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# Optimal Dredge Fleet Scheduling - Phase 2

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**Abstract**

The U.S. Army Corps of Engineers (USACE) annually spends more than 100 million dollars on dredging hundreds of navigation projects on more than $12,000$ miles of inland and intra-coastal waterways. This project expands on a recently developed constraint programming framework to allow for dredge resource planning over multiple years. Decision-making over multiple years introduces the need for a dredge job to be scheduled numerous times. Moreover, it adds to the complexity of how much to dredge at each project. Less dredging frees resources quickly, but likely leads to multiple visits to the same site over the planning horizon. Also key to this work is the rate at which sediment collects along a navigable waterway. This rate also impacts the frequency that a dredge must return to a project over a multi-year horizon. Our model allows for both static and variable job sizes. In all models presented in this work, the objective is to maximize the total cubic yards dredged. The results of this effort suggest that the necessary composition of a dredge fleet when long-term planning is pursued may be different than what is required for short-term planning. Also, the computational challenges to multi-year planning identified through this project offer a roadmap forward for dredge scheduling researchers.

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# 1 Project Description

## 1.1 Introduction

As discussed in detail in [7], the U.S. Army Corps of Engineers (USACE), provides maintenance dredging to navigable waterways each year. Their mission is to ensure reliable waterway transportation systems while reducing any negative impacts on the environment. Most of these dredging jobs are for movement of commerce, national security needs, and recreation. Dredging efforts include nearly $12,000$ miles of inland and intracoastal waterway navigable channels, including 192 commercial lock and dam sites in 41 states. The Corps dredges over 250 million cubic yards of material each year at an average annual cost of over \$1.3 billion to keep the nation's waterways navigable [9].

To protect against harm to local environmental species, dredging jobs must adhere to environmental restrictions which place limits on how and when dredging may occur. Allocating dredging vessels (whether government or private industry) to navigation projects historically has been done by the corps at the district-level with employees assigning projects in hope of maximizing the amount of dredging completed over a calendar year. More recently, work of Rainwater et al. [10] and Gedik et al. [1] have offered a quantitative alternative that utilizes an optimization technique to generative scheduling solutions to the dredge resource allocation problem. Specifically, these works make use of a constraint programming (CP) framework that exploits the mathematical structure of the scheduling decisions that dominate the dredge planning problem. Even with these quantitative tools, the dredge-selection process is typically decentralized. While mathematically the capability to centralize this process exists, the region-based organization of corps activities have limited the use of the optimization approaches to within these regions.

In the following section, we highlight current dredge scheduling capabilities available to USACE through previous work by University of Arkansas researchers [ [7], [1], [10]]. Then, we consider a remaining challenge facing USACE decision-makers, multi-year decision-making, and explain why existing solutions are insufficient to solve this issue. The remainder of the documents provide the models required to overcome this issue and computational results that make use of these models. We conclude with a high-level discussion of how this work will be used in 2018 and future work needed to expand the use of these efforts across the corps.

## 1.2 Recent Advancements in Dredge Scheduling Capabilities

The most basic decisions USACE faces regarding dredge maintenance operations are: (i) choosing which jobs should be dredged; (ii) determining which dredge should work on a job and (ii) selecting when a job should be dredged. Nachtmann et al. [7] developed one of the first optimization tools to address these questions. The approach utilized a customized constraint/integer programming approach that was shown to provide quality solutions to problems with 100+ jobs in reasonable time. Their approaches made the previously mentioned decisions subject to the requirements of how much a dredge must move between jobs, the amount of funds available to execute a dredging plan (fixed, transportation, operational) and environmental restrictions that limit the time intervals that dredging can take place. Rainwater et al. [10] and Gedik et al. [1] expanded these efforts significantly to allow for the real-world dredging considerations shown in Table 1.

Table 1: Dredge Scheduling Key Features

| **Feature** | **Description** |
|---|---|
| Partial dredging | Environmental windows may completely prevent dredging *or* simply reduce the amount to dredging. |
| Variable job sizes | There is a “minimum dredging requirement” that should be met as well as a “target requirement” that would be ideal also, if resources allow. |
| Multiple dredges on same job | Jobs can be dredged by any number of dredge vessels at the same time. |
| Multiple trips to the same job | Jobs may be partially completed and the dredge resources return at a later time (e.g. after environmental) window to complete the job. |
| Different operation rates for each job | The operation rates of dredge vessels may vary based on equipment type and job being dredged. |
| Different unit costs of dredging for each job | The dredging cost per cubic yard varies by job. |
| Dredge capability | Not all dredges can physically perform all jobs in every geographic location. For instance, some of then dredges in the fleet are too big to maneuver between some small ports. |

### 1.3 The Need for Multi-year Planning

In some decision-making scenarios, planning over multiple years is equivalent to solving a single-year model multiple times. In these cases, actions taken in a particular year have no impact on the actions that must be taken in subsequent years. If this were the case, the work by Rainwater et al. [10] would be sufficient to address the long-term planning needs of USACE. However, this approach is not valid in the case of maintenance dredging.

