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An integrated fuzzy risk assessment for seaport operations

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ABSTRACT

Seaport operations are characterised by high levels of uncertainty, as a result their risk evaluation is a very challenging task. Much of the available data associated with the system's operations is uncertain and ambiguous, requiring a flexible yet robust approach of handling both quantitative and qualitative data as well as a means of updating existing information as new data becomes available. Conventional risk modelling approaches are considered to be inadequate due to the lack of flexibility and an inappropriate structure for addressing the system's risks. This paper proposes a novel fuzzy risk assessment approach to facilitating the treatment of uncertainties in seaport operations and to optimise its performance effectiveness in a systematic manner. The methodology consists of a fuzzy analytical hierarchy process, an evidential reasoning (ER) approach, fuzzy set theory and expected utility. The fuzzy analytical hierarchy process is used to analyse the complex structure of seaport operations and determine the weights of risk factors while ER is used to synthesise them. The methodology provides a robust mathematical framework for collaborative modelling of the system and allows for a step by step analysis of the system in a systematic manner. It is envisaged that the proposed approach could provide managers and infrastructure analysts with a flexible tool to enhance the resilience of the system in a systematic manner.

1. Introduction

Critical Maritime Infrastructure (CMI) systems are the basis of the world economic growth. CMI systems can be defined as ports (comprising of assets that are capable of an intended service delivery such as access channels, turning basins, quay walls, jetties, aids to navigation, breakwaters, pilots, tugs, and stacking areas), the superstructure (i.e. logistics, ICT, handling equipment, warehouses, etc.), the operating procedures, management practices, complex interactions with the society to facilitate trade, the transfer of goods and services for economic development, vessels (e.g. LNG carrier systems, FPSOs, supply vessels, etc.), tank farms at industrial port, pipeline systems and their intermodal connections (Taneja et al., 2010).

CMI systems are susceptible to diverse risks in their field of operations as a result of the interaction and interdependence among their components and subsystems. Additionally, as a result of multiplicity of stakeholders and the operational complexity in CMI systems high levels of operational uncertainty in the CMI systems exist. The CMI systems typically operate in a dynamic environment in which the boundaries of safety are pushed, leading to the disruption of operations.

Serious accidents and cascading events, such as the 9/11 terrorist attacks in 2001, the lock-out of the American West Coast Port in 2002, the Fukushima nuclear disaster in 2011, and the recent piracy related activities off the Gulf of Guinea are clear examples of systemic failures and disruptions of CMI systems. As these systems become highly integrated and play a vital role in advancing the global economy, accidents gradually develop over time through a conjunction of several small failures (Perrow, 1984; Reason, 1990). Consequently, it is imperative to address the diverse risks of such accidents or disruptions proactively, particularly as new hazards and threats are constantly evolving due to the dynamic nature of the maritime environment.

When critical systems such as maritime infrastructure do not have the robustness to recover in the face of disruption, they present themselves as attractive targets to terrorism related attacks. Given that 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; disruptions at any point within their operation could potentially result in catastrophic and disastrous consequences.

Building resilience in maritime operations requires creating capabilities and a sustained engagement from the stakeholders involved in their operations. Additionally, academics and industrialists

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acknowledge that safety and security efforts that are aimed at mitigating risks will always reach a point of diminishing returns. In order to optimise the defence capability of the system, it is essential to constantly revise and update its risk model in such a manner that it would adapt, cope and recover to a desired level of functionality when facing adverse operational constraints. An emphasis on robustness in the system's operations provides a flexible and collaborative model for maritime systems to adopt.

Risk assessment of a CMI system is a complex task due to the integration of technical, organisational, operational and security issues into its daily operations. Conventional techniques such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode, Effects and Criticality Analysis (FMECA) and Bow-Tie (BT) have been widely used in reliability analysis of critical systems and have contributed immensely to the literature of risk analysis. However, most of the aforementioned approaches have prescribed setbacks which affect their application for quantitative risk analysis and management due to their inability to account for uncertainties associated with the system operation. As a result, methods such as the fuzzy set theory, the Analytical Hierarchy Process (AHP) and other preliminary assessment methods are nowadays widely used in many industrial sectors such as public entertainment (Fu and Li, 2010), deep water offshore well operations (Miri Lavasani et al., 2011) and petroleum tank farm storage services (Tao et al., 2012). Furthermore, they are used for the general safety assessment and evaluation of specific risks such as fire and explosion, chemical spills or toxic substances release and to assess the adequacy of the safety systems for the risk level in the fire safety engineering.

