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Budgeting maintenance dredging projects under uncertainty to improve the inland waterway network performance

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ABSTRACT

We model the problem of budgeting and selecting inland maintenance dredging projects to maximize the value of commodities that can be transported without disruption through the inland waterway system. We develop a heuristic to solve our stochastic optimization model and demonstrate that, by incorporating uncertainty in the amount of reactive (i.e., emergency) dredging, our model yields improved solutions as compared to related deterministic optimization models in the literature. We apply our model to provide a detailed analysis of U.S. waterway network.

1. Introduction

The inland navigation system is an important part of the U.S. maritime transportation system. Transporting products by water requires less fuel and is significantly cheaper per ton-mile than land-or air-based transportation modes. Inland waterways are responsible for transporting nearly 600 M tons of freight each year (U.S. Army Corps of Engineers, 2016b). Sustained operation of this vast infrastructure network depends on regular maintenance necessary to ensure safe, reliable, and cost-effective maritime transportation.

This research investigates allocation of limited budget resources to inland maintenance dredging projects to optimize system-level performance of the navigation system. Dredging is a regular maintenance operation that is necessary to ensure navigable conditions on the waterways. Throughout the U.S. system of inland rivers and navigable waterways, the U.S. Army Corps of Engineers (USACE) provides a 9-ft maintained channel via dredging activities as well as over 200 navigation lock and dam structures. For some portions of the system, this 9-ft depth can be difficult to achieve reliably because water levels change over time; that is, a period of dry weather or localized accumulation of sediment (known as *shoaling*) could cause this depth to fall below nine feet. As a result, insufficient or untimely dredging in a particular channel can result in water levels below the required 9-ft depth. This may cause immediate damages and/or delays (e.g., if a vessel or barge runs aground), and it can also result in more significant system-wide costs (see, e.g., Sanburn, 2012) due to draft restrictions and/or closure of portions of the inland waterway transportation system. We estimate, based upon manually filtering inland-specific dredging records over 1995–2015 from U.S. Army Corps of Engineers (2016a), that USACE spends in the range of $63 M to $143 M annually on inland dredging.

Motivated to reduce the risks to commercial navigation while operating in a constrained budget environment, we contribute a two-stage optimization model that allocates maintenance dredging funds into USACE districts and selects inland dredging projects in

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order to maximize the tonnage of commodities that can be transported without disruption. Optimization enables the identification of strategies for allocating inland dredging resources that are efficient with respect to both cost and risk.

In order to frame the contributions of our research, we now review the related literature on mathematical modeling approaches for allocating resources to the improvement of a transportation network.

Resource allocation models that select improvement projects under uncertainty are somewhat scarce in the literature. Some notable examples are provided by Ting and Schonfeld (1998) and Tao and Schonfeld (2007), who consider problems related to selecting and scheduling construction projects related to the inland waterway system. Khodakarami et al. (2014) also notes the impact of uncertainty in examining a dredging resource allocation problem that is most closely related to the work in this paper. We distinguish our work from this research in the coming paragraphs.

Project dependence refers to the notion that the feasibility and/or impact of one project depends on which other projects will be selected for completion. Project dependence complicates the project selection problem, and it has therefore been incorporated into a number of project selection models for a variety of transportation systems, including bridge (Mild et al., 2015) and roadway networks (Tao and Schonfeld, 2007, 2006; Asadabadi and Miller-Hooks, 2017). Relating to maritime transportation, the problems of allocating budget resources over time to (i) expand a series of locks (Jong and Schonfeld, 2001) and (ii) rehabilitate a tree-structured network of locks (Wang and Schonfeld, 2005) have been modeled under project dependence in the form of interconnected queueing effects. Waterway project dependence has also arisen due to logical relationships between projects (e.g., Wang and Schonfeld, 2008 consider precedence relationships and mutual exclusivity between projects), a concept that has also received much attention within an abstract setting (Jones and Wilson, 1979; Lenstra and Rinnooy Kan, 1978).

Dependent project selection models have also been applied to the specific application of dredging. Mitchell et al. (2013) utilize a mixed integer linear program and heuristic methods to select dredge projects to enable maximum flow of a set of origin-destination (o-d) commodity movements through the waterway network. In this paper, o-d flows may be restricted if insufficient dredging is completed on the route from origin to destination. Khodakarami et al. (2014) extend the model and solution methodology of Mitchell et al. (2013) to consider the effect of shoaling after dredging projects.

The work of Khodakarami et al. (2014) is closest to our research in that it also budget-limited maintenance projects for an o-d commodity flow network where uncertainty arises due to unpredictable natural/hydrologic conditions in the waterway segments. However, the model in Khodakarami et al. (2014) is a deterministic program that condenses, for the purposes of optimization, each location's shoaling probability distribution into an expected value. Our model, which incorporates uncertainty in how much budget is required for reactive maintenance in each USACE *district* (i.e., a regional jurisdiction organized along watershed boundaries), is a true two-stage stochastic program that enables weighing the risk associated with planning dredging operations. Furthermore, our research enhances previous models by examining the allocation of budget at the USACE district level, as opposed to allocating budget amounts to each individual project.

A number of important considerations have been taken into account in formulating our optimization model. Whereas some locations' dredging requirements are predictable (e.g., dredging on a regular cycle of one or more years has proven sufficient to ensure full waterway navigability), other locations—particularly stretches of open river including the lower Ohio and Mississippi—have needs for dredging that emerge dynamically due to unpredictable shoaling, and can cause disruptions to navigation if not remedied immediately. Therefore, our model separately considers the impact of *routine* (i.e., predictable) and *reactive* (i.e., dynamically emerging) dredging on the budgeting problem. Specifically, the requirements for reactive dredging in each district are uncertain at the time USACE specifies, as part of the federal budget development cycle, funding targets associated with each USACE district.

Our model is populated using data from the 12 USACE districts that overlap the Gulf Intracoastal Waterway, the Mississippi River, and its tributaries. In selecting dredging projects, we seek to maximize network-wide throughput of a set of origin-destination flows. Thus, by considering the impact of dredging projects on network-wide flows, our model incorporates *interdependence* among projects. We propose a genetic algorithm (GA) as a solution methodology by considering the structure of our problem to allocate the budget to the districts and solve the first-stage approximately. Then, to deal with the second-stage, another heuristic approach based on greedy method is developed inside the GA. The contributions of our research are as follows:

1. We present an optimization model for budgeting and selecting inland maintenance dredging projects that is the first to incorporate uncertainty in the budget required at each district for reactive dredging.
2. We develop a customized genetic algorithm, which exploits logical relationships between transportation corridors and dredging districts, in order to solve practically sized instances in a reasonable time.
3. We compare our model with the existing deterministic model of Khodakarami et al. (2014), which can also be used for the purpose of allocating inland dredging budgets, by solving various instances in Section 3. By incorporating uncertain requirements for reactive dredging, our model allocates budgets and selects dredging projects in a way that comparatively reduces the average disruption to transportation through the network.

The remainder of this paper is organized as follows: In the following section, we present the optimization model and provide a customized GA to solve the problem. Section 3 summarizes the results of computational experiments designed to investigate algorithm performance and solution insights for the U.S. inland waterway network. Section 4 provides conclusions and recommendations for future work in this area.