Dredging over multiple years introduces the need for a dredge job to be scheduled numerous times. Moreover, it adds to the complexity of how much to dredge at each project. Less dredging frees resources quickly but likely leads to multiple visits to the same site over the planning horizon. Also key to this work is the rate at which sediment collects along a navigable waterway. Therefore, how much dredging is done on a project in year $t$ directly impacts how much should be in in year $t+1$. The result of this fact is that all decisions across multiple years must be considered at the same time in order maximize the efficiency of a dredging plan. It is this comprehensive model that is presented in the remainder of this report. Note that each of the model features in Table 1 can be included in the multi-year model that follows in the remainder of this report. However, to more clearly focus on challenges and benefits associated with the creation of a multi-year schedule, the presentation of our new models are presented in the context of simply the base model discussed in the following section.

## 2 Base Scheduling Model

Nachtmann et al. [8] introduced a constraint programming model for the dredge scheduling problem to find high-quality feasible solutions for real sized problems with over 100 jobs and 30 dredge vessels. This model was improved in [10] and [1]. The approach overcomes the inability of ILOG CPLEX solver to even load all the variables and constraints of an integer programming-based formulation of the dredge problem. In the constraint programming model, the time-dependent binary variables modeled through the use of *global constraints* and *interval variables*. An interval variable represents an interval of time during which an operation occurs [2].

CP Optimizer, a constraint programming solver engine developed by ILOG, solves a model using constraint propagation and constructive search with search strategies [2]. Conveying information between constraints and variables is made possible by constraint propagation (filtering) iterative processes of global constraints. Each global constraint is associated with a propagation algorithm to remove the values of variables from their domains (van Hoeve and Katriel [11], Hooker [5]). The propagation algorithm is executed after each variable change. Since constraints are related to each other through shared variables, whenever a change occurs on the domain of a shared variable due to the propagation algorithm of a constraint, the filtering algorithms of other constraints are also triggered to evaluate possible other reductions in the domains of all variables (Lombardi and Milano [6], Harjunkoski and Grossmann [4]). Branching on an individual variable takes place only after all possible reductions on domains are made.

The base dredge scheduling formulation, originally developed by Nachtmann et al. [8], that is expanded upon in this work is presented in the remainder of this section. The following parameters and decision variables are used in developing the CP formulation.

**Sets:**

- $d \in D$, set of dredging equipment resources available in each time period,
- $t \in T$, set of consecutive time periods comprising the planning horizon,
- $j \in J$, set of dredge jobs that need to be completed over the planning horizon, and
- $w \in W_j$, set of RPs applicable to dredging job $j$.

**Parameters:**

- $b_w$, the beginning of RP $w$, $w \in W_j, j \in J$,
- $e_w$, the end of RP $w$, $w \in W_j, j \in J$,
- $r_d$, the operation rate (cubic yards/day) of dredge equipment $d \in D$
- $q_j$, the dredging amount of job $j \in J$ (in cubic yards),
- $t_{jd} = \lceil q_j / r_d \rceil$, the time (days) that it takes for dredge equipment piece $d \in D$ to complete job $j \in J$,
- $t_{jj'}$, the time (days) that it takes to move a dredging equipment piece $d \in D$ from job site $j \in J$ to job site $j' \in J, j \neq j'$,
- $c_j$, the cost for completing job $j \in J$, and
- $B$, the available budget for the planning horizon.
- $I(j)$, the *Intensity Function* [3] of job $j \in J$. That is $I(j) = 0\%$, if the job $j$ is not allowed to be processed at time $t$ such that $b_w \leq t \leq e_w$, $I(j) = 100\%$ otherwise.

- $TD[\text{Type}(j), \text{Type}(j')]$, the *Transition Distance* between job $j \in J$ and $j' \in J$. It is used to inform other global constraints that the travel time between job pairs $j$ and $j'$ should be at least $t_{jj'}$.

**Decision variables:**

- $y_{jd}$, optional interval variable when job $j \in J$ (with size $q_j$) is assigned to dredge vessel $d \in D$,
- $Y_j = \{y_{j1}, y_{j2}, \ldots, y_{jD}\}$, set of interval variables representing possible dredge equipment $d \in D$ that can be assigned to job $j \in J$,
- $Y_d = \{y_{1d}, y_{2d}, \ldots, y_{Jd}\}$, set of interval variables representing possible jobs $j \in J$ that can be assigned to dredge vessel $d \in D$ (the *interval sequence variable* for d),
- $z_j$, optional interval variable associated with job $j \in J$.

$$\max \sum_{j \in J} q_j z_j$$

subject to

$$\begin{aligned}
\text{Alternative}\,(z_j, Y_j) & \qquad j \in J & (1)\\
\text{Cumulative}\,(z_j, c_j, B) & & (2)\\
\text{Cumulative}\,(z_j, 1, |D|) & & (3)\\
z_j.\text{StartMin} = 1 & \qquad j \in J & (4)\\
z_j.\text{EndMax} = |T| & \qquad j \in J & (5)\\
\text{ForbidExtend}\,(z_j, I(j)) & \qquad j \in J & (6)\\
\text{NoOverlap}\,(Y_d, TD[\text{Type}(j), \text{Type}(j')]) & \qquad d \in D & (7)
\end{aligned}$$

The objective function above seeks to maximize the total dredged amount in cubic yards. Constraints (8) ensure that each job can only be assigned to at most one dredge vessel by choosing exactly one possible assignment from all possible assignments of dredge vessels to job $j$. The *Alternative* global constraints enforce if an interval decision variable $z_j$ is present in the solution then one and only one of the elements of $Y_j$ array of interval variables must be presented in the solution.