Large numbers of optional maritime safety and security control measures have been proposed by various regulations to optimise the operational efficiency of the system in such a manner that it will exhibit resilience to disruptions (Ferriere et al., 2005; King, 2005; Raymond, 2006; Rosenberg and Chung, 2008). The use of conventional risk assessment approaches to deal with newly arising hazards and threats (e.g. potential terrorist attack) to the maritime infrastructure reveals two major challenges they face in an uncertain environment. Yang et al. (2009) expressed the challenges faced by these systems as the lack of capability to process diverse data suitable for input into a risk inference mechanism and the lack of capability to analyse the interactive dependence between risk factors. As a result, one realistic way to analyse unavailable data is to employ subjective assessment using the combination of fuzzy logic and an Evidential Reasoning algorithm (ER). Compared to the traditional fuzzy inference mechanism (i.e. max–min fuzzy operations), an ER approach has the superiority of avoiding the loss of useful information in their inference processes; hence, it can be suitable for modelling complex systems.

The occurrence of natural disasters and the disruptions caused by man-made attacks on CMI systems are imprecise. It is therefore challenging to protect the systems from such perceived scenarios and understand their complex operational processes. The purpose of analysing the system in the face of severe disruptions is to promote security and reduce its susceptibility to hazards. It is important to emphasise that resilient systems are able to recover by delivering their designed expected value and minimising losses in a systematic fashion. Moreover, insufficiency of quantitative risk assessment of maritime related literature together with the vision to establish a secure and resilient CMI system has resulted in an urgent need for an integrated risk assessment methodology capable of tackling the uncertainties associated with the systems operation.

The aim of this paper is to propose an integrated fuzzy risk analysis model for assessment of seaport operations. This has been organised as follows. Section 2 reviews the existing literature on CMI systems, and presents and discusses the diverse range of risk factors associated with seaport operations. Section 3 explains the methodology of the study. Section 4 provides a case study to demonstrate the applicability of the proposed methodology. Sections 5 and 6 present a discussion of results and the conclusion.

2. Literature review

CMI systems are faced with high operational constraints due to the dynamic interactions among their interrelated components. The level of interdependences and complexity of the system's operations can be acknowledged through its description by the US Department of Homeland Security "as all areas and things of, on, under, relating to, adjacent to, or bordering on a sea, ocean, or other navigable waterway, including all maritime related activities, infrastructure, people, cargo, vessels and other conveyances" (Moteff and Parfomak, 2004). Analysing the systems in terms of their interdependences which include infrastructure characteristics, operational relationships, environmental impacts, technical efficiency, failure types and state of operation provides insight into their complexity.

Modern seaports, which are an integral component of CMI systems, focus their operations on continuous handling of flows and efficient transport. Meersman et al. (2009), as shown in Fig. 1, revealed that these systems progressed from performing cargo handling, stacking and distribution functions to being a complex transportation hub in logistic chains. A vessel operator controls a fleet of vessels with a set of characteristics; the land side can be understood as a system of ports operating at local, national and regional levels. It is worth mentioning that individual ports have several terminals, serving different types of loading technologies and cargoes.

In maritime operations, seaports serve as the business hub and provide critical infrastructure functions which involve customs, investments, developments and marketing (Berle et al., 2011). Detailed analysis of CMI operational processes and their component parts suggests that seaport infrastructure systems include the operating procedures, management practices and complex interactions with the society to facilitate trade and the transfer of goods and services for economic development (Taneja et al., 2010).

Maritime-related activities are operated at seaports which are located within densely populated and industrial locations that accommodate chemicals and weapons in their storage facilities (Nair et al., 2010). The flexibility in the flows of vessels and large amounts of bulk cargoes within these areas has created a huge amount of concern about their integrity because of the numerous opportunities for them to be tampered with for terrorism/sabotage -related acts. Additionally, their operations can be marred by several organisational and environmental risks that range from natural to man-made disasters with disruption likelihood that can potentially result in a large amount of direct and indirect financial losses (Hultin et al., 2004; Nilchiani and Mostashari, 2008). External risks that disrupt seaport operations include hurricanes, tornadoes, tsunamis, flood and chemical spills.

When studying the safety aspects of a seaport, a logical approach is to break down the system into functional entities comprising sub-systems and components. Safety modelling of these functional entities can be carried out to fit such a logical structure, then the interrelationships can be examined and a system safety model can be formulated for risk-based decision making in all phases of the system's life, from its conception and design to its operation, maintenance and decommissioning.

The risks associated with seaport operations are complex. This is evidenced by the fact that different risk categories discussed in literature affect the multiplicity of stakeholders involved in their operations. Complexities in the systems may further arise when