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Optimal Dredge Fleet Scheduling Within Environmental Work Windows

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Optimal Dredge Fleet Scheduling within Environmental Work Windows

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ABSTRACT

The U.S. Army Corps of Engineers (USACE) annually dredges hundreds of navigation projects through its fleet of government dredges and individual contracts with private industry. The research presented here seeks to examine the decision of allocating dredge resources to projects system-wide under necessary constraints including environmental restrictions concerning when dredging can take place due to migration patterns of turtles, birds, fish, and other wildlife, dredge equipment resource availability, and varying equipment productivity rates that affect project completion times. Our problem definition and model formulation of optimal dredge fleet scheduling within environmental work windows are discussed. In addition, sensitivity analysis is conducted to provide decision makers with quantitative insights into dredging efficiency gains that could be realized system-wide if environmental restrictions were relaxed. Such information can be used to guide USACE research efforts focused on understanding the true impacts of dredging operations on threatened, endangered, and sensitive species.

PROJECT DESCRIPTION

Background and Objectives

The U.S. Army Corps of Engineers (USACE) has the federal navigation mission to "provide safe, reliable, efficient, effective and environmentally sustainable waterborne transportation systems for movement of commerce, national security needs, and recreation." The USACE is responsible for nearly 12,000 miles of commercial, navigable U.S. inland and intracoastal waterways that serve thirty-eight states across the United States, including the Mississippi/Ohio River System, the Gulf Intracoastal Waterway, the Intracoastal Waterway along the Atlantic Coast, and the Columbia-Snake River System in the Pacific Northwest *(1)*. The Corps oversees and manages an extensive and aging navigation asset portfolio including 1067 navigation projects, 929 navigation structures, 844 bridges, and 171 lock sites. The Nation's maritime transportation system is an essential component of the Nation's freight transportation network, annually transporting approximately 20% of America's coal, 22% of U.S. petroleum, and 60% of the Nation's farm exports *(1)*. The Corps annually invests more than $1.5 billion in engineering, construction, and operations and maintenance (O&M) of the nation's waterways, ports, and harbors to make significant contributions to the Nation's economy and environment as shown in Figure 1 *(2)*.

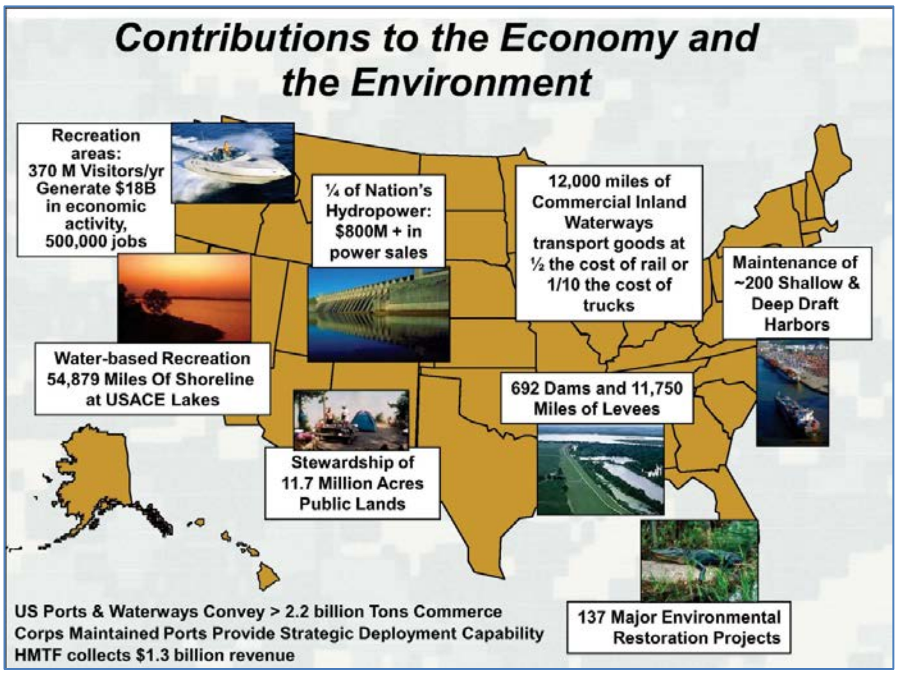

Figure 1 Corps contributions to the economy and environment *(4)*.

Each year the Corps conducts maintenance dredging at hundreds of navigation projects through its fleet of government dredges and individual contracts with private industry. The decision of assigning individual dredging plants (whether government or private industry) to navigation projects is typically made at the Corps District-level by awarding the contract to the lowest-cost bid that meets the scheduling demands of the dredge job. The U.S is divided into 38 Corps Districts, generally along watershed and state boundaries, and the resulting dredge-selection process is decentralized, with jobs in different Districts essentially competing for dredge fleet resources in some instances. It is anticipated that efficiencies can be gained by examining the jobs across Districts and studying the entire portfolio of dredging jobs at the system-level. In addition, there is interest in studying how any future placement of new environmental windows as well as tightening of existing environmental restrictions could impact system cost efficiency. This paper presents a system-level formulation that optimizes the decision of allocating dredge resources to projects under system constraints such as environmental windows, dredge resource cost and availability, and District-level project requirements. The research objective is to maximize the cumulative cubic yards dredged during a calendar year while adhering to budgetary, scheduling, and environmental restrictions.