Constraint (9) states that the total cost of dredging operations cannot exceed the total budget $B$. A CP *Cumulative* constraint models the resource usage over time and is computed using sub-functions such as *Step*, *Pulse*, *StepAtStart* and *StepAtEnd* [3]. In the programming of base model formulation, $StepAtStart(z_j)$ increases the total money spent on operations at the start of interval variable $z_j$ by the amount $c_j$. Constraint (9) ensures the total cost does not exceed the available budget. Similarly, in Constraint (10), the *Cumulative* global constraint, in conjunction with the $Pulse(z_j)$ function, is used to make sure that total number of occupied dredge vessels at any time cannot exceed the fleet size $|D|$. Constraints (11) and (12) specify the minimum start time and maximum end time of each job to the first and last day of the planning horizon, respectfully. The ForbidExtend Constraint (13) prevents job $j$ from being performed during its restricted period(s) $I(j)$. On the other hand, if interval variable $z_j$ is presented in the solution, it cannot overlap with the time intervals where its intensity function is 0%. Finally, the *NoOverlap* Constraints (14) ensure that, if both jobs $j$ and $j'$ are operated by dredge vessel $d$, then a minimal time $t_{jj'}$ must be maintained between the end of interval variable $y_{jd}$ and the start of the interval variable of $y_{j'd}$ and otherwise.

Note that in this model each job is satisfied at most once during the $|T|$ time periods. This limitation is overcome in the following section.

# 3 Multi-year Dredge Scheduling Model

In the multi-year dredging optimization model, similar to the base model, we seek to maximize the total cubic yards of dredging. A secondary objective that can be considered in this model is to minimize the total cost of dredging, which consists of operation and maintenance (O&M) costs over the planning time horizon. The ultimate goal of dredging is to keep the waterways navigable at the minimum cost. In the base model, we limit the operation cost of dredging to our available budget. However, in the multi-year model, preventive maintenance can reduce the total cost of dredging (O&M) over the extended time horizon. After a location is dredged, depending on the cubic yards of dredging (depth of the last dredging) and the filling rate of sediments at the bed of the waterway, it may not need additional dredging for a number of days.

To model the dredge fleet scheduling over multiple years we assume that the filling rate of the sediments is constant and does not depend on the depth of dredging. For instance, if the filling rate of project $j$ is 1 CY/day, we need to dredge that project again after 10 days if the last dredging size was 10 CY. In the case that the last dredging size of project $j$ was 20 CY, dredging is needed again after 20 days. There are two approaches to model the multi-year period scheduling: i) constant job sizes and ii) variable job sizes. These two approaches are explained in the following sections.

## 3.1 Fixed Job Size

In our first model, similar to the base model, we assume that the size of dredging for each project is constant. However, two alternative parameters are considered for addition to the base model.

- $l_j$: The number of periods that dredging is not required after the last dredging.
- $l'_j$: The number of days that dredging is not required after the last dredging.

Either $l_j$ or $l'_j$, which defines the number of days that dredging is not required after the last dredge on project $j$, can be utilized. $l_j$ is a special case of $l'_j$ in which the values of $l'_j$ is a multiple of the number of days in each period (e.g. 365 in a yearly based periods), for each project $j$.. The remainder of the parameter and decision variables of the multi-year model are taken from the base model and can be found in in Section 2.

## 3.2 Multi-year Fixed Job Size Model

The CP model is as follows:

$$\max \sum_{j \in J} q_j \times \text{PresenceOf}(z_j) \times z_j$$

$$\text{Alternative}\,(z_j, Y_j) \qquad j \in J \tag{8}$$

$$\text{Cumulative}\,(z_j, c_j, B) \tag{9}$$

$$\text{Cumulative}\,(z_j, 1, |D|) \tag{10}$$

$$z_j.\text{StartMin} = 1 \qquad j \in J \tag{11}$$

$$z_j.\text{EndMax} = |T| \qquad j \in J \tag{12}$$

$$\text{ForbidExtend}\,(z_j, I(j)) \qquad j \in J \tag{13}$$

$$\text{NoOverlap}\left(V_d, TD'_{\text{type}_j \text{type}_{j'}}\right) \qquad d \in D \tag{14}$$

The primary difference between this formulation and the base model is in Constraints (14). In the base model, $TD_{jj'}$ is the travel time between two projects (locations) $j$ and $j'$. In Constraints (14), $TD'$ is calculated as follows:

if ($j$ and $j'$ are the same projects in different periods) then

$$TD' = l_j \times |T| \text{ or } TD' = l'_j$$

else

$$TD'_{jj'} = TD_{jj'}$$

Computational results associated with this model are provided in Section 5.1.

