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Energy supply security for the Aegean islands: A routing model with risk and environmental considerations

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ABSTRACT

Energy security is important for islands not connected to mainland electricity grids. The Aegean archipelago comprises scattered islands, whose electricity supply relies on oil-based thermal power plants. These islands attract large numbers of tourists, while the archipelago is an environmentally sensitive area. Efficient maritime transportation of crude oil is critical for maintaining adequate power supply in the Aegean islands, especially during tourist seasons. Tanker closed-sea shipping operations in the Aegean Sea raise considerations on carbon footprint impacts. Also, despite potential impacts to local economies and the environment, the case of a maritime accident leading to an oil spill is largely overlooked. We investigate the possible integration of environmental and accident related objectives, in the decision-making process of planning an efficient oil maritime transportation service for the Aegean archipelago. We showcase a risk mitigation strategy for oil transport route planning considering spill-related impacts to local, tourism dependent economies under a more socially and environmentally conscious policy framework. We model the problem as a multi-objective capacitated vehicle routing problem and solve it using an alternating objective genetic algorithm. Results show that certain routes are considered optimal for both objectives, while risk reduction may be achieved at small operational cost increase.

1. Introduction

Maritime transportation is the primary mode for worldwide oil transportation; an estimated 1.7 billion tons of oil per year are shipped through large tankers (Siddiqui and Verma, 2015). Evidently, both the issues of cost-effectiveness and risk-minimization arise when considering tanker routes. While a lot of attention has been paid to the former, integrating the latter as an objective into route planning for tanker fleets has been a topic surprisingly underrepresented in the respective literature (Siddiqui and Verma, 2015). Obviously, different oil import routes are associated with different levels of oil-spill risk, as local conditions related to topology, population exposure and environmental considerations may be crucial on a case to case basis (Bigano and Sheehan, 2006). Reasonably, closed seas, such as the Aegean Sea, are at a higher risk of oil-spill in comparison to oceans, both due to higher accident probability and the larger impact of accidents, because of their proximity to the coast (Otay et al., 2013).

The Aegean Sea covers an area of 210 thousand square kilometers between the coasts of Greece and Turkey, and comprises more than two thousand islands. The Aegean archipelago is a popular touristic destination, attracting millions of visitors every year and an environmentally sensitive area, protected by the World Wildlife Fund (Bigano and Sheehan, 2006). Electric power generation for most of the Aegean islands entirely depends on the operation of autonomous, oil-based thermal power stations (APS). The seasonality in electric power needs sets a challenge for the islands' energy supply systems and APS operations. Indeed, the problem of energy security is exacerbated in the Aegean islands, as demand during summer months may exceed winter demand by 500%, with daily fluctuations of 60% (Kaldellis and Zafirakis, 2007). Consequently, the need for systematic, reliable and fast oil supply for APS operations renders the establishment of efficient routes of tanker ships an essential task for the livability of these communities. Nonetheless, regular tanker shipping operations in a closed sea entail environmental risks. This is coupled with the critical geographic position of the archipelago between the Bosporus Strait and the Mediterranean Sea, which results in a large additional maritime traffic and thus, a higher collision risk. An illustrative example is the collision of the large crude carrier Independenta carrying 94,000 tons of crude

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oil with a Greek cargo ship in the Strait of Bosporus, resulting in one of the 12 largest oil spills worldwide (Otay et al., 2013).

Regardless of its extent, an oil spill incident could deliver a substantial blow to the local economy, which heavily relies on tourism, an industry that bears significant costs following an oil spill (Xu, 2009; Grigalunas et al., 1986). While the actual disruption of touristic activities may be relatively short, it is the public's perception of prolonged and large-scale pollution that results in significant losses of revenue (Hayworth et al., 2011). This fact becomes even more relevant in the case of coastal and maritime tourism, where the marine environment is a major attraction for tourists. For instance, the Deepwater Horizon Oil Spill that occurred in the Gulf of Mexico in 2010 created major ramifications for the States of Louisiana, Alabama and Florida in terms of economic damage, with hotel cancellation rates reaching 60% following the spill (OCEANA, 2015). Similarly, as the main touristic product in the Aegean region is 'Sun and Sea holidays', an oil spill would inevitably divert tourists to other destinations.

Indeed, the loss of tourism revenue from a potential oil spill would be devastating to the local economies, as it is estimated that the contribution of tourism to the GDP of the Aegean islands ranges between 56% and 72% (INSETE, 2017). Further, the Greek Tourism Confederation reports that in 2015 Greece welcomed more than 2.5 million cruise tourists, while the revenues of Greek businesses from marine transport activities in 2015 amounted to €136 million; these revenues would certainly diminish if an oil spill occurred. Overall, the total contribution of travel and tourism to the Greek GDP is estimated as 18.6% or 32.8 bn euro, with the Aegean islands accounting for more than 50% of direct tourism expenditure (WWTC, 2017; INSETE, 2017). These figures underline the significance of tourism in the Aegean for the Greek economy, constituting one of the main drivers of growth and development.

