Journal of Environmental Management 223 (2018) 433–443

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Quantitative assessment of wildfire risk in oil facilities

Nima Khakzad[a,*], Mohammad Dadashzadeh[b], Genserik Reniers[a]

[a] Safety and Security Science Group, Delft University of Technology, The Netherlands
[b] Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, UK

ARTICLE INFO

Keywords:
Wildfire
Natech risk assessment
Domino effect
Oil terminal
Dynamic Bayesian network
Cost-benefit analysis

ABSTRACT

Despite frequent occurrence of wildfires around the world, the role of wildfires has rarely been taken into account in risk assessment of process plants in wildlands, especially that large inventory of flammable petroleum products in contact with the heat of wildfire can lead to severe domino effects. We have developed a dynamic risk assessment framework by integrating available models of fire spread and domino effect analysis with online maps of wildfire characteristics such as ignition probability and heat intensity to investigate the impact of wildfires on oil facilities. The framework is modular, so one can readily enhance its accuracy by replacing the current techniques with more sophisticated ones. The application of the methodology is demonstrated on an oil terminal.

1. Introduction

Natechs are referred to technological accidents such as release of hazardous materials, fires or explosions in industrial plants which are triggered by natural disasters like earthquakes, floods, and hurricanes. Compared to normal technological accidents, which are a matter of random failures or human error, natechs usually give rise to more catastrophic consequences since the likelihood of simultaneous damage to hazardous units (e.g., large storage tanks) and domino effects (chain of accidents) is much higher. Substantial release of petroleum products due to Hurricane Katrina in 2005 in the United States (the second largest oil spill disaster after the BP spill in the Gulf of Mexico in 2010) and fires in a refinery in Turkey due to the Kocaeli earthquake in 1999 are some examples among the others. Aside from direct damage to industrial plants caused by natechs, simultaneous damage to other infrastructures such as communication and power grids, pipelines, and transportation network hampers emergency response procedures, and thus aggravate the extent and severity of consequences (Campedel, 2008; Krausmann and Mushtaq, 2008).

Due to an ever-increasing growth of industrial facilities and thus the prolonging interface with nature on one hand, and anticipated increase in the frequency and severity of climatic disasters (floods, hurricanes, forest fires, etc.) on the other hand, the occurrence of natechs have been foreseen an increasing trend (Parry et al., 2007). According to a research conducted by the European Joint Research Centre (Forzieri et al., 2017), weather-related disasters such as heatwaves and cold spells, wildfires, droughts, floods and windstorms are expected to affect around two-thirds of the European population annually by the end of this century, potentially leading to a 50-fold higher fatalities (compared to today).

The hazard of wildfires has long been recognized, and there has been an exhaustive amount of work devoted to their modeling and ecological risk assessment (Preisler et al., 2004; Scott et al., 2012, 2013; Lozano et al., 2016). Wildfires can be categorized as hydro-geological events which are bound to increase especially due to climate change: every degree in warming associates with a 12% increase in lightning activity, as one of the triggers of wildfires (Romps et al., 2014). Likewise, for every degree in warming, 15% more precipitation is needed to offset the risk of wildfires (Flannigan et al., 2016). Despite the risk of wildfires (Fig. 1), their hazard has not yet, to our best knowledge, been accounted for in natech risk assessment of industrial plants. In Europe, for example, Seveso Directive III (2012) has only recently mandated the member states to consider the probability of natural disasters in the risk assessment of major accident scenarios when preparing safety reports (Article 10), with an explicit mention of floods and earthquakes in the Annex II. The most of European countries that consider natechs have likewise limited their programs to only a few natural hazards, mainly flood and earthquake (Krausmann and Baranzini, 2012).

Wildfires, like other types of fire, can be defined using the fire triangle, consisting of fuel (trees, grasses, shrubs, houses, etc), oxygen, and heat source. Lightning, burning campfires or cigarettes, hot winds, and even the sun can ignite a wildfire although four out of five of wildfires have reportedly started by people (National Geographic). Wildfires are more complicated than other fires in the sense that as they grow large enough they create their own weather and increase their speed. A wildfire can move at a speed of up to 23 km/h and the flames

* Corresponding author. Jaffalaan 5, Delft 2628 BX, The Netherlands.
E-mail address: n.khakzadrostami@tudelft.nl (N. Khakzad).

https://doi.org/10.1016/j.jenvman.2018.06.062
Received 15 January 2018; Received in revised form 8 June 2018; Accepted 19 June 2018

