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Innovative Applications of O.R.

Dynamic resource allocation to support oil spill response planning for energy exploration in the Arctic

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ABSTRACT

A mixed-integer linear program is proposed to model the dynamic network expansion problem of improving oil spill response capabilities to support energy exploration in the Arctic. Oil spill response operations in this region can be hampered by a lack of existing infrastructure, limited pre-positioned response equipment, and the possibility that response equipment might not arrive in time to mitigate the impact of a spill because of distance and infrastructure limitations. These considerations are modeled by two inter-related constraint sets with the objective of minimized total weighted response time for a set of potential oil spill incidents. One constraint set determines how to dynamically allocate response equipment and improve the infrastructures necessary to stockpile them within a network of response sites. The other set determines how to utilize this stockpile to respond to each task necessary for an incident by scheduling the equipment to complete tasks. These task completion times are subject to deadlines which, if not met, can, instead, require costlier follow-on tasks to be scheduled. The model, its assumptions, and data requirements were assessed by subject matter experts in the United States (U.S.) Coast Guard and a major Oil Spill Response Organization in the context of oil spill response logistics to support energy exploration initiatives in the U.S. Arctic.

1. Introduction

Planning, prevention, and response activities for sudden-onset extreme events are challenging, and consume large portions of federal, state, and municipal budgets and time; in FY2014, the United States (U.S.) Department of Homeland Security alone allocated 13.45 billion dollars for these activities (U.S. Department of Homeland Security, 2013). In this paper, the focus is on oil spill response in the U.S. Arctic. Energy exploration and growing maritime activity due to increasingly ice-free navigational waters have led to concerns over the region's capability to manage a major oil spill disaster (National Academy of Sciences, 2014; Papp, 2013). A mixed integer linear program is proposed to address the unique challenges of oil spill response in the U.S. Arctic and similar remote regions; this model provides decision-makers with new computational tools that examine how the dynamics of pre-staging equipment and improving response site infrastructures impact incident response times. This is believed to be the first model to incorporate the consequences of missed deadlines in terms of needing to complete a different task to mitigate the impact of the missed deadline.

This paper begins by describing this problem and presents a set of case study questions that guided the development of the case study and results. Section 3 describes previous work to develop related models for oil spill response, and the limitations and challenges of applying this earlier work to the Arctic. Section 4 introduces terminology, describes the model, and provides tables of notation. Section 5 discusses the method to generate test instances from a realistic case study of the Arctic. Computational difficulty of these tests is discussed (Section 6), and their results are presented (Section 7). The Online Appendix provides additional assumptions along with the complete model.

2. Problem description

The Beaufort and Chukchi Seas in the Alaskan Arctic are estimated to contain a combined 90 billion barrels of oil, 1,670 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids, in total accounting for 22 percent of the world's undiscovered and recoverable energy resources (Bird et al., 2008). Economic incentives to recover these resources have led to significantly

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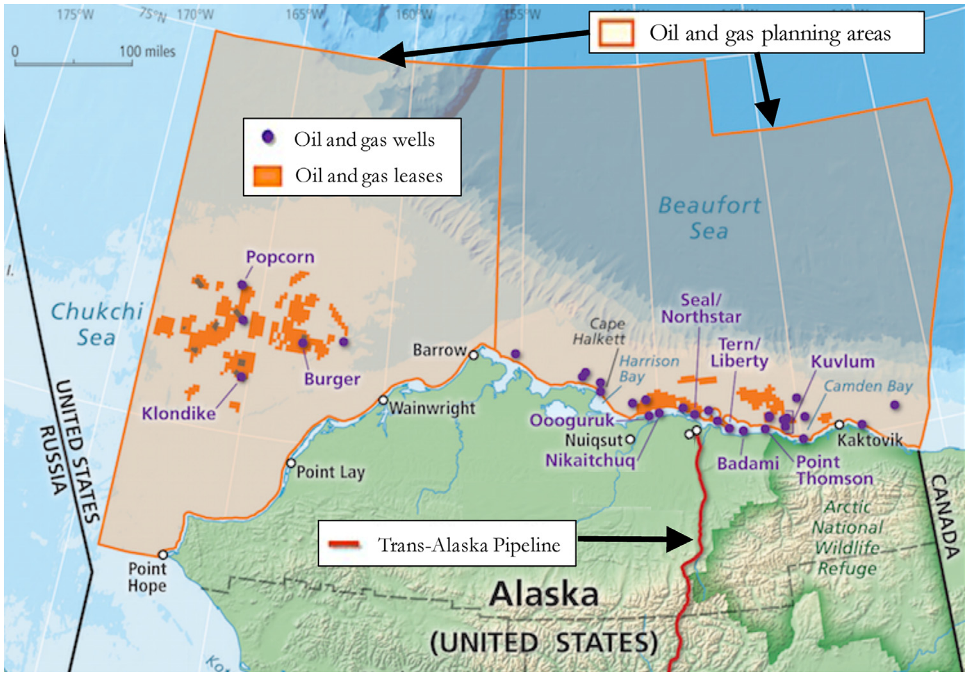