Over the last several decades, the USACE has observed an increase in the total cost associated with annual O&M dredging without a proportionate increase in total volume of material dredged as shown in Figure 2. A widely-held explanation for this increase in dredging costs is system inefficiencies brought on by compliance with seasonal environmental work windows. According to this view, factors that can reduce dredging efficiencies and increase overall costs include *(3)*:

- Use of a less efficient dredge plant for a given project
- Increased transport distances to acceptable placement sites
- Increased fuel costs due to seasonal differences or logistical problems
- Increased operational time due to reduced vessel speeds
- Allowances for longer mobilization/demobilization times
- Increased "down" time for dredge plant maintenance and repair
- Increased fuel usage during cold weather conditions
- Precautionary measures to prevent icing hazards
- Personnel availability constraints and equipment delays due to inclement weather
- Other personnel safety considerations.

The Corps describes environmental windows as “temporal constraints placed upon the conduct of dredging or dredged material disposal operations in order to protect biological resources or their habitats from potentially detrimental effects” *(3)*. The scheduling of environmental work windows is intended to minimize environmental impacts by limiting the conduct of dredging activities to time periods when biological resources are not present or are least sensitive to disturbance. Surveys conducted by the Corps indicate that approximately 80% of all Civil Works O&M dredging projects are subject to some form of environmental work window constraint, with wide variations across Districts with the Atlantic and Pacific Coast Districts reporting the highest percent of projects with restrictions (up to 100%) and the Districts in the Gulf of Mexico and Mississippi Valley regions reporting the lowest percentage (less than 20%) *(3)*. Dickerson, et al. *(3)* conducted an economic study that indicates “substantial cost increments arise in connection with environmental windows, and that substantial cost savings could be derived from resolution of over-restrictive windows.” Studies have shown that inconsistencies exist in the application of environmental windows and in the technical methods used to justify the need for such restrictions *(5, 6)*.

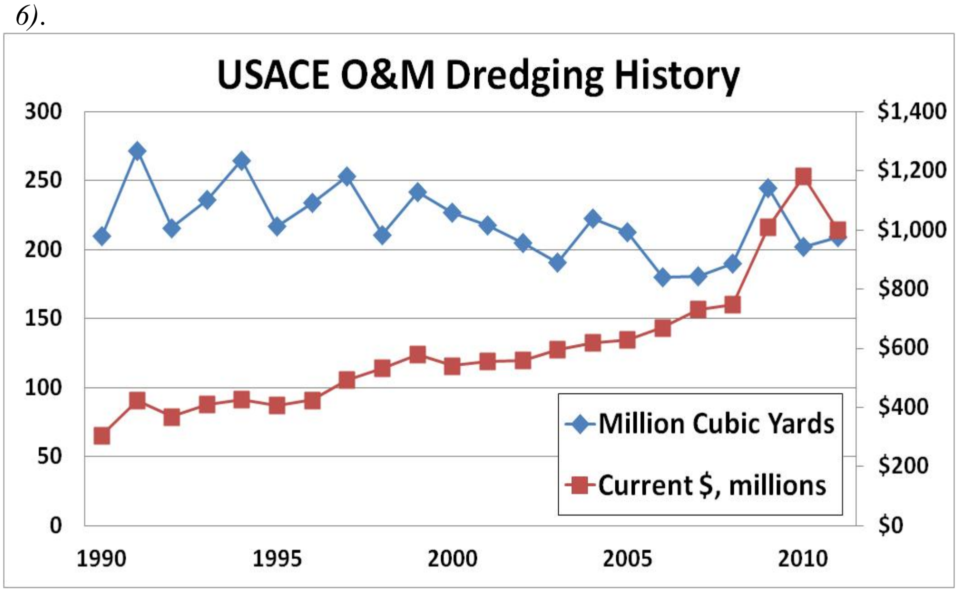

Figure 2 USACE O&M dredging history, USACE Institute for Water Resources.

Analytical Approach

Systems optimization approaches can support the Corps' development, maintenance, and oversight of a reliable and resilient maritime transportation system *(7).* Per the Corps' own Asset Management program, these approaches should support an integrated and holistic decision-making process, optimize limited resources with a risk-informed strategy, follow a consistent and repeatable process, and exhibit the highest degree of credibility, accountability, and synergy *(8).* However, Ratick and Garriga *(9)* recognize that dredge scheduling and sequencing optimization is challenging due to the high level of uncertainty surrounding the associated operational and economic conditions and natural processes. They develop a mixed-integer Reliability Based Dynamic Dredging Decision (RBD^3) model to maximize the overall channel reliability given limited resources of time, funds, and equipment *(9).* Menon and Lansey *(10)* take a probabilistic approach to maintenance dredging where dredging occurs beyond the authorized channel dimensions and may lead to longer time durations between dredging needs and reduce long-term maintenance costs. Mitchell et al. *(11)* present a systems-based approach for selected navigation projects for O&M dredging from a large portfolio subject to a global budget constraint. In the work presented here, a systems-based optimization approach is adopted in order to realize USACE dredge program efficiency gains achieved through scheduling and sequencing of dredging resources across the entire navigation portfolio of projects. Note that this problem formulation differs from the approach presented by Mitchell, et. al. *(11)* in that it seeks to optimally assign dredge vessels to particular projects to be dredged and also to schedule jobs optimally *after* a separate decision has been made concerning which projects are to be dredged within a given budget year.