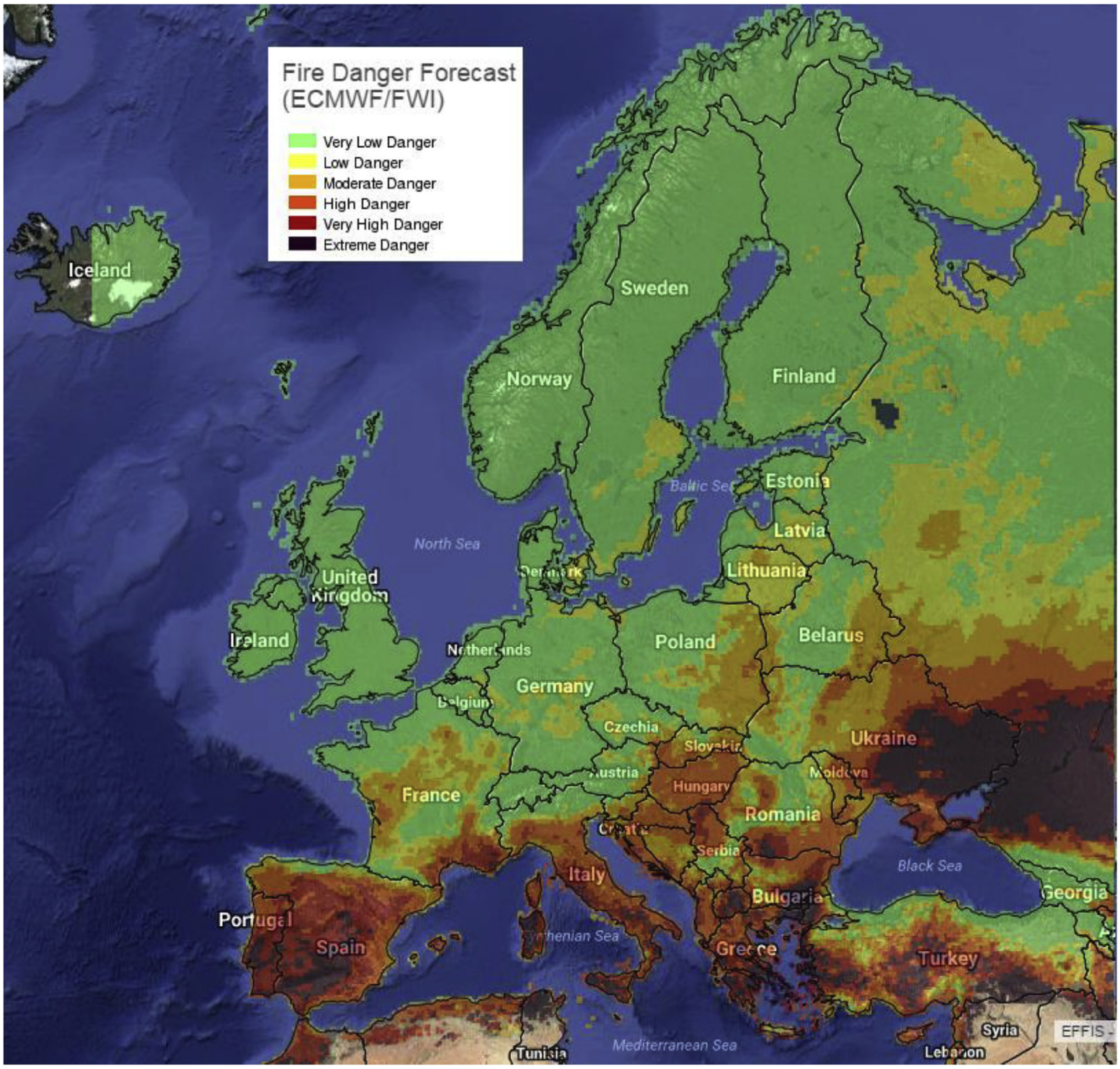

Fig. 1. Wildfire danger forecast as of August 17, 2017 (The European Forest Fire Information System).

can reach a height of up to 100 m. A favorite wind not only speeds up the wildfire spread but also can carry sparks and embers kilometers away, helping fire jump over roads and rivers.

In wildfire risk assessment, the ignition likelihood, burn probability (the probability that wildfire spreads to a certain spot), fire intensity, flame height, and type of exposure (people, the environment, assets) are the main factors to take into account (Scott et al., 2013). In wildfire-related risk assessment of process plants, the foregoing factors seem to play the key role although due to the large inventory of hazardous chemicals the severity and extent of the envisaged consequences could be far worse especially with the possibility of domino effects. Domino effects in process plants refer to a chain of accidents (fires and explosions) triggered by a primary fire or explosion so that the total consequences are much severer than that of the primary event. In domino scenarios, the escalation of a primary fire, for instance, to an adjacent unit takes place if the magnitude of heat intensity received by the unit is larger than a respective threshold (e.g., 15 kW/m^2 for atmospheric storage tanks); the neighboring unit is then expected to be damaged and thus be engaged in the chain of fires.

Many methodologies have been developed to model the spread of different types of wildfire such as surface fire (Rothermel, 1972), crown (or canopy) fire (Rothermel, 1991), and transition between surface and crown (van Wagner, 1977). Subsequently, a number of software tools such as FARSITE (Finney, 1998), FlamMap5 (Finney, 2006), FSPro (Finney et al., 2011a), and FSim (Finney et al., 2011b) has been developed to predict the likelihood and model the spread of wildfires based on historical records of wildfires in the region, weather conditions, type and density of vegetation in the landscape of interest (also known as fuelscape), and also the topology of the landscape.

There have been extensive studies on wildfire modeling (e.g., the ones mentioned above), vulnerability assessment of process equipment to external fires (Vilchez et al., 2001; Cozzani et al., 2006; Mingguang and Jiang, 2008; Landucci et al., 2009; Casal, 2017), and domino effect modeling in process plants (Bagster and Pitblado, 1991; Gledhill and Lines, 1998; Khan and Abbasi, 2001; Cozzani et al., 2005; Abdolhamidzadeh et al., 2010; Khakzad et al., 2013; Dadashzadeh et al., 2014; Khakzad, 2015). However, to the best of our knowledge, there has been no work devoted to the wildfire-related risk assessment in industrial plants.

In the present study, we aim to develop a methodology for wildfire-related natech risk assessment in process plants with an emphasis on domino scenarios. To this end, we will integrate in a framework the available techniques for wildfire spread modeling and domino scenario modeling to investigate the potential impact of wildfires on process plants in wildfire-prone areas. It however should be noted that the mutual impact of process plants on wildfires (due to their inventory of combustible and flammable materials) are beyond the scope of the present study. Wildfire characteristics and spread mechanism are discussed in Section 2. Domino effect modeling using dynamic Bayesian network is explained in Section 3. The application of the methodology