Developing a new model for estimating risk in a supply chain based on domino effect

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Abstract: The industrial world as we know it today has become a global network of demand and supply nodes, interlinked through interacting logistics systems. The Internet and related 'e-services' have opened up the demand and supply markets of the world, so that the 'next-door' marketplace could as well be the 'next-continent' marketplace. These systems are complex entities with multiple physical and virtual relationships, and multiple internal and external interfaces. On the other hand, high demands are put on both the quality of the products and services, and on the supply chain regularity and dependability. Whether the product is to be a part of a more complex product, or the final product for consumption or use by consumers or professional users, the product is expected to be available when needed, and as promised. In the search for improved effectiveness and efficiency of the supply chain systems, in this paper a mathematical model is developed for the quantitative assessment of delay risk based on interactions in a supply chain. Then interactions will be applied in order to carry out the overall quantitative risk assessment.

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1. Introduction

A supply chain is a worldwide network of organizations and their associated activities that work together to produce value for the customer. Supply chain management represents a critical competency in today's global market. By adopting e-business approaches, supply chains can, more rapidly and effectively, reap the benefits of reduced costs, increased flexibility and faster response times (Trkman and McCormack, 2009). Nowadays, supply chain networks that are temporarily integrated and driven by demands have emerged and operated for the lifespan of the market opportunity. However, the widespread use of information technology to create electronic linkages among partners may also result in unintended adverse effects on supply chain flexibility. Supply chains are confronted with increased business dynamics from both demand and supply, complex and dynamic relationships between partners, and much shorter response times to changes (Wang et al., 2008).

For many global supply chain networks that can comprise hundreds of companies with over several tiers of suppliers and intermediate customers, there are numerous presenting risks to consider and tackle (Goh et al., 2007). Furthermore, risk assessment is an essential and systematic process for assessing the impact, occurrence and the consequences of human activities on systems with hazardous characteristics (van et al., 2008) and constitutes a needful tool for the safety policy of a company. The diversity in risk analysis procedures is such that there are many appropriate techniques for any circumstance and the choice has become more a matter of taste (Cuny and Lejeune, 2003). A brief review in literature shows the risk analysis and assessment (RAA) techniques are classified into three main categories: (a) the qualitative, (b) the quantitative, and (c) the hybrid techniques (qualitative-quantitative, semi-quantitative). The qualitative techniques are based both on analytical estimation processes, and on the safety managers engineers ability. According to quantitative techniques, the risk can be considered as a quantity, which can be estimated and expressed by a mathematical relation, under the help of real accidents' data recorded in a work site. The hybrid techniques, present a great complexity due to their ad hoc character that prevents a wide spreading. Below, two quantitative risk assessment methods which can be appropriate for applying in interconnected supply chains, are presented. The presented model is based on the concept of this quantitative method (Brouwer and Blois, 2008).

1-1. Quantitative assessment of domino scenarios (QADS). The domino effect is assumed as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary events. Furthermore, an accident is usually considered as a "domino event" only if its overall severity is higher or at least comparable to that of the primary accidental scenario, while domino accidental scenarios result from the escalation of a primary accidental event. The escalation is usually caused by the damage of at least one equipment item. Due to the effects of the primary event, four elements may be considered to characterize a domino event: (i)

A primary accidental scenario, which triggers the domino effect. (ii) A propagation effect following the primary event, due to the effect of escalation vectors caused by the primary event on secondary targets. (iii) One or more secondary accidental scenarios, involving the same or different plant units, causing the propagation of the primary event. (iv) An escalation of the consequences of the primary event, due to the effect of the secondary scenarios (Mebaraki et al., 2012). The quantitative assessment of domino accidents requires the identification, the frequency evaluation and the consequence assessment of all the credible domino scenarios, including all the different combinations of secondary events that may be originated by each primary event. The identification of the credible domino scenarios should be based on escalation criteria addressing the possible damage of equipment due to the physical effects generated in the primary scenarios. In the approach to the frequency assessment of domino scenarios, the damage probability of a unit due to a given primary event may be considered independent on the possible contemporary damage of other units (Marhavilas et al., 2011).

1.2. The CREA (Clinical Risk and Error Analysis) method. CREA is a methodological approach for quantitative risk analysis, consisting of five steps (see Figure 1) according to the work of Tang (2006) and based on techniques well-established in industry, and have been adapted for the medical domain. CREA allows the analyst to join data which have been collected through direct observation of processes or interviews to clinical operators to statistical data reported in literature. The risk assessment for CREA method is condensed to the following: for each activity k, the probability $P(EM_{ik})$ of occurrence of the EM_i-th error mode (*EM*) and the severity index $D(EM_{ik})$ of the associated harm have to be calculated on the basis of available data and the experts' judgment; their product represents the Risk Index $R(EM_{ik})$ for each *EM*, as shown in the classical equation (1):

$$R(EM_{ik}) = P(EM_{ik}) \times D(EM_{ik}) \quad (1)$$

The Risk Index of each activity k is given by the sum of the risk indexes of each EM detected in the same activity (Koulouriotis et al., 2011).