## 3.3 Variable Job Size

In many cases, decision-makers have a notion of the amount of dredging that is necessary for the waterway to be navigable but are flexible to schedule additional dredging to delay the need for later dredging. In this approach, the size of dredging for each project is in between the range of [minimum requirement, target requirement]. In this model, the number of days (or periods) that a project does not require dredging is dependent on the size of the last dredging of that project. To model the problem, we introduce two sets of new decision variables to the model: i) gap times ($g_{dj}$), the gap time between the finish time of the project $j$ by dredge $d$ and start time of the next project by the same dredge and ii) cover activities ($c_{dj}$), the dredging time plus the gap time of project $j$ dredged by vessel $d$. These additional decision variables are shown in Table 2.

Table 2: Notation of CPDFS base model Formulation

| Notation | Description |
|---|---|
| **Additional Parameters** | |
| $f_j$ | The fill rate (day/CY) of the sediment at the bottom of the project $j$. |
| **Additional Decision Variables** | |
| $G_d = \{g_{1d}, g_{2d}, \ldots, g_{Jd}\}$ | Optional interval variable to simulate the gap time required after dredge vessel $d \in D$ finishes the project $j \in J$ and start its next project. |
| $C_d = \{c_{1d}, c_{2d}, \ldots, c_{Jd}\}$ | Optional interval variable that includes the dredging and gap time of project $j \in J$ when is dredged by vessel $d \in D$. |

In this model we use the expressions “typeOfNext” and “typeOfPrev” on the sequence variable to constrain the length of the gap activity as illustrated in the CP formulation in Section 3.4.

## 3.4 Multi-Year Variable Job Size Model

The multi-year variable size CP model is as follows:

$$\max \sum_{j \in J} q_j \times \text{PresenceOf}(z_j) \times z_j$$

$$\text{Alternative}\,(z_j, Y_j) \qquad j \in J \qquad (15)$$

$$\text{Cumulative}\,(z_j, c_j, B) \qquad (16)$$

$$\text{Cumulative}\,(z_j, 1, |D|) \qquad (17)$$

$$z_j.\text{StartMin} = 1 \qquad j \in J \qquad (18)$$

$$z_j.\text{EndMax} = |T| \qquad j \in J \qquad (19)$$

$$\text{ForbidExtend}\,(z_j, I(j)) \qquad j \in J \qquad (20)$$

$$\text{Span}(C_d, (V_d, G_d)) \qquad d \in D \qquad (21)$$

$$\text{EndBeforeStart}(V_d, G_d) \qquad d \in D \qquad (22)$$

$$\text{LengthOf}(g_{dj}) == TD[j][\text{TypeOfNext}(V_d, c_{dj}, \text{last})] \qquad j \in J, d \in D \qquad (23)$$

$$\text{IfThen}(\text{TypeOfNext}(V_d, c_{dj}) == j, \text{LengthOf}(g_{dj}) >= \text{SizeOf}(v_{dj}) \times f_j) \qquad j \in J, d \in D \qquad (24)$$

$$\text{NoOverlap}\left(C_d, TD'_{\text{type}_j \text{type}_{j'}}\right) \qquad d \in D \qquad (25)$$

As in the fixed job size model, the objective function is to maximize the total cubic yards of dredging. Furthermore, constraints (15-20) are the same as those in the base model with a 1-year planning horizon. Constraints (21) create cover activities ($C_d$) consisting of dredging ($V_d$) and gap times between dredging projects ($G_d$). Constraints (22) make sure that the interval variables of gap times start after the dredging activities on a job. Constraints (23-24) put limitation on the length of gap times between the dredging projects that are performed by the same dredge. If the projects have different locations, the length of the gap times are the travel time between the locations. This is imposed by Constraints (23). On the other hand, if the dredging projects are in the same location, but in different periods, Constraints (24) make sure that the required minimum days between them is accounted for. In Constraints (25) the CP model does not consider any overlap time between the cover activities, as required time is already considered in gap times. Computational results associated with this model are provided in Section 5.2.

# 4 Test Instances

In this section, the data collection to establish problem instances to exercise the multi-year model is presented. The data was provided by the USACE Dredging Information System. A total of 116 unique navigation channel maintenance dredging jobs are considered, as seen in Figure 1.