Satisfying the dredging requirements of the U.S. navigation channels requires the decision-maker to make the following decisions while adhering to a pre-determined budget:

1) Should existing government equipment be used for dredging or should private companies be contracted to provide the services?
2) Once resource procurement is secured, which project should be completed by which piece of equipment?
3) Given both the finite budget and limited amount of dredging equipment, in what order should each dredging job be accomplished and when should each job begin and end. In addition, what considerations should be made in scheduling the dredging projects?

Formally, these decisions can be expressed in the form of a mathematical model. A high-level representation of the dredging resource allocation and scheduling problem can be described as:

Maximize Cubic Yards Dredged

Subject to

- Environmental Windows: The EPA and state departments of environmental quality place restrictions on when dredging can take place due to migration patterns of turtles, birds, fish, and other wildlife *(12)*
- Resources Limitations: Not all dredge equipment can complete every type of project and the amount of dredge equipment available is limited
- Equipment Productivity: Dredge equipment has varying productivity rates that affect project completion times and environmental impacts
- Mobilization Considerations: Dredge equipment remains idle while it travels between dredge jobs.

From the perspective of operations research, Decisions 1 and 2 above can be characterized by a class of problems referred to as *Generalized Assignment Problems* (GAP). This type of problem identifies an optimal assignment of projects to limited procured equipment resources while ensuring that each project is served once and only once. The objective is to maximize the amount of cubic yards dredged over a specified time horizon. In general, this and other assignment problem variants are a part of a particular class of transportation linear programming problems with the supplies (equipment resources) and demands (projects) equal to integers (often equal to one). The *GAP* was originally studied by Ross and Soland *(13),* who proposed a branch-and-bound algorithm to solve the problem to optimality. In their work, assignment constraints are deleted, and the remaining assignment problem is solved to obtain a valid upper bound. Then, a secondary penalty problem is solved to correct violated capacity restrictions. Since then, a large number of additional branch-and-bound approaches for the GAP have been proposed. These works are differentiated by the varying approaches used to bound the solution. Fisher *(14)* considered the strength of bounds obtained by solving (i) the Lagrangian relaxation formed by relaxing capacity constraints, (ii) the Lagrangian relaxation obtained by relaxing assignment constraints, or (iii) solving the LP relaxation formed by relaxing binary constraints. Their work discusses interesting trade-offs between solving computationally difficult relaxations that provided sharper bounds, as shown to be the case with the relaxation given by (ii), versus weaker bounds obtained in less time.

In addition to the well-studied branch-and-bound procedure, a number of decomposition-based approaches have been proposed for the GAP. Building on the Lagrangian relaxation efforts discussed previously, Jörnsten and M. Näsberg *(15)* proposed a Lagrangian decomposition methodology that combined the two relaxations formed by relaxing either the assignment or capacity constraints. They showed that the bound obtained by the resulting relaxation solution is at least as strong as either of the bounds obtained by the individual Lagrangian relaxation alternatives. While their testing is limited to only ten instances, results suggested that the approach is an effective alternative to the traditional Lagrangian relaxations of the GAP. Even with the advances of exact algorithms for the GAP, it remains computationally impractical to solve very large instances. For this reason, a great deal of the literature is devoted to meta-heuristics for the GAP. Notable amongst these are tabu search *(16),* genetic algorithms *(17),* and simulated annealing algorithms *(18)*.

Decision 3 above is also a well-studied operations research problem that is typically referred to as a job-scheduling problem. In this problem class, jobs (i.e. dredging projects) are assumed to have an earliest start date and latest completion date. Using information regarding the length of time that each piece of equipment takes to complete various jobs (i.e. dredging effort), a scheduling model can be used to produce work schedules that can: (i) minimize the *total* time it takes to complete all projects and (ii) minimize the maximum time spent on any *individual* project.

METHODOLOGY

Problem Definition and Model Formulation

In this section, a mixed integer mathematical model is introduced in which available dredge vessels are assigned to unsatisfied dredging jobs over a finite planning horizon. As mentioned in the previous sections, the objective is to maximize the amount of cubic yards dredged over a finite time horizon. A feasible dredging schedule must conform to restricted periods (RPs) of each project. Environmental window and restricted period concepts are complementary to each other in the sense that for a specific project, time windows available for dredging are called environmental windows whereas restricted periods represent the times when dredging is prohibited. Before explaining the details of the IP, required notation to account for the key components of the scheduling problem is given below:

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;
- $w \in W_j$, set of restricted periods applicable to dredging job j.

Parameters

- b_w is the beginning of restricted period $w \in W_j$; $j \in J$;
- e_w is the end of restricted period $w \in W_j$; $j \in J$;
- r_d is the operation rate (cubic yard/day) of dredge equipment $d \in D$;
- q_j is the dredging amount of job $j \in J$ (in cubic yard);
- $t_{jd} = \left\lfloor \frac{q_j}{r_d} \right\rfloor + 1$ is the time (in days) that it takes for dredge equipment piece $d \in D$ to complete job $j \in J$;
- $t_{jj'}$ is the time (in 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 is the cost for completing job $j \in J$;
- B is the available budget for the planning horizon.

Decision Variables

- y_{dj}, binary variable with value 1 if dredging equipment piece d is used to complete job j;
- z_{djt}, binary variable with value 1 if dredging equipment piece d begins work on job j in period t.