Fig. 1. Oil and gas wells, leases, and planning areas in northernmost Alaska (National Academy of Sciences, 2014).

increased maritime traffic and the potential for seasonal offshore drilling to occur, spurring interest in examining resource allocation challenges pertaining to the region's oil spill response capability (Huntington et al., 2015; National Academy of Sciences, 2014; National Petroleum Council, 2015). Issues concerning the lack of deepwater ports, few roads, and limited air and maritime navigational infrastructure, combined with few potential storage locations and extreme seasonal environmental conditions, complicate these challenges, including the supply, access, and deployment of emergency response equipment (Brigham, 2010; National Academy of Sciences, 2014). Fig. 1 (National Academy of Sciences, 2014) shows the offshore energy exploration, planning, and development areas in the Arctic relative to the small number of sparsely populated villages in which Arctic oil spill response infrastructure resides.

Resource allocation challenges associated with a large oil spill incident from vessel spills and oil drilling operations are of concern to Arctic decision-makers (United States Coast Guard, 2013; U.S. Department of the Interior Bureau of Ocean Energy Management, 2011a,b). Arctic oil spill response requires the deployment of oil spill response equipment, or *resources*, such as oil absorbent boom, skimmers, and maritime vessels, in order to complete *tasks*, the pieces of work necessary to restore an affected region to normalcy (Alaska Clean Seas, 2012; 2013). However, any planned response is often reliant on private industry resources under current oil spill contingency plans (Alaska Clean Seas, 2012; 2013; Hamilton, White, Lammers & Myerchin, 2012; U.S. Department of the Interior Bureau of Ocean Energy Management, 2011a,b). Arctic decision-makers are concerned with how to stockpile these resources and improve the infrastructure in Arctic communities; how these stockpiles influence resource deployments and improve spill response; and how these decisions help ensure an effective response.

The oil spill *response sites*, formed by Alaskan communities that stockpile resources within their infrastructure and mobilize them to complete tasks during a response, are modeled as a network. Resource allocation models for networks of Arctic response sites must address challenges regarding seasonality, location, scale, and scope. Decision-makers are interested in four key concerns related to these challenges: (i) reliance on a few remote response sites to mobilize resources for deployment at a potential spill incident; (ii) dynamics involving fluctuations in resource stockpiles; (iii) lack of sufficient mobilization capacity at each response site (e.g., a site's ability to prepare resources for transit to the spill incident), and task completion capacity at each incident location (e.g., the ability to concurrently complete tasks at an incident); and (iv) limited budgets to build infrastructure to store response resources (e.g., booms, skimmers, vessels, etc.). These concerns motivate the case study (CS) questions, which influence the model's formulation and focus the computational tests and sensitivity analyzes of the case study:

CS1: What are the impacts on response times of budgetary limitations?
CS2: How does geographic position within the response network influence the scale and scope of a stockpile?
CS3: What is the optimal stockpile improvement policy?
CS4: What is the optimal infrastructure investment policies?
CS5: How do bottlenecks and delayed resource deployments impact the solution?
CS6: What are optimal task completion policies?
CS7: How does the inclusion of additional response sites impact the solution?

Prior research on related problems is considered in order to determine the basis for the modeling efforts.

3. Relevant past research

Prior work has examined resource allocation in the context of oil spill response using goal-, mixed-integer-, and stochastic-programming, as well as econometric models. This work has assumed that response resources can be sited in proximity to an incident, such that the assumption of an adequate on-time response is valid. Charnes, Cooper, Harrald, Karwan, and Wallace (1976) and Charnes, Cooper, Karwan, and Wallace (1979) conducted work that developed goal-programming models for U.S. Coast Guard resource

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