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A system dynamics simulation model of chemical supply chain transportation risk management systems

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ABSTRACT

Unforeseen events can interrupt the operational process and have a negative impact on the chemical supply chain transportation (CSCT) system. A number of research studies have addressed the risk management issues in chemical supply chain (CSC) or CSCT. However, most of the existing methodologies lack inbuilt and practical techniques that take into consideration the complex interactions and dynamic feedback effects, which can significantly affect the reliability of risk management outcomes. This paper suggests a novel modelling and simulation method to address the dynamic risks effects in the CSCT, especially the consideration of time-dependent system behaviour in different operational conditions. Furthermore, the flexibility of the model modification is adapted to enhance the practice in risk mitigation. A transparent decision support tool is provided to compare the outcomes of different risk mitigation processes, which offers decision makers an alternative CSCRM mitigation package.

1. Introduction

The chemical supply chain (CSC) involves the sourcing, conversion, transportation and warehousing of raw materials into final chemical products and their delivery to customers across national boundaries (Tsiakis and Papageorgiou, 2008). Due to the geographic dispersion of the members of the supply chain, CSC requires highly coordinated material, information and finance flows, with the conveyance of hazardous substances between the members of the CSC – chemical supply chain transportation (CSCT) – regarded as one of the most significant operational processes in terms of risk (Reiskin et al., 1999). Hazardous characteristics of chemical substances, uncertainties and disruptions pose significant challenges to CSCT operations as well as the surrounding environment, which potentially threatens ecological balance and endangers human health (Bonvicini et al., 1998; Papageorgiou, 2009). In response, the supply chain members have to implement a large variety of methods to manage their supply chains in order to maintain the effectiveness and efficiency of supply chain operations (Thun and Hoenig, 2011). In addition, governments and authorities have introduced a substantial body of legislation, regulatory guidance and recommendations to ensure the safety of CSCT operations (Furuhama et al., 2011; Fisk, 2014; Scruggs et al., 2014). Both academia and CSC operators appreciate the need to improve safety and reliability of CSCT chains, to prepare for, respond to and recover from risk scenarios, especially after the 9/11 attacks in 2001 (Mullai, 2009) and the frequent natural disasters (Rao and Goldsby, 2009; Ehlen et al., 2014).

In spite of the challenges arising from the internal system and external environment, the CSC is required to deliver a competitive business performance (Manuj and Mentzer, 2008). To manage undesired events, a large number of studies have been devoted to extending current knowledge and enhancing the application of CSCRM. It is important to credit the previous publications that have developed various conceptual or analytical models to investigate different kinds of risks in the CSC, as these have provided the dynamic analysis that underpin this proposed modelling and simulation research. In particular, García-Flores and Wang (2002) and Gao et al. (2009) developed agent-based models to simulate the dynamic behaviour of the CSCs and estimate the compromised risk management decisions. Taking into consideration the characteristics of chemical products, a dual model was built by Liu et al. (2011) to analyse both internal and external transportation risks in a CSC. Kleindorfer and Saad (2005) have demonstrated a conceptual model to assess and mitigate CSC risks based on the accident data of the U.S. chemical industry from 1995 to 2000. Adhitya and Srinivasan (2010) developed a dynamic model to simulate CSC

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operations under the changes of customer behaviour, business policies, and environmental issues. Laínez and Puigjaner (2012) discuss the state-of-the-art of risk management strategies that attempt to broadly outline the risk perspectives in the CSC.

However, it is interesting to observe that many studies in CSCRM are carried out to analyse a specific kind of risk, instead of offering a holistic risk management framework. For instance, Ferrio and Wassick (2008), You et al. (2009), Tong et al. (2011), Oliveira et al. (2013) and Cai (2014) provide stochastic programming approaches to investigate CSC planning problems with risk consideration. Laínez et al. (2009), Carneiro et al. (2010), Oliveira and Hamacher (2012), Oliveira et al. (2013), and Ruiz-Femenia et al. (2013) investigate the financial problems in the CSC and provide retrofit actions to control and optimise investment decisions. However, further analysis is required to provide advantageous risk management techniques under a broader context to assess a more exhaustive variety of extreme and disruptive events in CSCT.

In CSCRM research, it is difficult to understand clearly the complex CSC structure, operating procedures and related aspects from the available quantitative data. Experts use their experiences to judge the risk consequences and to illustrate CSC operations (Tse, 2013). However, the majority of existing risk analysis methods are restricted by using a combination of qualitative and quantitative data. A novel method is required to conduct risk analysis and risk mitigation based on multiple data sources, such as numerical data, expert judgement, and interviews (Kaggwa, 2008).

