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A risk assessment approach to improve the resilience of a seaport system using Bayesian networks

Andrew John [a], Zaili Yang [a], Ramin Riahi [b,1], Jin Wang [c]

[a] Liverpool John Moores University, UK
[b] Liverpool John Moores University, James Parsons Building, Byrom Street, Liverpool L3 3 AF, UK
[c] Liverpool Logistics, Offshore and Marine (LOOM) Research Institute at Liverpool John Moores University, UK

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ABSTRACT

Over the years, many efforts have been focused on developing methods to design seaport systems, yet disruption still occur because of various human, technical and random natural events. Much of the available data to design these systems are highly uncertain and difficult to obtain due to the number of events with vague and imprecise parameters that need to be modelled. A systematic approach that handles both quantitative and qualitative data, as well as means of updating existing information when new knowledge becomes available is required. Resilience, which is the ability of complex systems to recover quickly after severe disruptions, has been recognised as an important characteristic of maritime operations. This paper presents a modelling approach that employs Bayesian belief networks to model various influencing variables in a seaport system. The use of Bayesian belief networks allows the influencing variables to be represented in a hierarchical structure for collaborative design and modelling of the system. Fuzzy Analytical Hierarchy Process (*FAHP*) is utilised to evaluate the relative influence of each influencing variable. It is envisaged that the proposed methodology could provide safety analysts with a flexible tool to implement strategies that would contribute to the resilience of maritime systems.

1. Introduction

Over the last few years, many critical maritime infrastructure (CMI) systems have been ageing and deteriorating at a fast rate due to their challenging field of operations. However, given the importance of these systems in advancing global economy, decision makers have the challenging task of maintaining a balance between safety, security, sustainability and resilience of their systems to diverse operational uncertainties leading to disruption of the systems (John et al., 2014).

High-profile accidents, such as the 9/11 terrorist attacks in 2001, the lock-out of the American West Coast Port in 2002, and the Fukushima nuclear disaster in 2011, which forced some shipping firms to avoid key ports and sea lanes in Japan, are clear examples of systemic failures and disruptions in these complex socio-technical domain.

When critical maritime systems do not have the robustness to recover in the face of disruption, they present themselves as attractive targets to terrorism-related attacks. Because a large proportion of the world's trade is transported by sea, the global economy is heavily dependent on the effective operation of these systems, resulting in a high level of systemic complexity; disruptions at any point within their operation could potentially result in catastrophic and disastrous consequences.

Modelling of these systems can provide useful insights regarding how failures might propagate and lead to their disruption, and also the basis for the development of robust frameworks and approaches that can be used for the analysis of the systems (Codetta-raiteri et al., 2012). Building resilience in CMI requires creating capabilities and a sustained engagement with the stakeholders involved in their operations. Additionally, academics and industrialists acknowledge that safety and security efforts that are aimed at mitigating risks will always reach a point of diminishing returns. A more realistic way of optimising the system's defence capability is to incorporate resilience into its operations to adapt, cope and recover to a desired level of functionality.

An emphasis on resilience operation of the systems provides a flexible and collaborative modelling of the systems to address the diverse risks of disruption proactively, particularly as new hazards and threats are constantly evolving. Additionally, insufficiency of resilience-related literature in the maritime domain together with the vision to establish secure and resilient maritime operations (Mansouri et al., 2010; Mostashari et al., 2011) has resulted in an

E-mail addresses: j.andii44@yahoo.co.uk (A. John), z.yang@ljmu.ac.uk (Z. Yang), r.riahi@ljmu.ac.uk (R. Riahi), j.wang@ljmu.ac.uk (J. Wang).
[1] Tel. 44-151-2312477; fax: 44-151-2073460

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urgent need to develop a modelling approach using an intelligent decision tool that can provide insight to decision makers on how to optimise the performance effectiveness of seaport operations.

As graphs have proven to be a natural language for analysts to represent dependence and independence relations among variables, and thus provide an excellent language for communication and discussing relations among variables, a Bayesian belief network (BBN) is used to assess the influencing factors leading to disruption of operations. Unlike rule-based approaches for risk analysis (e.g. approximate reasoning approaches), BBN has the ability to model randomness and capture non-linear causal relationships in complex socio-technical systems (Ren et al., 2005; Yang et al., 2008).

However, both the fuzzy logic-based approach and BBN have limitations in safety analysis of complex systems. A common criticism of fuzzy reasoning approaches is their inability to conduct inference inversely; it is a feed-forward approximate reasoning approach, i.e. when a model is given a set of inputs, it can predict the output, but not vice versa; while the BBN approach is criticised due to the fact that it requires too much information in the form of prior probabilities, which is usually difficult to obtain in risk assessment. Research by Eleye-Datubo et al. (2008), Huang et al. (2006), Halliwell et al. (2003) and Bott and Eisenhawer (2002) has revealed that merging fuzzy logic and BBNs for safety and reliability studies of complex systems can be beneficial in compensating for their individual shortcomings. It is important to emphasise that the concept of the Fuzzy Bayesian Network (*FBN)* can be expressed in different ways to address various research needs and interests.