Regarding the characteristics of supply chains, calculating the risk in these systems is never an easy task as there are many qualitative factors concerned with designing and decision making processes. In the literature, domino events are widely employed methodology to facilitate risk calculation process, because of existing interactions between different units. Despite of the vast research efforts on risk assessment, all works dealt with supply chain risks focus on particular supply chain risks and/or contexts, but do not explore the process of supply chains such as rate, distance and performance of different units, however these considerations ameliorate abnormalities in supply chain processes and integrate decisions across the supply chain. Their approach to risk estimation is limited as they do not provide the basis for an integrated supply chain management framework. In this paper, these previous works are synthesized and extended through the development of a modeling procedure for a supply chain and calculating the risk deal with supporting customers. The proposed method is enriched by estimating escalation of domino effect in a supply chain.

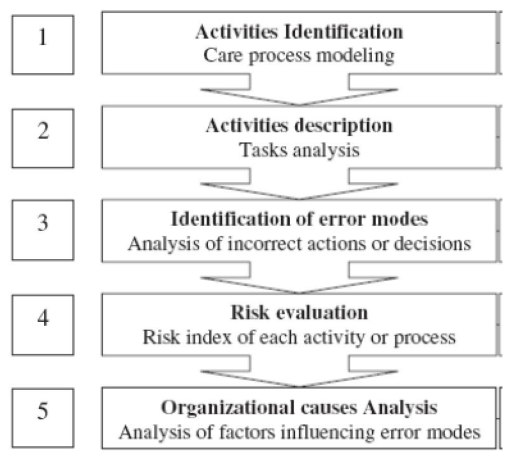

Figure 1. Foundamental steps of CREA (Cavallin 2006)

The rest of the paper is organized as follows. In next section related materials and method is introduced for modeling process. It formulates a model and solution methodology to estimate domino effect based on mathematical and statistical methods. Section 3 provides results of implementation. Then, conclusions and future research opportunities are addressed in the final section.

2. Materials and Methods

Domino phenomenon has been recognized long before, but the definition of the domino effect has not been unified. Many scholars give the different definition in different literatures, but it is generally believed: domino accident is that an initial accident happens and spreads to neighbouring device, makes one or more secondary accidents happen, and then leads to more serious consequences accident than initial accident (Aihua et al., 2012). In addition the assessment and mitigation of industrial risk, the analysis of potential escalation of primary scenarios leading to severe accidents due to ''domino effect'' is of utmost importance (Antonioni et al., 2009). Therefore, the linear model is developed in this section by means of different domino scenarios and is applied in mathematical formulation afterwards. The modeling process includes 4 steps:

step 1. Identifying the concept of supply chain process.

step 2. Illustrating failure scenarios in supply chain. Mapping all failure scenarios are not an easy task, as failures are not homogeneous and different consequences are result of different activities. Furthermore, different scenarios occur in different period which can not be recognized. With considering different failure events in a scenario, tree of failures can be traced. Figure 2 shows a failure modes in a supply chain.

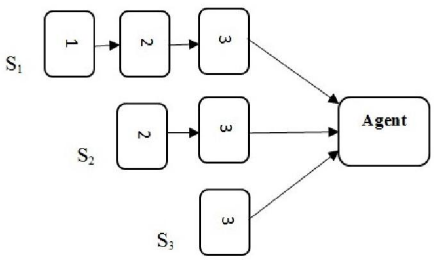

Figure 2. Tree of failure process in a supply chain

S_1 is first scenario showing that there is failure mode starting from unit 1, then unit 2 and 3 may/may not work properly.

S_2 is second scenario showing that there is failure mode starting from unit 2, then unit 3 may/may not working properly.

S_3 is third scenario showing that there is failure mode in unit 3, then unit 1 and 2 are working properly, but we never consider S_3 in modeling activities, since more than one unit is needed for estimating domino effect.

step 3. Calculating occurrence probability of scenario by means of probability rules in relation (2):

$$a_z = P(failure\ in\ scenario\ S_1) = P(failure\ in\ 1 \cup failure\ in\ 2 \cup failure\ in\ 3)$$

$$a_z = 1 - P(\overline{failure\ in\ 1} \cap \overline{failure\ in\ 2} \cap \overline{failure\ in\ 3}) \quad (2)$$

Step 4. All parameters, decision variables and scenarios are introduced here, as follows:

i index of subagents

j index of domino effects

a set of failure probability of agents (a_i denotes failure probability of agent i).

x set of subagents ($x \in \{0,1\}$, if x=0 then the sub agent is out of order and will not take into account in scenario).

z set of target agents ($z \in \{0,1\}$, if z=0 then the agent is out of order and will not take into account in scenario).

c set of domino effects (c_{ij} denotes j-th domino effect caused by i-th subagent).

n active units in a scenario.

