective, we conclude supply chain risk management, as a system, consists of 5 sets of management process: (1) establish the context, (2) risk identification, (3) risk analysis, (4) risk evaluation, (5) risk treatment (Figure 1). ISO defines risk as effect of uncertainty on objectives. An effect is a deviation from the expected positive and/or negative. Objectives can have different aspects, such as financial, health and safety, and environmental goals and can apply at different levels. Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.

![Figure 1. Supply chain risk management process](image)
This view of supply chain risk management framework can assist in managing risks effectively through the application of the risk management process at varying levels and within specific contexts of the supply chain operations. The framework ensures that information about risk derived from the risk management process is adequately reported and used as a basis for decision making and accountability at all relevant organizational levels and among all supply chain partners. Each specific supply chain partner or application of risk management brings with it individual needs, perceptions and criteria. Therefore, a key feature of this International Standard is the inclusion of “establishing the context” as an activity at the start of this generic risk management process. Establishing the context will capture the objectives of the supply chain, the environment in which it pursues those objectives, its stakeholders and the diversity of risk criteria—all of which will help reveal and assess the nature and complexity of its risks.

These five major supply chain risk management processes can be subdivided into more categories and steps, which are beyond the current research. In this paper, we focus on supply chain risk identification which is the first step in developing a risk assessment process. With the ever-increasing importance and complexity of the modern supply chain systems, it is essential that risk identification be addressed in terms of its overall risk management system. Comprehensive and systematic identification is critical, because a risk that is not identified at this stage will not be included in further analysis.

The aim of risk identification is to generate a comprehensive list of risks based on those events that might create, enhance, prevent, degrade, accelerate or delay the achievement of objectives. From the ISO point of view, risk identification is the process of finding, recognizing and describing risks. It involves the identification of supply chain risk sources, events, their causes and their potential consequences. ISO suggests risk identification can involve historical data, theoretical analysis, informed and expert opinions, and stakeholder’s needs. Risk identification establishes the exposure of the supply chain to risk and uncertainty. This requires an intimate knowledge of the factors critical to success and the threats and opportunities related to the achievement of objectives. It should be approached in a methodical way to ensure that all value-adding activities along the supply chain have been evaluated and all the risks flowing from these activities defined.

Supply chain risk identification involves a comprehensive and structured determination of potential supply chain risks associated with the given supply chain networks. Successful companies excel at identifying risk to their supply chains, and at creating powerful mitigation strategies that neutralize potentially negative effects. Understanding the variety and interrelationships of SC risks is important as well. Such an understanding can be achieved by considering threats and resources. While threats refer to the broad range of forces, which could produce adverse results, resources refer to assets, people or earnings, which could be affected by the threats. One can start by first enumerating all possible threats that could produce adverse results for the performance of the supply chain (Chopra and Sodhi 2004; Tummala and Schoenherr 2011).

In fact, identifying potential supply chain risks and unearthing a suitable strategy to mitigate these risks have been found to be the key success factors irrespective of the kind of participating firms (Rao and Goldsby 2009). The supply chain managers should identify sources of risk, areas of impacts, events and their causes and their potential consequences. Identification should include risks whether or not their source is under the control of the firms, including cascade and cumulative effects, even though the risk source or causes may not be evident. With a clear understanding of the types of supply-chain risks, managers in many types
of industries can tailor effective risk-reduction approaches to their own companies (Chopra and Sodhi 2004).

It is essential to apply effective risk identification tools and techniques to supply chain risk management. To address the multiple perspectives of risks in supply chain and to consider all conceivable elements, Hierarchical Holographic Modeling (HHM) has turned out to be particularly useful in modeling large scale, complex, and hierarchical supply chain systems. The multiple versions and perspectives of HHM add strengths to supply chain risk analysis. The HHM methodology is grounded on the premise that in the process of modeling large scale and complex systems, more than one mathematical or conceptual model is likely to emerge. Next section describes HHM and explains why its philosophy provides the necessary theoretical and practical foundation for risk identification in supply chain operations.