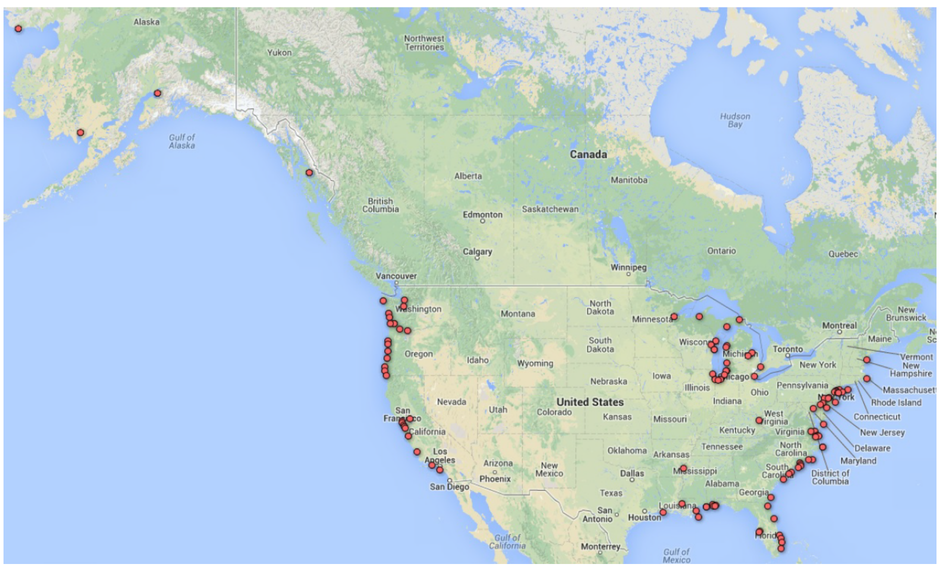


Figure 1: Graphical Depiction of 116 Dredge Jobs Locations

The dredging jobs volumes and costs are shown in Table A1. These values were calculated by averaging over the range of years for which DIS data was available for each job [8]. An average of 416,427 cubic yards, with a standard deviation of 702,096 cubic yards, was dredged across 116 jobs. The largest dredging job considered averaged 5.4 million cubic yards and the smallest job considered in the set had an average of 4,376 cubic yards dredged each year. From a dredging cost perspective, the most expensive job in the pool considered was \$14,477,345, while the minimum cost was \$46,440. The average expenditure per job was \$1,922,51. All type of costs associated with dredging jobs from start to finish including the mobilization/demobilization, fuel, labor, maintenance, etc. are considered in calculation of each job cost.

The DIS historical data was also used by Nachtmann et al. [8] to gather information on performance data for the individual Corps-owned dredge vessels, as well as the dredging companies performing contract work for the USACE. As emphasized in [8], the statistical average of dredge vessel production rates was derived over specific years (see Table A2).

For the 116 jobs considered, a total of 130 unique restricted periods were identified and used within the optimization model. The number of unique restricted periods exceeds the number of dredging jobs because in some instances. As explained in [8], these RPs were identified using the USACE Threatened, Endangered, and Sensitive Species Protection and Management System. Table 3 summarizes the types of restricted periods considered in our experiments.

Table 3: Summary of Restricted Periods (RPs) (duration: days)

| **RP Type** | **Total Duration** | **Avg. Duration** | **No. of Jobs with RP** |
|---|---|---|---|
| Fish | 12,541 | 187 | 67 |
| Marine Turtles | 5,773 | 222 | 26 |
| Birds | 3,221 | 179 | 18 |
| Marine Mammals | 3,006 | 137 | 22 |
| Crustaceans | 1,496 | 150 | 10 |
| Marine Mussels | 832 | 104 | 8 |
| TOTAL: | 26,869 | 178 | 151 |

The distance between jobs was used to calculate travel time of dredge vessels. The model assumed an average travel rate of 50 miles per day for dredge vessels moving between jobs. The new parameter, $l_j$, was derived from the historical data of the dredging projects in different locations.

# 5 Computational Results

## 5.1 Fixed Job Size Results

The results of running the fixed job size model over a 3-year horizon are shown in Table 4. For all multi-year dredge scheduling experiments in this report IBM ILOG CPLEX Optimization Studio 12.7 [3] and IBM ILOG CP Optimizer 12.7 were used to solve the CP models. All test problems were run on a Core(TM) i7 CPU @ 2.93 GHz, 8 GB RAM computer.

Table 4: 3-year fixed job size model
$|J| = 116, |D| = 30$. (Time: sec, Obj.: CY)

| Model | CPU Time | Travel Time | Idle Time | Dredge Time | Objective Function |
|---|---|---|---|---|---|
| **1-year period** | | | | | |
| | 180 | 2,301 | 571 | 4,759 | 30,764,006 |
| **3-year period** | | | | | |
| | 180 | 436 | 8,899 | 6,830 | 50,689,363 |
| | 360 | 457 | 7,365 | 7,378 | 53,962,173 |
| | 600 | 482 | 9,801 | 8,503 | 58,476,983 |
| | 3,600 | 104 | 7,024 | 10,440 | 70,054,718 |
| | 14,400 | 105 | 4,658 | 5,363 | 72,572,157 |
| | 28,800 | 102 | 6,123 | 13,754 | 73,020,392 |
| | 57,600 | 104 | 6,610 | 9,233 | 73,305,773 |

Table 4 shows the impact of solving a 1-year versus 3-year dredge scheduling problem. Each row of the table presents how the solution is improving as the computational time increases. This is a vital lesson from the efforts of this project. In the single-year work done over the last 3 years [ [10], [7], [1]] quality solutions were obtained in less than 30 seconds. This is not the case when the model is expanded to multiple years (more discussion on this in Section 6). Note that objective improves significantly as run time is increased fro 180 to 8 hours (28,800 seconds). However, from 8 hours to 16 hours, the improvement is only 0.4%. According to 4, the total cubic yards of dredging in the 1-year model (base model) is more than 30 mCY, but we do not dredge triple this amount in a 3-year period even after 16 hours running time (73 mCY). However, it is not clear that this suggests a degradation in solution quality for multi-year schedules. Since jobs are monitored over multiple years, it is conceivable that more sophisticated planning is creating opportunities for reduced dredging. Prior models assumed that full dredging of jobs was necessary each year. It is also possible that the explosion of solution space is limiting the ability of the optimization engine to find more attractive solutions. It is interesting to note that a hint to this issue may be found in the ratio of travel to idle time. With the longer time horizon, solutions can be found that reduce the amount of travel days significantly. However, the amount of idle time subsequently increases. This suggests that the composition of the dredge fleet may be significantly different when scheduling is considered over multiple years instead of focusing on maintenance needs only in the short term.