Given the definitions above, the dredge scheduling (DS) optimization model can be represented as the following mixed-integer linear program.

$$\text{maximize} \sum_{j \in J} \sum_{d \in D} q_j y_{dj}$$

$$\text{subject to} \qquad \text{(DS)}$$

$$\sum_{d \in D} y_{dj} \leq 1 \qquad j \in J \qquad (1)$$

$$\sum_{j \in J} \sum_{d \in D} c_j y_{dj} \leq B \qquad (2)$$

$$\sum_{t \in T} z_{djt} = y_{dj} \qquad j \in J;\ d \in D \qquad (3)$$

$$\sum_{t'=t}^{\min\{T, t+t_{jd}+t_{jj'}\}} z_{dj't'} \leq 1 - z_{djt} \qquad j \in J;\ j' \in J;\ j \neq j';\ d \in D;\ t \in T \qquad (4)$$

$$\sum_{d \in D} \sum_{t=\max\{1, b_w - t_{jd}\}}^{e_w} z_{djt} = 0 \qquad w \in W_j;\ j \in J \qquad (5)$$

$$(t + t_{jd})\, z_{djt} \leq |T| \qquad j \in J;\ d \in D;\ t \in T \qquad (6)$$

$$y_{dj} \geq 0 \qquad d \in D;\ j \in J \qquad (7)$$

$$z_{djt} \in \{0, 1\} \qquad d \in D;\ j \in J;\ t \in T \qquad (8)$$

The objective of the model is to maximize the total cubic yards of material dredged over the planning horizon. Constraint (1) ensures that job *j* is satisfied by at most one piece of dredging equipment *d*, whereas Constraint (2) states that the total cost incurred by such assignment cannot exceed the total budget. Constraint (3) requires that if job *j* is satisfied by equipment *d*, exactly one start day for that work must be specified for that assignment. Constraint (4) specifies that if job *j* is started in period *t*, by equipment *d*, then equipment *d* cannot begin another job, *j*', until $t_{jj'} + t_{jd}$ periods have passed (i.e. the time to complete job *j* on dredge equipment *d* plus the time to travel to job *j*' from job *j*). Constraint (5) prevents a job from beginning, or ending, on a day that overlaps with a restricted period. Constraint (6) ensures that if a job is dredged, the completion time occurs before the end of the planning horizon. Finally, Constraints (7)-(8) specify the appropriate domain of each variable in the model. The challenges associated with solving the DS are discussed in the following section. A logic-based solution approach is described that has been shown to solve DS efficiently.

Solution Approach

As with many integer programs, providing the exact optimal schedules for each dredge vessel and for each job gets more challenging as the number of decision variables and constraints increase. It has been observed that a commercial optimization solver, ILOG CPLEX, cannot even start solving the (DS) model with a medium level problem instance ($|D|$=10 and $|J|$=32). This limitation is due to the extreme memory needed to load all required decision variables and constraints in the IP representation of DS. Therefore, to overcome this limitation, DS was reformulated as a constraint programming (CP) model in which the scheduling and allocations restrictions were handled by *global constraints* and *interval variables*. This approach allowed high-quality feasible solutions to be obtained with a reasonable amount of computational time. The solutions offered in Results Section reflect the best-found solution after 1 hour of computational effort.

Data Collection and Analysis

Historical USACE dredging data dating back to the mid-1990s was utilized to parameterize the model. The data was provided by the Corps' Dredging Information System (DIS: http://www.navigationdatacenter.us/data/datadrgsel.htm), and a total of 116 unique navigation channel maintenance dredging jobs were identified as seen in Figure 3, and dredging volumes and costs were averaged over the range of years for which DIS data was available for each project. Of the 116 unique dredging jobs identified, an average of 416,427 cubic yards was dredged for each with a standard deviation of 702,096 cubic yards. 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 expenditure was $46,440. The average expenditure per project was $1,922,517, with a standard deviation of $2,444,404 .

The DIS historical data was also used 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. Hundreds of dredging jobs conducted by thirty different companies over more than a decade were considered in order to obtain representative daily production rates. It is important to note that this treatment considered the total cubic yards dredged for each project divided by the total number of days over which dredging took place. Therefore, delays encountered due to inclement weather conditions, equipment maintenance and failures, and any other type interruption are reflected in the final baseline daily production rate. Using the sample in Table 1, the average dredge production rate was 7,556 cubic yards per day with a standard deviation of 5,633. The minimum average production rate for the set of contractors was 1,238 cubic yards per day and the maximum average production rate was19,245 cubic yards per day. As noted, these figures reflect a statistical average of many dredging projects conducted over many years, and therefore should not be interpreted as baseline or design production rates for any individual dredging vessel in the Corps or industry fleet.

For the 116 jobs considered, a total of 130 unique restricted periods were identified and used to establish Constraint (5) within the DS optimization model. The number of unique restricted periods exceeds the number of dredging jobs because in some instances a single navigation project can be subject to multiple environmental restrictions. These RPs were identified using the USACE Threatened, Endangered, and Sensitive Species Protection and Management System (http://el.erdc.usace.army.mil/tessp/index.cfm). For each of the 116 dredging jobs for which records were compiled from DIS, any corresponding environmental restrictions were noted along with the affected species and the start and end dates of the period during which dredging may not take place. The longest restricted period had a length of 274 days and the minimum restricted period length in the data set was 29 days. The average length of all RPs considered was 143.6 days with a standard deviation of 71.2 days. Table 2 summarizes the types of restricted periods considered by the DS model.