THEORETICAL DEVELOPMENT/MODEL

Hierarchical Holographic Modeling

Hierarchical Holographic Modeling (HHM) is holistic philosophy/methodology aimed at capturing and representing the essence of the inherent diverse characteristics and attributes of a system—its multiple aspects, perspectives, dimensions, and hierarchies (Haimes 1981). HHM states it is virtually impossible to represent the multiple perspectives of the system with single model analysis and interpretation. Each of these models may adopt a specific point of view, yet all may be regarded as acceptable representations of the whole system (Haimes 1995). The term holographic refers to the desire to have a multi-view of system when identifying vulnerabilities (as oppose to single view or a flat image of the system). The term hierarchical refers to the desire to understand the intricacy that characterizes the many different levels of the system’s organizational, functional, and decision making hierarchy(Haimes 1981, 2009, and 2012).

In the HHM scheme, plural models represent the various aspects of the system, with each model termed a holographic subsystem. The HHM approach recognizes that no single vision or perspective of a system is adequate to represent a system and its component parts. Instead, the HHM approach identifies and coordinates multiple, complementary decompositions of a complex system. Haimes 2009 argued that the structural nature of multilevel decomposition shows the following advantages: (1) Decomposition methods can reflect the internal hierarchical nature of large scale multi-objective systems. (2). Trade-off analysis can be performed among subsystems and the overall system. (3)Through decomposition, the complexity of a large scale multi-objective system can be relaxed by solving smaller sub-problems.

Haimes (1981) summarized the distinctive attributes of the HHM approach as: (1).It provides a holographic view of a modeled system, and can be used to identify most, if not all, major sources of risk and uncertainty. (2).It adds both robustness and resilience to modeling by capturing various systems’ aspects and other societal elements. (3). It adds more realism to the entire modeling process by recognizing that the limitations of modeling a complex system via a single model are circumvented by a model that addresses specific aspects of the system. (4).It provides more responsiveness to the inherent hierarchies of multiple objectives and sub-objectives and multiple decision makers associated with large scale and complex systems.

It has been extensively and successfully used for identifying risk scenarios in numerous projects (Haimes, 1981, 1998; Lambert et al. 2001, Pan et al 2010). The literature shows many risk identification methods, evaluation techniques, and issue investigation schemes build on the general principles embodied by the HHM. The SEI taxonomy methodology indicate a vision that
is harmonious with HHM: the taxonomy is hierarchical in structure, is constituted by progressive levels of detail and abstraction, provides a way to address the multiple dimensions of a problem, and serves to identify areas of concern in a software acquisition endeavor (Haimes 2012, Haimes and Chittister 2012). Using the software acquisition HHM model, a systemic exploration of the software acquisition risk can be conducted through the multiple visions of the model. HHM has also been extensively and successfully deployed to study risks for project development, chemical risks from modern metal mining operations, and global sustainable development, government agencies, such as U.S. Department of Homeland Security and Virginia Department of Transportation (Haimes 1998, 2012).

**HHM for Supply chain risk management**

HHM has turned out to be particularly useful in modeling large scale, complex and hierarchical systems, and risk identification in a wide variety of applications. The dominating attributes of modern supply chain system are their multi-dimensional nature, hierarchical competing objectives, multiple participants, and inherent uncertainty (Lambert et al. 1998; Mentzer 2001). Supply chain risk is a complex phenomenon that can be divided into sources and types of risk (Svensson 2000, Kleindorfer and Saad 2005, Rao and Schoenherr 2011).

Recognizing the kinship of these applications to the supply chain management, we argue and further demonstrate the efficacy, appropriateness, and desirability of the HHM as a framework for analyzing supply chain risk identification. The multidimensionality of supply chain operations and coordination of those activities across functions and across firms defy the capability of any single model to represent the essence of the supply chain system. A complete enumeration of risks in a complex supply chain system can only be achieved when risk identification addresses different aspects of the system. The process of supply chain risk identification can be aided by the consideration of multiple, complementary decompositions of the system using HHM.