Besides, the developed CSC and CSCT systems are presented with the nature of static models and established upon the sequence event chains (Leveson, 2004). It ignores that the information feedback among the logical loops emerging from the interactive relationships governs the changes of system behaviour, which should be taken into consideration during risk modelling and simulation. Meanwhile, simple algebraic equations are frequently adapted to predict the cause and effect relationships between the supply chain components, but nonlinear relationships exist as the norm rather than the exception. It is imperative to develop a methodology that can capture and represent both linear and nonlinear relationships among the system in order to address the dynamic risk impacts in the complex CSCT system.

This study, therefore, provides a novel risk management method employing limited qualitative and quantitative data/information to manage a more exhaustive variety of risks. It offers a methodological approach to deal with the existing causal relations and feedback effects between the CSCT system and its associated hazardous events. Instead of assessing the risks based on expert knowledge or historical data, the risk effects are addressed through combining the modelling approaches for the quantification of the system performance with interactive risk analysis procedures. Taking the advantages of the flexibility of model modification, the outcomes of risk mitigation methods are estimated to ensure that the particular risk mitigation approaches indeed support CSCRM. Furthermore, the proposed method can be generalised to provide a flexible and rigorous RM tool for other industries.

The proposed research addresses the risks existing in the transportation stage of the CSC, and predicts the outcomes of alternative risk mitigation decisions using a novel SD-based CSCRM method. It does this by: (1) developing the CSCT risk models based on the cause and effect relationships within the system boundaries; (2) running created models under different scenarios to explore the system performance; (3) benchmarking the series of system behaviour in the initial situation and in the risk scenarios to screen out the critical hazards; (4) offering a flexible model modification function to measure the outcomes of alternative risk mitigation solutions; and (5) providing a novel approach to evaluate risk management decisions that might improve CSCT system performance.

This paper is organised as follows: Section 2 describes the sequential development of the SD model, i.e. by constructing a causal loop diagram, by establishing a stock and flow diagram using Vensim© software, and by model validation. A number of risk experts and analysts were surveyed to generate different sets of input values to estimate risk consequence. In this way, the risks are assessed by benchmarking the comparisons of the system performance in different risk scenarios. Section 3 outlines the simulation results obtained from each of the risk scenario and corresponding risk mitigation scenario, and Section 4 summarises the key findings and their relevance to academia and the chemical industry, together with suggestions for future research.

2. Modelling approach

2.1. Characteristics of the SD method

Forrester (1961) first proposed SD theory to predict the behaviour of dynamic systems and analyse the efficacy of decision-making by modelling and simulation. In the literature, SD method has been widely applied to analyse the industrial risks (Garbolino et al., 2009, 2010; Oehmen et al., 2010; Bouloiz et al., 2013). In the supply chain management discipline, SD modelling technology has been introduced to deal with inventory management, bullwhip effect, strategy assessment and information delays (Ge et al., 2004; Janamanchi and Burns, 2007; Campuzano et al., 2010; Peng et al., 2014). Although there are alternative risk management tools that can be employed to investigate supply chain risks, SD method is implemented to deal with the CSC risks in this research because of its potential as an analytical method to address dynamic system behaviour governed by the information feedback (Kumar and Yamaoka, 2007; Tako and Robinson, 2012).

In the theory, SD is a broad concept that can be divided into two aspects: 'system' represents the structure of the system and the concept of feedback effect, while 'dynamics' reflects the changes in the behaviour of the system components over time. In a developed causal loop diagram, the assumed interactions between the variables are formalised to demonstrate the interdependence within the system boundaries. A closed chain of causal relations is defined as the feedback loop, which could be positive or negative (Lertpattarapong, 2002). The positive loop is unstable and oscillated that triggers systems to grow, evolve and collapse, while the change of negative loop towards a stable situation.

SD is concerned with the qualitative and quantitative analysis of the dynamic performance in large-scale systems, both retrospectively and prospectively. The application of SD method to CSCRM not only simulates the CSCT operations, but also predicts dynamic behaviour as the system changes under different risk circumstances (Angerhofer and Angelides, 2000). It takes account of the logical interaction of the components in the supply chain system and observes the causal effects between the risk factors and the system behaviour when time is factored into the sequence. Changes and new situations can be adapted in developed SD models to explore the dynamic outcomes in different scenarios.

SD methodology comprises a set of rigorous procedures to describe the supply chain structure and its behaviour in terms of process, information, decision-making and organisational limits. Yeo et al. (2013) suggest that the SD modelling process can be characterised by three phases: logical modelling, model quantification and model application. Fig. 1 describes a novel SD-based CSCRM framework, which is developed from the SD modelling process described in Yeo et al.

The first step in SD modelling process is problem definition, which indicates the purpose of the study and specifies the system boundaries. Secondly, the key variables are identified and