TABLE 1 Dredge Vessel Production Rates.

DE	Production Rate (cubic yard/day)	DE	Production Rate (cubic yard/day)
1	1238	16	6837
2	1301	17	6965
3	1637	18	8332
4	1962	19	8443
5	1989	20	9007
6	2296	21	10436
7	2375	22	10478
8	2709	23	10959
9	2855	24	12347
10	3311	25	12882
11	3481	26	15556
12	3728	27	17080
13	3941	28	17282
14	4532	29	17537
15	5941	30	19245

TABLE 2 Summary of Restricted Periods (RPs) Used by DS Model.

Restricted Period Type	Cumulative Number of Restricted Project Work Days	Avg. RP Duration (days)	Number of Projects with RP
Fishes	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** (out of 42,340 possible)	**178**	**151**

The distance between jobs was needed to account for travel time of dredge vessels and resulting implications for scheduling. A from-to distance matrix was constructed by using a GIS layer that computed travel distance on the waterways between all prospective job locations. This enabled the DS optimization model to run without incurring the additional computation expense of dynamically computing travel times as scheduling solutions were explored. For simplicity, the DS model assumed an average travel rate of 50 miles per day for dredge vessels moving between projects.

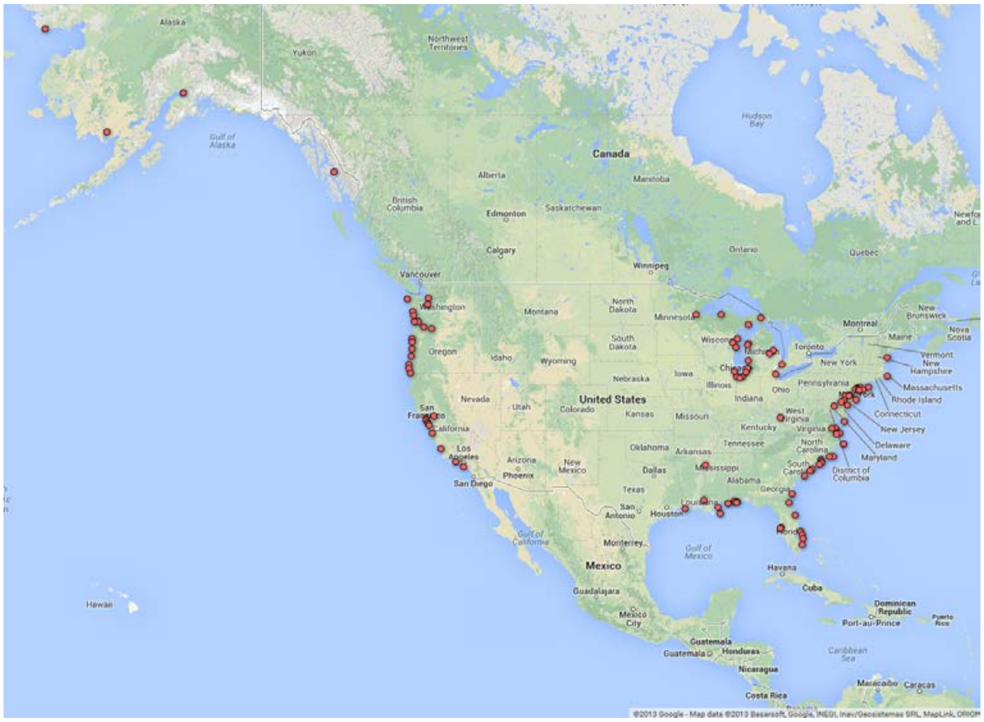

Figure 3 Graphical depiction of 116 dredge project locations.

RESULTS

This section demonstrates the ability for the model described in the Problem Definition and Model Formulation Section to provide efficient dredge schedules using the methodology outlined in Solution Approach Section. The results contain 10 problem instances, each with a specified relaxation of the scheduling constraints imposed by environmental restrictions. In each instance, all 116 jobs discussed in the Data Collection and Analysis Section were considered for scheduling. Correspondingly, 116 restricted periods of varying durations (see the Data Collection and Analysis Section) were included in our base study. The decision model was given 30 dredge vessels to complete the 116 jobs in each of the 10 instances. Note that each job is unique in terms of dredge volume requirement and that each of the 30 dredge vessels perform at different production rates. In each instance, the total budget available was fixed to be 75% of the total of the average annual costs for all 116 dredging jobs considered.

Before considering the impact of relaxing the duration of restricted periods, Table 3 offers project assignments to dredge vessels, when individual tasks start and end, and travel and idle times of each assignment for the baseline case. Note that in the base case scenario (0% reduction in restricted period duration), all 116 restricted periods considered are strictly enforced. For this baseline example, the optimal solution for the DS model calls for 106 projects to be dredged by 24 distinct vessels over the yearlong planning horizon. Recall that the DS model seeks to maximizes the total cubic yardage of material dredged across all projects, as opposed to dredging as many individual jobs to completion as possible. This is the reason that the optimal solution leaves 10 dredging jobs uncompleted. Table 3 summarizes the solution to the DS model for the baseline scenario with 0% relaxation of the restricted periods. Each of the dredging projects to be dredged is listed along with the specific dredge vessel (DE) assigned to that project, the calendar day number (1-365) of the dredging start and end date, subsequent travel days required to get to the next dredging project, and any idle time spent waiting on RPs to end. With some notable exceptions, individual dredges tend to move between projects within the same general geographic region, thereby minimizing travel times. Also, idle times are concentrated onto a relative handful of instances, with only 12 cases of idle time exceeding 10 days, and many of the dredge vessels having 0 idle days over the course of the year.