To overcome the shortfalls of single planar models and to identify all sources of risk associated with supply chain operations, HHM assumes an iterative approach to providing the structure for identifying all risks. If one fails to identify a risk source with the current views of the HHM, then expansion of the model to include a new decomposition is possible. This process will eventually capture all risk sources (Heimas 2009).

![Figure 2. A supply chain system](image-url)
While many definitions of supply chain management exist in the literature, it is widely accepted that supply chain management is a systematic, strategic coordination of the traditional business functions within a particular company and across companies within the supply chain, for the purpose of improving the long-term performance of the individual companies and the supply chain as a whole (Cooper et al 1997; Lambert et al 1998; Mentzer 2001). In general, a supply chain involves the flows of material, information, and finance in a network consisting of customers, suppliers, manufacturers, and distributors (figure 2). Material flows include both physical product flows from suppliers to customers through the chain and reverse flows via product returns, servicing, and disposal. Information flows involve order transmission and delivery status. Financial flows include credit terms, payment schedules, and consignment and title ownership arrangements (Lambert et al., 1998; Lee 2000; Mentzer, 2001).

In the literature, supply chain risks are categorized in various ways and from different perspectives, e.g. from a corporate governance or financial risk agenda, or even in terms of a multi-level complex system (Christopher and Lee 2004; Rao and Goldsby 2009; Tang and Musa 2010, Manuj and Mentzer 2008). However, based on the basic components of the supply chain system, the synthesis of the identified risks from different perspectives can generate a more complete image of the overall supply chain risks. To identify the risks lined to the components of supply chain, the framework logically should identify six basic structural components: environmental risk, supply risk, demand risk, material flow risk, information flow risk, and financial flow risk (figure 2).

The figure depicts the multiple views of the risk identification problem for the supply chain system using the HHM approach. The methodological framework for identifying all resources of risk associated with the six dimensions or perspectives, which provide a more detailed classification of requirements, were developed: (1). environment. (2). supply (3). material flow
These six head topics, including the major visions, concepts and perspectives of success in dealing with the supply chain risk, can provide an adequate starting point for identifying a wide array of possible, significant risk scenarios. Note that each model is represented within the HHM framework by a separate sub-model. Each of the six subdivisions and the corresponding sub-subdivisions are represented by a set of objective functions; constraints; and decision variables. Obviously there will be common goals and objectives, as well as separate and possibly conflicting and competing objectives.

Most of these risks are overlapping and do not exist in isolation. Moreover, macro, policy, competitive, and resource risks manifest themselves in the form of a combination of supply, demand, operational, and security risks (Juttner et al 2003; Manuj and Mentzer 2008). The synthesis of the identified risks from different perspectives can then generate a more complete image of the overall system risk. Building upon the framework and literature survey, we further identify and clarify the potential risks associated with different sub-models, with an understanding that each sub-model can be further decomposed into sub-systems.

**Environmental risk**

Environmental risk elements are those that affect the overall business context across the supply chain. Given the complexity and uncertainty inherent in the supply chain environment, the competition face by firms has changed dramatically. While the magnitude of this impact across different industry sectors may be different, the underlying premise is recognizable; each will be affected to some extent general environmental uncertainties (Rao and Goldsby 2009; Kouvelis et al., 2006). Juttner (2005) argued that environmental scanning to monitor changes in the macroeconomic or political environment, along with operating flexibility that allows a firm to respond to those changes, is critical to a firm’s ability to manage supply chain risks.

Broadly categorized, potential supply chain environmental risks include political instability and terrorism, economic uncertainty, social and cultural uncertainty, and natural disasters (Chopra and Sodhi 2004; Manuj and Mentzer 2008; Rao and Goldsby 2009). These risks elements are external to and uncontrollable from the firm’s perspectives. They can seriously disrupt or delay material, information and cash flows, any of which can damage sales, increase costs or both. These factors directly or indirectly impact upon the focal firm or on those upstream or downstream, or on the marketplace itself. They may affect a particular value stream or any node or link through which the supply chain passes.