Hence, determining oil maritime transportation routes that do not only minimize transportation costs, but also consider the risk associated with oil spills is important, especially when oil transportation dictates electric power supply of island communities. Given the environmental and socioeconomic importance of the Aegean Sea region, the lack of shipping management strategies integrating oil-spill risk considerations is rather surprising (Miliou et al., 2011). Whereas oil spill clean-up costs are typically incurred by the state, the socioeconomic cost associated with the decline in tourism would be devastating for the local economies, an issue so far overlooked in relevant research and practice. Improved management strategies and preventive measures are, thus, required in order establish a more socially and environmentally conscious policy framework to reduce the risk associated with oil transport in the area, without compromising energy security of the archipelago. The goal of this paper is to provide a strategic-level tool for supporting decisions on efficient oil-supply and energy security of the Aegean islands and to showcase a straightforward, yet efficient risk mitigation strategy which can in fact be implemented in practice.

In this context, this paper deals with planning routes of an efficient maritime crude oil transportation network for the Aegean islands, taking into account operational, environmental and accident considerations. A multi-objective model is developed and solved with the use of an appropriate meta-heuristic (genetic) algorithm. The remainder of the paper is structured as follows: next, a brief background on the associated problem of oil-maritime transportation route design is offered. Then, the problem overview, model formulation and solution method are presented. The model application is described in detail for the case of supplying the 25 Aegean islands featuring APS (24 of those are not interconnected to the country's main electric grid); the model calibration and results are presented and discussed. The paper concludes with the findings of the study.

2. Background

Crude oil is considered a hazardous material for transportation purposes due to the extreme consequences of a potential oil-spill (Hayworth et al., 2011) and thus, the design of a maritime crude oil network belongs to the class of hazardous materials (hazmat) transportation design problems (Siddiqui and Verma, 2015). The hazmat transportation network design problem has been increasingly attracting researchers' attention over the past few decades, mostly in the context of road and rail transport (Kara and Verter, 2004; Erkut et al., 2007; Erkut and Gzara, 2008; Verter and Kara, 2008; Sun et al., 2015). The objective of the problem is the determination of the route(s) that minimize transport risk while ensuring economic viability for the carrier (Verter and Kara, 2008). The definition of transport risk widely varies among published studies, however a typical approach in the hazmat literature has been to use the product of the probability and the consequence of the undesirable event, as in the U.S. Department of Transportation 1989 guidelines for transporting hazmats (Erkut and Verter, 1998). In the case of oil maritime transportation, transport risk stems from the possibility of an oil spill occurring during tanker movement, entailing various and severe economic, social and environmental ramifications. In relevant literature, risk assessment methodologies have been employed to estimate the expected risk cost for oil spills; the interested reader is referred to Siddiqui and Verma (2013) for a thorough review on risk estimation in the case of crude oil maritime transportation. In general, spill-related costs consist of cleanup costs, environmental damages and socioeconomic costs, compensation of damages to third parties, operational losses etc., the amount of which vary based on oil type, spill location and size, and the characteristics of the affected area (Vanem et al., 2008).

In the context of crude oil maritime transportation network design, few studies have integrated these costs in the route determination process; most of these emerged following the 1990 Oil Pollution Act in the United States, focusing on the Gulf of Mexico. Li et al. (1996) presented a strategic planning model for marine oil transportation in this area, aiming to facilitate decision makers by allowing the assessment of various routing and shipping scenarios in a multimodal and multiproduct network. The subsequent study by Douligeris et al. (1997) expanded on the idea of a comprehensive decision support system for marine oil transportation, proposing a national model for the United States. The model analyzed oil spill and oil demand data in order to identify oil flow patterns in the U.S., estimate the associated risks and suggest improvements to the existing network structure. Building upon the work by Li et al. (1996), Iakovou et al. (1999) presented a model for hazardous materials route planning considering multiple origins and destinations for the Gulf of Mexico, focusing on the prevention of overloading certain links to minimize transportation risk. Iakovou (2001) later presented an interactive multi-objective model, integrating risk analysis and routing. More recently, Siddiqui and Verma (2015) presented a bi-objective mixed integer programming model to handle both routing and scheduling for tanker ships. Other relevant work on maritime oil transportation includes the studies by Li et al. (2015) and Wang and Lu (2015) on oil-import portfolio optimization, taking into account several factors, such as oil-spill probability, import/export country, geographic factors such as chokepoints, as well as weather conditions and pirate attacks.

Overall, there are still ample grounds for research on link-based risk estimation and routing for marine oil transportation networks (Iakovou, 2001). Besides methodological aspects, a gap in the respective literature concerns the modeling of socioeconomic impacts and their incorporation in tanker route planning. In fact, to the best of the authors' knowledge no study has taken into account socioeconomic costs stemming from oil spill incidents in maritime crude oil transportation routing. In contrast to spill cleanup costs, an average value for which can be estimated based on data from past oil-spills, environmental and socioeconomic costs are much harder to quantify, as they almost entirely depend on the characteristics of the affected area in relation to the amount of oil spilt (Vanem et al., 2008; Vandermeulen, 1996). However, they are usually assumed proportionate to the cleanup costs,