With the baseline results for the DS model established, it is interesting to explore how much additional dredging would be possible under various scenarios in which the restrictive windows are relaxed. In order to conduct this sensitivity analysis, a separate set of experiments was designed in which the duration of each restricted period is reduced by a specified percentage. Note that the restricted periods are reduced by moving the start dates back and the end dates forward by equivalent amounts. To interpret the figures discussed in the remainder of this section, note that '0% reduction' indicates that the original set of restricted periods were accounted for, while '100% reduction' implies that there is no restricted periods embedded in the problem. All other input parameters for the DS model remain unchanged.

TABLE 3 Solution for the Baseline Scenario (0% RP Relaxation).

Project	DE	Start	End	Travel	Idle	Project	DE	Start	End	Travel	Idle
PORTAGE LAKE HARBOR MICHIGAN	6	60	72	4	75	BON SECOUR RIVER	24	19	56	15	0
BURNS HARBOR IN	6	151	196	0	0	MURRELLS INLET SC	24	71	116	34	0
CHESAPEAKE AND DELAWARE CANAL	7	334	363	0	0	SOUTH HAVEN HARBOR MICHIGAN	24	150	152	2	27
EVERETT HARBOR AND SNOHOMISH RIVER	8	166	263	0	0	MICHIGAN CITY HARBOR, IN	24	181	186	24	2
NOME HARBOR	9	120	130	0	0	MISS RIVER - GULF OUTLET (MRGO)	24	212	289	0	0
LONG ISLAND INTRACOASTAL WATERWAY	11	1	24	0	0	WELLS HARBOR	25	1	2	3	0
SCHUYLKILL RIVER	12	1	72	0	0	CAPE COD CANAL	25	5	15	4	0
DEL R PHILADELPHIA TO TRENTON	13	7	69	9	196	EAST ROCKAWAY INLET	25	19	34	6	0
SILVER LAKE HARBOR NC	13	274	329	0	0	LYNNHAVEN INLET, VIRGINIA	25	40	48	29	3
BONNEVILLE LOCK AND DAM-LAKE BONNEVILLE	14	1	3	15	0	ST. JOSEPH HARBOR MICHIGAN	25	80	84	23	0
C AND LW RIVERS BELOW VANCOUVER WA AND PORTLAND OR	14	18	80	0	0	HUDSON RIVER NY (MAINT)	25	107	121	18	0
MOSS LANDING HARBOR, CA	15	1	7	5	0	PALM BEACH HARBOR FL	25	139	149	6	0
MORRO BAY HARBOR CA	15	12	39	130	0	TAMPA HARBOR FL	25	155	236	21	16
DULUTH-SUPERIOR HARBOR MINNESOTA	15	169	183	0	0	FIRE ISLAND TO JONES INLET	25	273	360	0	0
PORT ORFORD OR	16	1	2	128	0	PASCAGOULA HARBOR	26	1	78	98	36
TWO RIVERS HARBOR WISCONSIN	16	130	139	25	0	PETALUMA RIVER	26	212	225	109	0
PERDIDO PASS CHANNEL	16	164	201	24	0	BARNEGAT INLET	26	334	365	0	0
BUTTERMILK CHANNEL	16	225	238	2	18	RUDEE INLET, VIRGINIA	27	1	3	1	0
SHINNECOCK INLET	16	258	342	0	0	NORFOLK HARBOR, VIRGINIA	27	4	8	2	0
BAYPORT SHIP CHANNEL	17	1	7	9	0	COLD SPRING INLET	27	10	13	1	0
ONTONAGON HARBOR, MICHIGAN	17	16	23	33	0	MANTEO (SHALLOWBAG) BAY NC	27	14	30	4	0
AIWW - WILMINGTON DISTRICT NC	17	56	120	1	0	LOCKWOODS FOLLY RIVER, NC	27	34	38	3	0
CAPE FEAR RIVER ABOVE WILMINGTON NC	17	121	178	38	0	TOWN CREEK SC	27	41	55	9	0
BIG SANDY HARBOR	17	216	242	0	0	YORK RIVER - VIRGINIA	27	64	97	5	0
WATERWAY ON THE COAST OF VIRGINIA	18	1	13	4	0	NJ INTRACOASTAL WATERWAY	27	102	113	18	0
MOREHEAD CITY HARBOR NC	18	17	87	21	0	PONCE DE LEON INLET FL	27	131	136	34	0
DETROIT RIVER MICHIGAN	18	108	133	0	0	GRAND HAVEN HARBOR MICHIGAN	27	170	173	3	0
SIUSLAW RIVER OR	19	1	7	3	0	CALUMET HARBOR AND RIVER	27	176	187	1	0
YAQUINA BAY AND HARBOR OR	19	10	19	128	0	WAUKEGAN HARBOR IL	27	188	191	24	0
HOLLAND HARBOR MICHIGAN	19	147	153	3	0	MISS RIVER OUTLETS AT VENICE LA	27	215	304	0	0
ARCADIA HARBOR MICHIGAN	19	156	157	2	0	CHETCO RIVER OR	28	1	2	4	0
STURGEON BAY HARBOR	19	159	167	2	0	COOS BAY OR	28	6	30	6	0
MANISTIQUE HARBOR, MICHIGAN	19	169	178	27	0	HUMBOLDT HARBOR AND BAY	28	36	123	1	27
MISS RIVER - BR TO GULF	19	205	286	0	0	RICHMOND HARBOR	28	151	157	8	1
ST. CLAIR RIVER MICHIGAN	20	1	9	18	0	SEATTLE HARBOR	28	166	174	17	0
WILMINGTON HARBOR DE	20	27	63	109	71	SAN RAFAEL CREEK, CA	28	191	200	1	0
SAN FRANCISCO HARBOR	20	243	336	0	0	SAN LEANDRO MARINA - JACK D. MALTESTER CHANNEL	28	201	208	13	0
QUILLAYUTE RIVER	21	1	7	4	0	SUISUN BAY CHANNEL	28	221	234	13	0
UMPQUA RIVER OR	21	11	22	3	0	OAKLAND HARBOR	28	247	260	1	0
WILLAPA RIVER AND HARBOR	21	25	31	19	0	REDWOOD CITY	28	261	295	7	0
LOS ANGELES-LONG BEACH HARBORS	21	50	62	20	7	VENTURA HARBOR, CA	28	302	365	0	0
GRAYS HARBOR AND CHEHALIS RIVER	21	89	145	32	0	PORT EVERGLADES HARBOR	29	1	4	13	0
ANCHORAGE HARBOR	21	177	264	0	0	MOBILE HARBOR	29	17	91	9	5
MILWAUKEE HARBOR, WISCONSIN	22	1	5	7	18	JACKSONVILLE HARBOR FL	29	105	173	100	0
SAGINAW RIVER MICHIGAN	22	30	53	7	0	SACRAMENTO RIVER	29	273	290	11	0
GREEN BAY WISCONSIN	22	60	75	28	78	OCEANSIDE HARBOR CA	29	301	343	0	0
JAMES RIVER, VIRGINIA	22	181	209	0	0	OCEAN CITY HARBOR AND INLET AND SINEPUXENT	30	1	3	2	0
ROGUE RIVER AT GOLD BEACH OR	23	2	4	5	0	CHINCOTEAGUE INLET, VIRGINIA	30	5	7	22	0
DEPOE BAY OR	23	9	13	5	0	GULFPORT HARBOR	30	29	83	15	0
COLUMBIA RIVER AT MOUTH, OR AND WA	23	18	92	50	0	GEORGETOWN HARBOR SC	30	98	133	12	0
DILLINGHAM SMALL BOAT HARBOR	23	142	153	151	30	JAMAICA BAY	30	145	157	2	0
FORT PIERCE HARBOR FL	23	334	352	0	0	FLUSHING BAY AND CREEK	30	159	163	6	44
ROSEDALE HARBOR MS	24	1	8	11	0	BALTIMORE HARBOR AND CHANNELS	30	213	331	0	0