**Supply Risks**

Supply risk is the possibility of an event occurrence associated with inbound supply that may cause failures from supplier(s) or the supply market, such that the outcome results in the inability of the focal firm to meet customer demand within anticipated costs, or causes threats to customer life and safety (Zsidisin et al. 2004; Juttner 2005). Manuj and Mentzer (2008) argue supply risks reside in the course of movement of materials from supplier's suppliers to the focal firm, and include reliability of suppliers, supplier resource inflexibility, and single versus multiple sourcing, make or buy decisions, centralized versus decentralized sourcing, and security issues.

Similarly Rao and Schoenherr (2011) argued the components include quality of service, delivery performance risks, supplier fulfillment errors, selection of wrong partners, high capacity
utilization supply source, inflexibility of supply source, poor quality or process yield at supply source supplier bankruptcy, rate of exchange, percentage of a key component or raw material procured from a single source. A supplier maybe unavailable to complete an order for a number of reasons, including problems sourcing necessary raw materials, low process yield due to increased scrap, equipment failure, damaged facilities, or the need to ration its limited product among several customers. Transportation disruptions occur while products are in transit and add to the delivery lead time.

**Demand risk**

Demand risk is the possibility of an event associated with outbound flows that may affect the likelihood of customers placing orders with the focal firm, and/or variance in the volume and assortment desired by the customer (Manuj and Mentzer 2008). Demand risk relates to potential or actual disturbances to the flow of product, information, and in this instance cash emanating from within the network, between the focal firm and the market. In particular, it relates to the processes, controls, assets and infrastructure dependencies of the organizations downstream and adjacent to the focal firm (Christopher and Lee 2004).

Manuj and Mentzer (2008) argued the sources of demand risk reside in the movement of goods from the focal firm to the customer’s customers. The elements of risk could be delayed/inappropriate new product introductions (leading the firm to either miss market opportunities or inventory write-offs/stock-outs due to inaccurate forecasting), variations in demand (caused by fads, seasonality, and new product introductions by competitors), and chaos in the system (caused by overreactions, unnecessary interventions, and distorted information from the downstream supply chain members). From a slightly different angle, Rao and Schoenherr suggested the elements include order fulfillment errors, inaccurate forecasts due to longer lead times, product variety, swing demands, seasonality, short life cycles, and small customer base information distortion due to sales promotions and incentives, and exaggeration of demand during product shortage.

**Material flow risk**

Material flow risk is the possibility of an event associated with the focal firm that may affect the firm’s internal ability to produce goods and services (Tang and Musa 2011). Material flow involves the physical movement within and between supply chain elements. These include the transportation of goods, delivery movement, storage and inventories. Sources of material flow risk reside within the firm and may result from a breakdown in core operations, inadequate manufacturing, or lack of processing capability, quality and schedule of production, transportation incapability, and inability to access inventories and so on. High levels of process variations, changes in technology may render the current facilities obsolete and changes in operating exposure.

Tang and Musa (2011) suggested the perspectives of risk events can be further categorized into the stages of source, make and deliver. Source involves inquiring physical products or services. Typical risk issues are single sourcing risk, sourcing flexibility risk, supplier selection/outsourcing, supply product monitoring/quality and supply capacity, which are discussed in supply risks. The major issues at make stage involve product and process design risk, production capacity risk, and operational disruption. On the deliver side, main risk issues include demand volatility/seasonality, balance of unmet demand and excess inventory. These issues are all affected by the forecasting difficulties due to seasonality, volatility off ads, new product adoptions and short product life.
Information flow risk

Information flow risk is a threat from an unknown third party who may or may not be a member of the supply chain and whose motivation is to steal proprietary data or knowledge and/or destroy, upset, or disable a firm’s operations (Manuj and Mentzer 2008). Information flow is the bonding agent between material flow and financial flow. Value adding activities in a supply chain are often triggered by information flows such as demand, inventory status, order fulfillment, product and process design changes and capacity status. The sources of information security risk include individuals within the firm leaking vital information to competitors, system hackers, and weak security/firewalls of members of the supply chain. Significant elements of infrastructure security risks are public and private utility services, such as electricity and communications (Manuj and Mentzer 2008).