## 5.2 Variable Size Results

The results of running the variable job size multi-year model over a 3-year planning horizon are shown in Table 5. In this case, we look at instances with differing numbers of jobs and resources. As in the previous section, the rows associated with each instance show the improvement in solution as computational runtime increases.

Table 5: 3-year variable job size model, $size_j \in [0.25q_j, q_j]$
(Time: sec, Obj.: CY)

| Instance | CPU Time | Travel Time | Idle Time | Dredge Time | Objective Function |
|---|---|---|---|---|---|
| $\boldsymbol{|J| = 32,}$ $\boldsymbol{|D| = 30}$ | | | | | |
| | 600 | 420 | 0 | 1,555 | 29,305,326 |
| | 1,800 | 178 | 172 | 3,632 | 40,727,519 |
| | 3,600 | 252 | 91 | 2,758 | 43,363,005 |
| | 14,400 | 257 | 250 | 2,512 | 43,438,479 |
| $\boldsymbol{|J| = 57,}$ $\boldsymbol{|D| = 30}$ | | | | | |
| | 600 | 735 | 387 | 1,915 | 35,508,544 |
| | 1,800 | 1,035 | 341 | 1,752 | 39,610,354 |
| | 3,600 | 531 | 189 | 2,856 | 47,857,016 |
| | 14,400 | 460 | 485 | 5,708 | 63,439,094 |
| $\boldsymbol{|J| = 116,}$ $\boldsymbol{|D| = 30}$ | | | | | |
| | 600 | 1,398 | 595 | 1,673 | 37,297,785 |
| | 1,800 | 993 | 1,607 | 1,679 | 37,333,463 |
| | 3,600 | 1,566 | 711 | 1,834 | 37,991,946 |
| | 14,400 | 983 | 380 | 2,626 | 44,708,321 |

As shown in Table 5, the objective function is improved with an increase in runtime. However, the objective function of the instances with 57 jobs and 30 dredges shows greater improvement than instances with 116 jobs and 30 dredges when we run the model for more than half an hour (1800 sec). The reason is the solution area expands dramatically when we increase the number of jobs and make it very difficult for CP to find high-quality solutions. The expansion in the feasible region comes from two major changes in the multi-year model with variable job sizes. First, there is an infinite number of values that individual job sizes can take in the variable job size variant of the problem. Second, we use auxiliary sets of interval variables to determine the required time between two consecutive projects in the same location in different periods of time (allowing for multi-year planning). Interesting to note is that the ratio between travel and idle time in the variable job size problem variant is more typical of what was viewed in single-year planning. This again suggests that the composition of the dredge fleet is very sensitive to model assumptions (single versus multi-year and fixed versus variable job sizes). The results also reemphasize that, first the first time, problem scale is a computational challenge for realistic scheduling instances. This will be discussed further in Section 6.

# 6 Impact and Future Work

This work provides two models that serve as the first quantitative tools for multi-year dredge planning at the USACE. The models introduce an interdependence between jobs not needed to this point in dredge scheduling research. This new interdependence has been captured compactly through the novel use of covering constraints to minimize complexity and variable space explosion. Practical insights into the change in dredge resource needs as one move from a single-year to multi-year perspective are noteworthy. Moreover, the significant deviation in the dredge travel versus idle time are magnified in a multi-year planning horizon. However, it is clear that this more general model requires significantly more computational time from those developed for the single-year dredging problem in previous work. This suggests that the focus of dredge optimization work for the USACE should shift from building more flexible models (the focus of the last 2 years of research) to time spent on methodological enhancements in the constraint programming framework. Specifically, computational investigation into intelligent variable branching, quick-start meta heuristics and integrated CP/optimization tools that make use of a highly parallelized computing environment are necessary paths forward.

The achievements in this project have been communicated to leadership at USACE. An update version of dredge optimization code is scheduled for transfer to USACE systems in mid-January 2018. Decision-makers will be using this updated tool at Winter 2018 planning meetings in the Northwest USACE region.

# References

[1] Ridvan Gedik, Chase Rainwater, Heather Nachtmann, and Ed A Pohl. Analysis of a parallel machine scheduling problem with sequence dependent setup times and job availability intervals. *European Journal of Operational Research*, 251(2):640–650, 2016.

[2] IBM. Ibm ilog cplex optimization studio cp optimizer users manual version 12 release 6. `http://www-01.ibm.com/support/knowledgecenter/SSSA5P_12.6.1/ilog.odms.studio.help/pdf/usrcpoptimizer.pdf`. Accessed: January 2015.

[3] IBM. Ibm ilog cplex optimization studio v12.3, 2011. `http://pic.dhe.ibm.com/infocenter/cosinfoc/v12r3/index.jsp`. Accessed: October 2013.

[4] Harjunkoski Iiro and Grossmann Ignacio E. Decomposition techniques for multistage scheduling problems using mixed-integer and constraint programming methods. *Chem. Engng*, (26):1533–1552, 2002.