The change in total volume of dredging as the durations of the restricted periods decrease is shown in Figure 4. Enforcing all restricted periods in the baseline case results in the smallest total dredge volume nationally whereas the maximum total dredged volume is obtained for the extreme instance where the restricted periods are done away with entirely. The total dredge volume level is non-decreasing between these two peaks because of the fact that any solution that is feasible with RPs relaxed by x % is also feasible to a problem with the same restricted periods relaxed (x + Δ) %. This plateau effect can be observed when the RPs are relaxed from 40% of baseline to 50%, and again from 60% to 70% and 80%. It is further observed that a decrease in restricted windows by 30% allows for an additional 4,907,852 cubic yards to be dredged. This is an increase itself of almost 15%. Similarly, a complete relaxation of restricted periods yields 12,484,717 additional cubic yards (27% increase). In addition to total dredge amount, the DS model enables the collection of other statistics such as the total travel, idle and dredge time to finish all the dredging jobs. For each of the 10 problem instances, these statistics are summarized in Figure 5. Note that dredge resources that are not assigned to any projects because they are not necessary to achieve the optimal solution can be removed from the fleet and assigned to some other operations. Therefore, idle time reported in Figure 5 only accounts for the idle time of a dredge vessel that handles at least one project. Moreover, the calendar days before and after a particular dredge is utilized within the DS model is not reported as idle time.

