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Modelling performance variabilities in oil spill response to improve system resilience

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A B S T R A C T

The Environmental Defense Centers (EDCs) of Brazil provide response services following oil spill accidents. EDCs near affected areas rapidly organize and execute emergency response activities in order to minimize the environmental and economic impacts of spills. The current research applied ergonomic principles and methods (interviews, direct observation and focus groups) to describe common EDC system operations, and to identify constraints and conflicting procedural practices. Results of ergonomic field studies were modeled and analyzed using the Functional Resonance Analysis Method (FRAM), which can show how functional variability in planning, preparedness, execution, resources, economic and human factors affect the quality of emergency response activities. The FRAM analyses provide guidance for improving the resilience of oil spill emergency response systems.

1. Introduction

The risk of spilling oil into the environment is inherent to the petroleum processing industry. Up to 8.8 million tons of oil are unintentionally released into the environment each year, with most spills directly related to human activities (Fingas, 2011). The effects of these spills are all too apparent: dead wildlife, oil-covered marshlands and contaminated water being chief among them. Oil spills can occur during several points in the "life cycle" of petroleum processing, including during oil exploration and production, transport (by vessel, railroad, tanker truck, or pipeline), refining, storage, consumption or usage, and waste disposal.

Major accidents in the petroleum industry have increased global awareness of the risks of oil spills, the damage they cause to the ecosystem, and impacts on human activities (Alkazimi and Grantham, 2015). Impacts of these accidents include financial costs of oil spill recovery activities and regulatory fines, a loss of natural resource and processing labor, damage to the environment, and injuries to workers and the public (Carvalho and Vidal, 2001). In addition to human-caused (e.g., accident-related) spills, oil and hazardous oil products can be released following natural disasters such as earthquakes and hurricanes (Cruz and Krausmann, 2009), thus imposing a threat irrespective of the commercial demand for petroleum products.

To mitigate and minimize the major impacts of oil spills, specialized organizations that are part of the Global Response Network (GRN) share information and provide centers of expertise in spill preparedness, response performance and recovery techniques. One such organization, the Environmental Defense Center (EDC) of Brazil, is responsible for establishing and maintaining capabilities to respond to oil spills of any size, anywhere in Brazil. As a complex socio-technical system, the effectiveness of EDC operations depends on effectiveness in managing the large degrees of variability and unpredictability that characterize interactions among humans, equipment, technology, and organizational components.

This article introduces the results of an investigation of EDC operations during responses to major oil spills. Ergonomic field studies provided direct observation, interview, and focus group data which were used to construct a system model that could be

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used to highlight constraints and contradictions in the system. The model was then analyzed using the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2004, 2012). FRAM is particularly well-suited for mapping dynamic dependencies in complex systems. It is used to provide a better understanding about how functional variability in planning, preparedness, execution, resource availability, economic factors, and human factors affect emergency response actions. The results of FRAM analyses can provide information for ways to increase the overall resilience of such systems.

The notion of modeling and mapping dynamic dependencies with systemic models and especially FRAM is already used in several contexts (computer science, ecological sciences, medicine), some in relation to industrial safety applications (Nouvel et al., 2007; Lundberg et al., 2009; Herrera and Woltjer, 2010; Carvalho, 2011; Belmonte et al., 2011). Nevertheless, as indicated by Underwood and Waterson (2013) there is a gap between research and practice which could hinder the awareness, adoption and usage of systemic models.

1.1. Response to oil spills

Despite all preventive actions being taken by the industry, an oil spill can be seen as a *normal accident*, using Perrow (1984) definition of *normal* as something not desired or prescribed but that can happen due the nature of processes involved. Recovery from normal accidents such as oil spills can be managed through the combined efforts of system elements in the presence of adequate resources to mitigate or minimize the harm (e.g., to the environment, finances, etc.). Managing oil spill recovery, however, involves additional factors that require precise, fast and coordinated actions that take into account the type of oil spilled, the location of the spillage, the proximity of the spill to sensitive environments, and other environmental factors.