Thus domino effect estimation modeling depends on how scenario occurs and is constructed as follows in relation (3):

$$\max = \prod c_{ij} x_i$$
$$\sum_i a_i x_i + \sum_{i,j} c_{ij} x_i \le a_z z$$
$$\sum_i x_i + z = n + 1$$
$$c_i \ge 0 \quad (3)$$

Then we apply the model to S_1 for instance and describe solution methodology.

In S_1, there is failure mode starts in unit 1, then units 2 and 3 affected with the failure. This scenario contains 4 failure modes as following:

1) Unit 1 has a failure but units 2and 3 are working properly, then failure of unit 1 propagates as domino effect. It is calculated by means of relation (3) and results relation (4):

$$\max = c_{11} x_2 \times c_{12} x_3$$
$$a_1 x_1 + c_{11} x_2 + c_{12} x_3 \le a_z z$$
$$x_1 + x_2 + x_3 + z = 4 \quad (4)$$
$$c_{11}, c_{12} \ge 0$$

Where failure in x_1 propagates to x_2 and x_3 and domino effects is limited by a_z (probability of the scenario), calculated by relation (2) and results relation (5):

$$a_z = \text{P(failure in scenario)} = \text{P(failure in 1 U failure in 2 U failure in 3)}$$
$$a_z = 1 - P(\overline{\text{failure in } 1} \cap \overline{\text{failure in } 2} \cap \overline{\text{failure in } 3}) \quad (5)$$

2) There are failure mode in units 1and 2, then unit 3 is working properly. Therefore modeling process will consider domino effect from 1, 2 in relation (6):

$$\max = c_{11} x_2 \times c_{(1,2)2} x_3$$
$$a_1 x_1 + a_2 c_{11} x_2 + c_{(1,2)2} x_3 \le a_z z$$
$$x_1 + x_2 + x_3 + z = 4$$
$$c_{11}, c_{(1,2)2} \ge 0 \quad (6)$$

Where failure in x_1 and x_2 propagates to x_3.

3) There are failure mode in units 1and 3, then unit 2 is working properly. Domino effects come from

units 1 and 3 in relation (7):

$$\max = c_{11}x_2 \times c_{(1,2)2}x_3$$
$$a_1x_1 + c_{11}x_2 + a_3c_{(1,2)2}x_3 \le a_z z$$
$$x_1 + x_2 + x_3 + z = 4$$
$$c_{11}, c_{12} \ge 0 \quad (7)$$

4) There are failure modes in units 1, 2 and 3, then all units are responsible for domino effects in relation (8):

$$\max = c_{11}x_2 \times c_{(1,2)2}x_3$$
$$a_1x_1 + a_2c_{11}x_2 + a_3c_{(1,2)2}x_3 \le a_z z$$
$$x_1 + x_2 + x_3 + z = 4$$
$$c_{11}, c_{(1,2)2} \ge 0 \quad (8)$$

This modeling process continues for S_2, as well. Since this procedure suggests linear models all the models are solved in Lingo software easily, thus it simplest the methodology of assessment in a supply chain.

3. Results

In order to evaluate the possibility of modeling a series of computational tests is run in this section. Required data have been obtained from expert teams that have designed the electronic supply chain network since specialists in this field are appropriate options to evaluate reliability of supply chain. Table 1 demonstrates failure probability of all units:

Table 1. Failure probability of units obtained from expert teams

units	*Failure probability*	a_z
1	0.12	0.3
2	0.14	0.3
3	0.07	0.3

Construction of model in the agent:

scenario S_1 is assumed and data are assigned in relation (4) as following and solution is provided by Lingo:

$$\max = c_{11}x_2 \times c_{12}x_3$$
$$0.07x_1 + c_{11}x_2 + c_{12}x_3 \le 0.3z$$
$$x_1 + x_2 + x_3 + z = 4$$
$$c_{11}, c_{12} \ge 0$$

and all information provided in table 1are assigned in relations (6)-(8). Results gained from Lingo software are demonstrated in Table 2:

Table 2. Domino effects gained from Lingo

Supply chain	*Scenario*	*Domino effect*
A	S_1	(0.115,0.95)
	S_2	(0.1,0.83)

Since in some models produce two separate domino effect, it is preferred to consider this effect as interval scale. In other words, the deterministic model will be led to better responses, without loss of modality, if all answers are adapted to interval data.

4. Conclusion and discussion

The industrial world as we know it today has become a global network of demand and supply nodes, interlinked through interacting logistics systems. The Internet and related ‘e-services’ have opened up the demand and supply markets of the world, so that the ‘next-door’ marketplace could as well be the ‘next-continent’ marketplace. These systems are complex entities with multiple physical and virtual relationships, and multiple internal and external interfaces which are the major preference in research arias. Judging from the growing number of papers in research journals and various stories in professional magazines, supply chain risk management is a field of growing important. Thus estimating the risk and managing it, is critical for today’s supply chains. In this paper we focused on quantitative methods of risk measurement, in particular estimating domino effect.

In addition, a linear model was presented for estimating domino effect which is understandable with mathematical relation and easily be solved with Lingo. As supply chains shifted to e-services, some other variables such as net transactions can be apply in this model which can be considered as further researches.

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