Tang and Musa (2011) argue that the risk of information accuracy may cause by information accessibility, information efficiency and data accuracy. Inaccurate information should further affect decision making in supply chain. The threats of information system security and disruption could be internally due to ill-manage system, or externally by nature disaster. The information system risk can also be considered at application, organizational and inter-organizational levels (Finch 2004).

Intellectual property risk has grown rapidly as supply chain become less vertically integrated and more global, and companies outsource to the same manufacturers used by competitors. Barry (2004) argued that intellectual property risk is associated with increasing information flow in supply chain network and in the meantime inability of protecting information sharing, for instance trade secret exposure. Information outsourcing allows company to focus on the core-competence. However, it also increases the risk of opportunism of vendors, information security apprehension, hidden costs, loss of control, service debasement, disagreements, disputes and litigation and poaching.

Financial flow

Financial flow risk involves the chance of inability to settle payments and improper investment, such as the chance a business’s cash flows are not enough to pay creditors and fulfill other financial responsibilities. The common risks components are exchange rate risk, price and cost risk, financial strength of supply chain partners and financial handling/practice (Tang and Musa 2011). The level of financial risk relates to the amount of debt a business incurs to finance those operations. The more debt a business owes, the more likely it is to default on its financial obligations. Taking on higher levels of debt or financial liability therefore increases a business’s level of financial risk.

The vulnerability of financial strength of a supply chain member, may easily affect the entire supply chain network. The risk arises from financial handling and practice, credit uncertainty and default risk. Credit uncertainty involves problems with collectibles. These can cause inherent delays in payments to the other supply chain members, in effect creating a cycle that is difficult to resolve. An increasing velocity and quantity of payment should complicate the financial flow and need urgent attention. In a global supply chain context, exchange rate has a major influence on a firm’s profit, supplier selection, market development and other operation decisions.
CONCLUSIONS

This paper offers a first attempt at identifying potential supply chain risks by devising a hierarchical holographic modeling (HHM), which is grounded on the premise that complex systems and processes should be studied using more than one single perspective. Supply chain systems are hierarchical in nature, and thus the risk management of such systems is driven by this hierarchical reality and must be responsive to it. We argue the HHM provided an efficient means to examine the scope and depth of the analysts’ and the program managers’ understanding of supply chain risk issues. We do not discuss the theoretical and methodological grounding of the HHM as a methodology (see Haimes 1981, Haimes 1991, 1998 for more detailed discussions); rather, we focus on the application of the HHM framework as guidance for practical practitioners.

The principle advantage of hierarchical multilevel modeling is that it breaks down a large complex system into its component subsystems. It allows each subsystem to be studied, analyzed, understood, and managed at a lower level of the hierarchical independently of other levels, and coordinated at a higher level of the hierarchy. As Haimes 2012 indicated, it might be argued that decomposition is fairly easy; the real challenge is resolving the conflicts and interactions between and among the subsystems and ensuring that the sub-models account for all critical states of the system, as well as for the specified system’s overall objectives and constraints.

The framework articulated here, together with differential risks embedded in the network structures, provides a beginning point for the management of disruption risks in supply chains. The risks associated with each subsystem within the hierarchical structure contribute to and ultimately determine the risks of the dominate role in the allocation of resources. Managers within the organizations would be in the best position to assess the vulnerabilities on a case by case basis. It can serve as a reasonable starting point for identifying risks across linkages in the supply chain. By understanding the variety and interconnectedness of supply chain risks, managers can tailor balanced, effective risk reduction strategies for their companies. The refinement of the HHM supply chain risk identification model, and the development of assessment and mitigation approaches in supply chain risk management, for specific sectors and archetypes of supply chains present important challenges for research going forward.

REFERENCES

References available upon request.