International practices use principles of tiers preparedness and response to establish suitable capabilities to adequately cope with oil spills at the local, regional, national and international levels. The tiers serve to categorize spills in terms of their potential severity. Each tier can be escalated to the next, depending on the scale of the event and its development over time. Spill responders consider a range of factors in each emergency response scenario that may influence planning processes as well as the nature of the plan, with regard to required equipment, people and other operational expenses. Considering mostly the primary factors of size and location of a spill, the three tiers can be defined as:

- Tier 1: spills occurring near or at an operator's own facilities and having a relatively minor impact on operations. Most petroleum processing industrial facilities should have sufficient capability on-site to respond tier 1 spills.
- Tier 2: spills larger in size and/or further from available response resources, thus requiring resources beyond the tier 1 capability. A broader range of stakeholders may be involved in the response than a single industrial facility.
- Tier 3: spills that are likely to cause major national and international ecological impacts due to their scale. Tier 3 spills may require substantial resources from a range of national and international sources (Barber and Varghese, 2012).

Oil spill response emerges as a balance between conflicting objectives: removing and potentially recovering the spilled oil from the spill site, causing minimal further harm to the environment, and accounting for available resources and worker safety issues. Response activities and strategies can be summarized as:

- *Salvage operation actions*: Preventative measures can be put in place to slow the development of an oil spill and make it more manageable/less costly in a spill occurrence. Salvage operation actions commonly involve installation of salvage control units around areas that may be sensitive to spills. For example, semi-permanently installed preventative or protection booming can be used as barriers to impede the flow of oil over the surface of water.
- *Mechanical containment and recovery of spilled oil*: in the event of a spill, mechanical containment activities can be executed to prevent the spilled oil from reaching where it is most damaging, such as in shallow water or on the shoreline. Mechanical containment operations can involve deploying booms to corral the spilled oil on the surface of a body of water. The controlled oil can then be recovered using skimmers or vacuum devices and return it to a secure containment.
- *Usage of oil spill dispersants*: Oil spill dispersants are chemicals that can be sprayed into spilled oil to facilitate its rapid removal from the water surface, or to allow it to disperse into the water at concentrations that are minimally impactful.

The EDC in Brazil uses a varied combination of these activities and strategies in contingency and emergency situations in partnership with national and international petroleum processing industries. This facilitates speeded response to spills by providing capabilities where the oil is produced, transported, stored and consumed, with the dual goals of protecting the environment while minimizing operational costs and safety risks.

The EDC was created in 2000 after a series of major spill accidents, shown in Table 1, culminating with an accident involving a rupture in the Rio de Janeiro refinery's pipeline. This catastrophic event resulted in a spill of 1.2 million liters of oil in the Guanabara Bay, affecting several areas such as rivers, beaches, mangroves, and other protected areas (Carvalho and Vidal, 2001).

As of 2015, there are nine EDC centers located at strategic points around Brazil: Amazônia, Maranhão, Rio Grande do Norte, Bahia, Centro-Oeste, Bacia de Campos, Rio de Janeiro, São Paulo, Minas Gerais. The proximity of the EDCs to petroleum activities can be seen in Fig. 1.

The EDC system operates seven days a week, 24 h a day to support contingency plans for local (tier 1) spills through Operational Units associated with oil processing industrial facilities, and can mobilize to add their capabilities in addressing larger-scale (higher tier) spills as well. Each EDC Operational Unit must be prepared to respond to tier 1 emergencies within distances of approximately 250 miles in no more than 8 h. They may also be called upon if the size and/or location of higher-tiered spills require their mobilization. Fig. 2 illustrates how each type of response involves different elements of planning, equipment, people and other operational expenses. In addition to considering the spill tier, four types of response kits must be ready to move as they can be specialized for activities on land, on a beach, in maritime water or in rivers.

2. Complex system modelling

According to Hollnagel (2012) many socio-technical systems have reached levels of complexity that make them very hard (or even impossible) to model linearly with a complete system description. Nevertheless, most conventional models use linear chains of events to describe the system without adequately considering interacting environmental, organizational, or human contributions. Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Cause-Consequence Analysis are based on this approach (Leveson, 1995).