[5] Hooker John N. Integrated methods for optimization (international series in operations research and management science). *Springer-Verlag New York, Inc., Secaucus, NJ, USA,*, 2006.

[6] Lombardi Michele and Milano Michela. Optimal methods for resource allocation and scheduling: a cross-disciplinary survey. *Constraints*, (17):51–85, 2012.

[7] Heather Nachtmann, Kenneth Mitchell, Chase Rainwater, Ridvan Gedik, and Edward Pohl. Optimal dredge fleet scheduling within environmental work windows. *Transportation Research Record: Journal of the Transportation Research Board*, (2426):11–19, 2014.

[8] Heather Nachtmann, Edward Pohl, Chase Rainwater, and Ridvan Gedik. Resource allocation for dredge scheduling and procurement: A mathematical modeling approach. *The Report submitted to Coastal and Hydraulics Lab U.S. Army Engineer Research and Development Center*, October 2013.

[9] U.S. Army Corps of Engineers. Inland waterway navigation: Value to the nation. `http://www.corpsresults.us/`. Accessed: July 2015.

[10] Chase Rainwater, Heather Nachtmann, and Fereydoun Adbesh. Optimal dredge fleet scheduling within environmental work windows. *MarTREC Report*, September 2016.

[11] van Hoeve Willem-Jan and Katriel Irit. *Handbook of Constraint Programming*. Elsevier, 2006.

# Appendix

Table A1: 116 Project Properties (volumes: CY, costs: USD)

| Job ID | Volume | Cost | Job ID | Volume | Cost |
|---|---|---|---|---|---|
| 000030 | 439,726 | 3,201,839 | 011810 | 577,711 | 2,972,600 |
| 000360 | 900,709 | 5,533,068 | 011860 | 156,607 | 1,104,938 |
| 046063 | 4,376 | 46,441 | 011880 | 30,523 | 420,827 |
| 074955 | 2,267,192 | 14,477,345 | 012030 | 544,338 | 2,338,424 |
| 000950 | 466,950 | 2,989,574 | 012550 | 123,064 | 9,739,760 |
| 001120 | 2,001,129 | 2,523,736 | 008190 | 174,603 | 998,309 |
| 088910 | 39,308 | 1,016,772 | 072742 | 26,937 | 644,784 |
| 010222 | 178,088 | 791,822 | 012801 | 67,578 | 318,000 |
| 076060 | 451,796 | 1,261,920 | 012990 | 217,888 | 967,081 |
| 080546 | 6,723 | 275,719 | 073567 | 34,637 | 302,055 |
| 002080 | 2,472,603 | 6,685,844 | 013080 | 723,937 | 2,628,970 |
| 002250 | 102,032 | 1,242,273 | 013330 | 44,401 | 334,654 |
| 041015 | 85,093 | 2,409,673 | 013590 | 119,668 | 1,891,959 |
| 003630 | 277,836 | 786,758 | 013680 | 1,193,406 | 2,009,923 |
| 002440 | 2,890,491 | 3,793,482 | 013880 | 252,670 | 251,296 |
| 002410 | 179,782 | 1,612,871 | 013940 | 192,277 | 980,108 |
| 002620 | 116,357 | 2,307,509 | 014310 | 82,949 | 748,816 |
| 002640 | 396,079 | 909,977 | 076031 | 46,686 | 481,990 |
| 014360 | 5,413,965 | 5,452,500 | 014370 | 4,510 | 102,371 |
| 008160 | 67,221 | 1,231,600 | 021530 | 26,009 | 144,042 |
| 003130 | 13,252 | 226,709 | 014760 | 59,003 | 690,963 |
| 076106 | 35,672 | 321,356 | 015100 | 572,395 | 2,405,442 |
| 022140 | 45,533 | 142,900 | 015280 | 95,491 | 723,544 |
| 003600 | 808,778 | 1,502,833 | 015600 | 21,003 | 178,236 |
| 003840 | 397,516 | 1,745,287 | 087072 | 83,378 | 146,508 |
| 004550 | 243,898 | 1,489,330 | 087455 | 32,688 | 453,483 |
| 004610 | 38,598 | 306,499 | 015870 | 295,967 | 1,881,768 |
| 004710 | 201,116 | 1,122,792 | 057420 | 231,639 | 1,709,816 |
| 004800 | 117,090 | 719,437 | 016130 | 833,305 | 2,509,084 |
| 005050 | 80,528 | 733,469 | 076063 | 120,808 | 900,546 |
| 005220 | 191,015 | 1,708,370 | 074709 | 145,537 | 942,239 |
| 005700 | 261,440 | 1,058,165 | 016550 | 261,985 | 1,363,696 |
| 005880 | 1,117,205 | 9,124,564 | 067318 | 127,064 | 310,965 |