The main objective of this paper is to propose a modelling approach based on the Fuzzy Bayesian Network (*FBN*) to optimise the performance effectiveness of seaport operations. This has been organised as follows. Section 2 reviews the existing literature on resilience of CMI systems, presents and discusses the diverse risks factors associated with the systems, and analyses schemes to enhance the resilience of the systems. Section 3 discusses the modelling approach using a BBN. Section 4 explains the methodology of the study. Section 5 provides a case study to demonstrate the implementation of the proposed methodology. Section 6 presents the analysis of the experiment/discussion of result, and Section 7 presents the conclusions of the study.

2. Literature review

The literature review examines resilience engineering literature, schemes to enhance the resilience of critical maritime infrastructure systems, and the analysis of the diverse risks and operational features of these systems.

2.1. Resilience of critical maritime infrastructure systems

Over the last decade, safety analysts have acknowledged the limitations in the existing approaches to the assessment of complex systems and resilience engineering (RE) has been suggested to overcome such limitations (Hollnagel et al., 2008)). RE focuses on theories and tools to create foresight about the changing patterns of risk scenarios before disruption occur. Subsequently, significant effort has been made in trying to highlight the basic features of resilient systems and the development of robust, flexible and acceptable concepts, principles and methods that can serve as the basis for developing approaches to enriching the field of resilience in order to optimise critical systems operations (Hollnagel et al., 2008; Nemeth et al., 2009; Woods, 2000).

The term resilience has various definitions due to different perspectives. It is considered as the capacity of a system or organisation to bounce back after a mishap (Widalsky, 1988). The research characterises resilience as the capacity to cope with unanticipated dangers after they have emerged. Reason and Hobbs (2003) defined resilience as the properties of an organisation to make it more resistant to its operational hazards, while Rosness et al. (2004) defined resilience as the capacity of an organisation to accommodate failures and disturbances without producing serious accidents. However, Hollnagel et al. (2007) defined resilience as the inherent capacity of a system to adjust its functioning prior to or following changes and disturbances so that it can sustain operations even after a major mishap or in the face of continuous disruption or stress. Thus, the implication of these definitions from the literature is that, for a system or an organisation to be resilient, it must have the following capabilities:

- Anticipate future threats and opportunities.
- Respond to regular and irregular threats in a robust yet flexible manner.
- Monitor on-going developments.
- Learns from past failures and success alike.

Since complex systems operations involve uncertainty, security incidents may be characterized by the exploitation of vulnerabilities in the system to achieve a certain degree of disruption. Hence, resilience can be used as an innovative management strategy to achieve a high level of security in an uncertain and dynamic environment. Benefits derived from strategic implementation of resilience in complex systems operations can be in the form of (Johnsen and Veen, 2013; Weick and Roberts, 1993):

- Increased focus on proactivity, i.e. mindful of anticipating unexpected and uncertain events that may disrupt system processes in a systematic fashion.
- Ability of the system to adjust operation in the face of adverse operational scenarios in order to maintain its functionality.
- Ability to prepare for the unexpected in a pragmatic environment.

The Committee on Marine Transportation Systems (CMTS) lists resilience as one of the five most pressing and current challenges to CMI systems and has outlined a framework for increasing the resilience of the system that is consistent with the national response framework (Omer et al., 2012). However, the literature makes little effort to analyse and quantify how the resilience of these systems can be assessed using robust yet flexible modelling tools.

Omer et al. (2012) proposed a framework for assessing the resiliency of maritime transportation systems (MTS) based on the methodology of a network infrastructure resiliency assessment framework. The framework consists of three stages in which a network model is extracted from the physical network and its resiliency metrics are identified and modelled using the network optimisation technique. Although showing some attractiveness, the method has still been criticised for not addressing uncertainties in measuring resilience and not providing clarity and insight on the Vensim software used for the assessment in a precise and succinct manner that can be understood by analysts who are not well versed with advanced computational algorithm.

Mansouri et al. (2010) proposed a risk management approach based on a decision analysis framework which was also based on common fundamental elements that defined the resiliency of port infrastructure systems. The framework develops a systemic approach to the decision making process in regard to assessing the vulnerabilities of the system and devising and valuing resiliency strategies. Nair et al. (2010) presented an approach to measure the resilience of a port system using the measure of intermodal (IM) resiliency. IM resiliency is measured as the ratio between the