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Transportation risk analysis using probabilistic model checking

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ABSTRACT

Transportation and supply chain activities represent essential components in many endeavors covering both public and private domains. However, the underlying transport networks are complex and potentially fragile due to weather, natural disasters or other risk factors. Thus, assessing transportation related risk represents a key decision support capability along with the ability to evaluate contingency options for risk mitigation. In this paper, we address these issues by adopting probabilistic model checking to evaluate the risk and contingency options related to transportation tasks. In this pursuit, risk related properties are assessed for behavioral models capturing the transport system. Moreover, we show the usefulness of constructing decision trees that can provide insightful means of risk appraisal. The proposed approach can help decision makers evaluate contingency options and determine lower and upper cost bounds for risky transportation tasks such as those involved in humanitarian aid provision. The proposed approach is also illustrated with a case study.

1. Introduction

During the past decade, risk management has been increasingly applied on a wide range of activities both by government organizations and as part of industry core business practices as discussed by Beasley, Clune, and Hermanson (2005). Logistics and supply chain activities represent essential components in a wide area of activities both in civilian and military domains and the expected outcomes depend on the success or failure to carry out the underlying transport tasks. Past incidents provide a glimpse on the risk factors for transportation systems. A notable example is represented by hurricane Katrina, which in 2005 severely affected the transport infrastructure[1] after landfall, thereby disrupting the relief efforts. Another significant incident happened in 2010, when the ash ejected from the eruption of a volcano in Iceland forced many European countries to close their airspace[2], resulting in a massive disruption of air traffic. Thus, transportation activities can significantly benefit from performing risk analysis.

From a conceptual standpoint, risk is traditionally conceived as "reflecting variation in the distribution of possible outcomes, their likelihoods, and their subjective values" March and Shapira (1987). More recently, according to Fernández-Muñiz, Montes-Peón, and Vázquez-Ordás (2012), commenting on the OHSAS 18001 standard, risk is defined as "the combination of the likelihood of an occurrence of a hazardous event or exposure(s) and the severity of injury or ill health that can be caused by the event or exposure(s)".

According to "Transport Canada", the underlying concepts relate to the chance that something unwanted is going to happen, the resulting consequences if it does, and the uncertainty of the outcome. In this setting, risk management is introducing the idea that the likelihood of an event happening can be reduced, or its consequences can be minimized. In essence, the risk management objective for transportation is to reduce accident likelihood and severity of failed deliveries while keeping cost under an acceptable threshold. Notable benefits can result from applying risk management on transportation. It supports strategic and organizational planning and allows decision makers to handle uncertainty (unexpected and unwanted events). It also allows getting hold of opportunities resulting from risk mitigation, and enhances stakeholders' communication among other things as outlined by Richardson, Ampt, and Meyburg (1995).

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[1] <http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf>.
[2] <http://web.archive.org/web/20100418203523/http://news.bbc.co.uk/2/hi/science/nature/8621992.stm>.

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Risk management is explored in literature by March and Shapira (1987), Christopher and Lee (2004), Jüttner (2005), Manuj and Mentzer (2008), Waters (2011), Wieteska (2013), particularly in the context of global supply chains. However, as noted by Manuj and Mentzer (2008), stakeholders are more interested in often encountered risk factors, generally corresponding to low-impact events while disregarding unlikely factors, although their potential impact may be high (e.g. air/water/land contamination). In logistics and transportation, risk varies depending on the route, especially when environmental conditions are adverse. In this respect, the perception of risk plays an important role for the stakeholders as described by Rundmo, Nordfjærn, Iversen, Oltedal, and Jørgensen (2011). Since different route choices will result in different risk levels it is necessary to evaluate and address the risk levels associated with different routes as part of planing and decision making activities. In this pursuit, we investigate in this paper a risk assessment technique based on formal analysis of transportation systems using probabilistic model checking. The contributions of our paper can be summarized as follows:

- Elaboration of an approach based on probabilistic model checking for transportation risk assessment along with an exemplifying case study;
- Capturing risk prone transportation tasks as Markov Decision Process (MDP) which can be formally analyzed by probabilistic model checking;
- Provision of decision making support based on evaluating decision trees constructed from the outcome of probabilistic model checking;
- Assessment of risk properties expressed in probabilistic temporal logic.