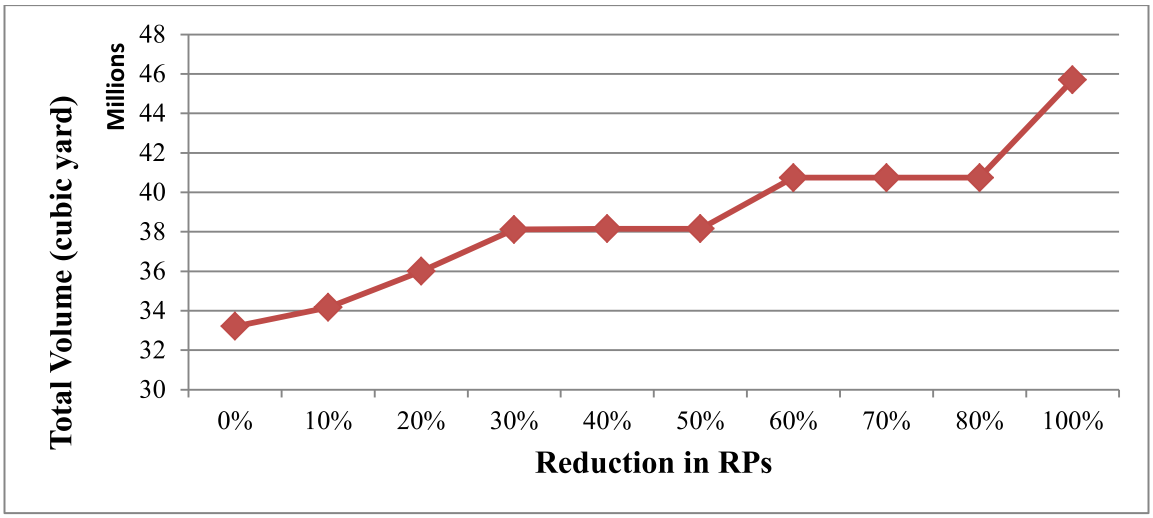

Figure 4 Change in total volume (objective function).

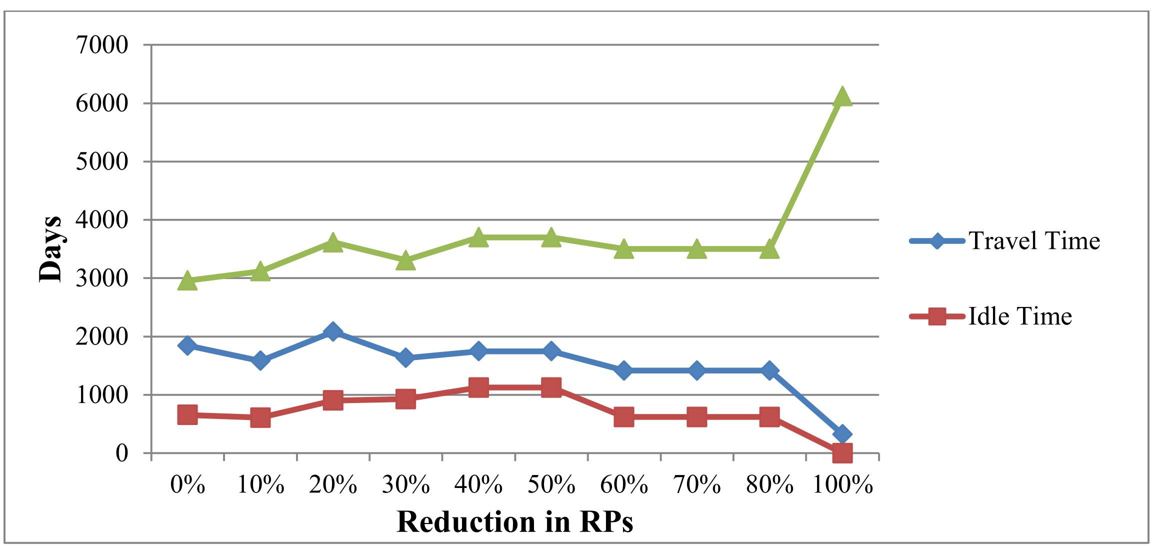

Figure 5 Total travel, idle and dredge time for each problem instance.

CONCLUSIONS

The dredging resource allocation and scheduling problem provides unique challenges in addition to those studied in the classical scheduling models. Of particular interest are the dredge scheduling restrictions known as environmental windows, which limit when dredging can take place due to migration patterns of turtles, birds, fish, and other wildlife. These restrictions can be modeled by treating time as a resource and limiting it within the framework of a generalized assignment problem, and opportunities exist to provide decision-makers with quantitative insights into how efficiencies might be obtained if targeted research were to show that particular restricted periods could be relaxed without adverse consequences for sensitive and endangered species. This work offers a mathematical representation of the decision aspects necessary to accurately address this question. Advancements in logic-based solution approaches allow the decision-maker to real-size dredge scheduling challenges faced by the USACE. This work offers more efficient detailed schedules of dredge resources under current operational restrictions. It also offers quantitative evidence to support the productivity gains that can be realized with less restrictive environmental windows.

It should be noted that the full range of RP relaxation scenarios presented in this sensitivity analysis are included simply to demonstrate clearly that the constraining effects of RPs on the overall USACE dredging program scheduling and efficiency can be quantified. In reality, as discussed by Suedel et. al. *(19)*, RP relaxations can only be implemented in localized areas after extensive research has been conducted to pinpoint species migratory patterns and sensitivities to dredging activities. Furthermore, to keep the DS model as formulated in context with the USACE annual O&M dredging program, recall from Figure 2 that in recent years the Corps has dredged in excess of 200M cubic yards of material on an annual basis. The scope of the DS model therefore needs to be extended to include more O&M dredging projects before it can be directly applied to USACE decision making.

This paper introduces a systems-based approach to achieving increased efficiencies for annual USACE O&M dredging of navigation projects. The results of the dredge scheduling optimization model developed through this work can shed significant quantitative insight into potential efficiencies to be gained through the sequencing of maintenance dredging jobs throughout the calendar year. Perhaps more importantly, this work provides a basis for directing future research efforts towards restricted periods that have the most significant impact on overall dredge program efficiency, as captured by the objective function within the DS model. Additional potential applications of this work include providing insights into required next-generation dredge fleet (both USACE and industry) capabilities for efficient O&M mission execution. For example, sensitivity analysis of the DS model results could show whether it is more efficient to introduce many smaller dredges with lower daily production rates, or a few large dredges with very high production rates.

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