Continued on the next page

Table A1 – continued from previous page

| **Job ID** | **Volume** | **Cost** | **Job ID** | **Volume** | **Cost** |
|---|---|---|---|---|---|
| 041016 | 63,380 | 2,260,932 | 073644 | 572,249 | 4,008,166 |
| 006260 | 186,551 | 1,183,650 | 016800 | 216,709 | 864,890 |
| 006480 | 668,425 | 2,073,745 | 016860 | 47,674 | 284,901 |
| 006670 | 41,563 | 311,454 | 017180 | 22,153 | 159,881 |
| 006770 | 577,424 | 1,543,516 | 017370 | 306,546 | 5,944,930 |
| 006910 | 147,811 | 2,153,095 | 074390 | 633,833 | 8,574,738 |
| 007150 | 1,038,304 | 1,534,705 | 017300 | 64,118 | 1,162,671 |
| 007610 | 42,408 | 283,559 | 017350 | 42,577 | 389,861 |
| 007810 | 167,704 | 1,416,099 | 017380 | 49,558 | 2,497,492 |
| 007860 | 1,494,596 | 4,048,374 | 017760 | 64,262 | 950,325 |
| 008410 | 1,189,684 | 12,991,774 | 017720 | 212,214 | 1,588,367 |
| 054000 | 225,664 | 1,427,334 | 017960 | 1,037,987 | 4,895,841 |
| 008430 | 283,367 | 1,151,256 | 073598 | 229,090 | 456,000 |
| 010020 | 67,571 | 380,810 | 018710 | 55,762 | 326,262 |
| 010040 | 80,000 | 1,579,250 | 018750 | 105,955 | 443,959 |
| 074719 | 122,930 | 864,000 | 024190 | 1,086,812 | 1,486,174 |
| 010310 | 102,424 | 751,304 | 019550 | 97,935 | 442,630 |
| 010490 | 74,288 | 519,202 | 019560 | 50,777 | 331,749 |
| 010580 | 261,769 | 1,845,812 | 039023 | 9,868 | 66,150 |
| 011060 | 59,190 | 419,900 | 019990 | 53,971 | 258,289 |
| 011270 | 40,729 | 530,127 | 020040 | 323,758 | 1,262,279 |
| 000068 | 681,961 | 1,419,778 | 020030 | 1,171,297 | 6,527,537 |
| 011410 | 944,417 | 1,496,737 | 072852 | 33,939 | 4,687,087 |
| 000063 | 1,505,100 | 5,388,149 | 020290 | 75,373 | 468,695 |
| 011670 | 1,282,956 | 2,509,501 | 073803 | 561,192 | 2,499,452 |
| | | | **Total:** | 48,305,584 | 223,012,020 |

Table A2: Production Rates of Dredge Vessels (cubic yards/day)

| **Row** | **Vessel** | **Rate** |
|---|---|---|
| 1 | BARNEGAT BAY DREDGING COMPANY | 1,238 |
| 2 | PORTABLE HYDRAULIC DREDGING | 1,301 |
| 3 | TNT DREDGING INC | 1,637 |
| 4 | ROEN SALVAGE COMPANY | 1,962 |
| 5 | LUEDTKE ENGINEERING CO. | 1,989 |
| 6 | MADISON COAL & SUPPLY CO. | 2,296 |
| 7 | CURRITUCK | 2,375 |
| 8 | M.C.M. MARINE INC. | 2,709 |
| 9 | SOUTHWIND CONSTRUCTION CORP | 2,855 |
| 10 | LAKE MICHIGAN CONTRACTORS, INC | 3,311 |
| 11 | KING COMPANY, INC. | 3,481 |
| 12 | COTTRELL ENGINEERING CORP. | 3,728 |
| 13 | FRY | 3,941 |
| 14 | MERRITT | 4,532 |
| 15 | GOETZ | 5,941 |
| 16 | B+B DREDGING CORPORATION | 6,837 |
| 17 | WRIGHT DREDGING CO. | 6,965 |
| 18 | MARINEX CONSTRUCTION CO INC | 8,332 |
| 19 | SOUTHERN DREDGING CO., INC. | 8,443 |
| 20 | YAQUINA | 9,007 |
| 21 | WEEKS MARINE, INC (ATLANTIC) | 10,436 |
| 22 | LUHR BROS. INC. | 10,478 |
| 23 | MCFARLAND | 10,959 |
| 24 | KING FISHER MARINE SERV., INC. | 12,347 |
| 25 | NORFOLK DREDGING COMPANY | 12,882 |
| 26 | NATCO LIMITED PARTNERSHIP | 15,556 |
| 27 | GULF COAST TRAILING CO. | 17,080 |
| 28 | GREAT LAKES DREDGE & DOCK CO. | 17,282 |
| 29 | MIKE HOOKS INC. | 17,537 |
| 30 | PINE BLUFF SAND & GRAVEL CO. | 19,245 |
| 31 | MANSON CONSTRUCTION CO | 21,726 |
| 32 | HURLEY | 24,618 |
| 33 | WEEKS MARINE, INC.(GULF) | 29,147 |
| 34 | POTTER | 32,841 |
| 35 | ESSAYONS | 33,870 |

Continued on the next page

Table A2 – continued from previous page

| **Row** | **Vessel** | **Rate** |
|---|---|---|
| 36 | BEAN STUYVESANT, LLC | 34,716 |
| 37 | T.L. JAMES & CO., INC. | 35,324 |
| 38 | BEAN HORIZON CORPORATION | 38,665 |
| 39 | WHEELER | 41,463 |
| 40 | JADWIN | 66,418 |