The remainder of the paper is organized as follows. Section 2 discusses the related work. Section 3 provides important background information. Thereafter, the system description along with the assumptions and the proposed approach are presented in Section 4. Section 5 discusses the enhanced decision making support that can be obtained via decision trees. Then, Section 6 describes the application of probabilistic model checking for the assessment of risk related properties expressed in Probabilistic Computation Tree Logic (PCTL). Finally, Section 7 provides a number of summarizing remarks before drawing the conclusion and commenting on future work.

2. Related work

In the transportation context, the main risk management area of concern is to reduce the occurrence of accidents, the penalties incurred in case of accidents and the accompanying severity levels, as described by Christopher and Lee (2004). Transport planning and management also involve the perception of risk that decision makers might have for different means of transportation as discussed by Rundmo et al. (2011). An additional aim of the aforementioned work is to examine the relative importance of perception for transport risk factors relative to the perception of non-transport factors. Generally, when transporting products from different locations (depots) to various destinations (demand points), one has to manage the way that the products are shipped and to assess, to the extent possible, the potential risks that might affect such shipment as discussed by Manuj and Mentzer (2008). Such assessment can be performed as part of business process modeling. In this respect, a general approach on risk management is provided by World Customs Organization (2010). Business processes modeling can leverage model-based systems engineering involving flow-charts and activity diagrams which can be formally assessed. In the context of systems engineering design, Jarraya, Soeanu, Debbabi, and Hassaïne (2007) present an automated verification and performance analysis approach for time-constrained activity diagrams modeled as discrete time Markov chains. The proposed approach uses the PRISM[3] probabilistic model checker. Soeanu et al. (2012) detail a symbolic model checking approach for service delivery planning with applicability for search and rescue operations. The proposed approach uses the NuSMV[4] model checker.

Decision trees have been used by Berger, Gerstenfeld, and Zeng (2004) to assess the risk in a network of suppliers and select the most adequate number of suppliers. Hulett and Hillson (2006) have applied decision trees for risk analysis and assessment in the context of calculating the expected value of a project and identifying project alternatives. We employ similar concepts in relation to the use of decision trees but our concern revolves around loss mitigation and potential cost avoidance.

Applied system dynamics can be used to gather insights into potential risk factors that can affect mission critical processes and applications. This technique has been used by NASA to perform risk analysis on the safety-related decision making structure as described by Dulac (2005) and also in the manned space program, to improve the understanding of the factors involved in the Columbia shuttle accident. Moreover, stochastic dynamic programming has been applied by Besnard (2007) in the context of power systems in order to develop an optimal intervention plan to minimize the risk of equipment failure. Integer Programming (IP) has been used by Caulkins, Mead, Hough, and Osman (2007) to find a combination of security countermeasures with the goal of maximizing system security under fixed resources. Furthermore, Petri Nets have been used by Iordache and Antsaklis (2006) for safety analysis, work-flow modeling, verification and authorization and also by Cukic and Leteef (1998) in the context of high-risk scenario identification.

The approach for supply network risk assessment presented by Deleris and Erhun (2005) rests on a flow model of the network combined with Monte Carlo simulation. This approach incorporates external events to evaluate uncertainty in supply networks. It accounts for the dependencies between products and facilities, and enables a high-level analysis of "loss of product volume" due to network structure and adverse external events.

A methodology to generate a robust logistics plan that can mitigate demand uncertainty in humanitarian relief supply chains is proposed by Ben-Tal, Chung, Mandala, and Yao (2011). This paper deals with optimizing dynamical assignment of emergency response and evacuation traffic flow. It uses a cell transmission model as dynamic traffic assignment model and a min–max criterion adjusted for dynamic optimization. This work focuses on mitigating the uncertainty of demand in the aftermath of a disaster while our work focuses on transport risk mitigation.

The paper by Li, Hu, and Huang (2013) develops an improved fuzzy logic model suitable for risk management in the marine oil transport system. The model improves the normal fuzzy expert system via proactive, reactive and database loops. Experimental results are used to showcase the benefits in terms of improved risk assessment. This work leverages fuzzy logic which deals with degrees of truth or relative truths while probabilistic reasoning aims at making predictions about events based on partial knowledge. In our scope of interest, we favor probabilistic modeling of the transport system as Markov chain since this model allows the assessment of properties expressed in probabilistic temporal logic via probabilistic model checking.

[3] <http://www.prismmodelchecker.org/>.

[4] <http://nusmv.fbk.eu/>.