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A Multimodal Network Approach to the Inland and Coastal Waterway System

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Multimodal Transportation on a Waterway System

Abstract

The inland waterway system carries a significant percentage of the national freight. Maintenance operations including dredging and dam repair are important to maintaining the effective and efficient operation of the system. Dredging projects are for recovery of the navigational channel draft from the shoaling effect while lock/dam repair is about maintaining a maximum possible operational hours to reduce the waiting and delay of vessels therein. The special feature in this study is that the shoaling effect is random, as is subject to weather and other effects. This study specially deals with maintenance fund allocation to these maintenance requests by first proposing a multimodal approach for formulating the waterway maintenance problem in a connected network, which considers rivers, locks/dams, and highways and railways.

The random shoaling effect essentially renders a two-stage stochastic problem, which is in our case solved by a deterministic approximation. The solution identifies maintenance projects to fund for the most system benefit in terms of serving the most OD demand at the least cost. Improving the locks and dams has a random effect on the delay function, so a probability distribution is considered for the delay. The unwanted interruption delays, which is not related to the traffic, are detected from the data set; and two functions, a linear and a non-linear respectively, formulate the amount of improvement gained by the number of hours delay reduced.

The historical origin-destination tonnage data and associated flows along the routes of each commodity OD are used to optimize the maintenance project selection based on the needed dredging depth of each project, the future dredging needs, and the lock and dam rehabilitation needs. Another distinct feature of the model is that it considers interdependence of the maintenance projects, which means the benefit along a route does not realize if not all the improvement projects along a route are conducted. The model is applied to the Ohio River basin network which includes the land side routes. The results show the importance of considering the lock and dam rehabilitation costs in different budget scenarios for each linear or non-linear delay cost approximation. The optimal decision heavily favors lock/dam repair over dredging along the navigable river channels.

Key Words: *Multimodal network, Waterway system, Dredging, Shoaling, Stochastic programming*

1 Project Description

The US maritime transportation system carries a significant amount of the national freight. About 600 million tons of commodity is transported through the inland waterway system each year, accounting for about 15 percent of the national freight (1)(2). In addition, the vast majority of the international trade go through the coastal ports and harbors. The navigable waterway system is comprised of bridges, ports, lock & dams, and other terminals as well as shipping vessels. The marine ports and terminals also transfer domestic freights between waterway and land transportation. Therefore, maintenance of the waterway transportation system is important. The maintenance operation in marine transportation ensures enough channel depth for inland waterways and the coastal ports while repair of locks and dams reduces the vessel delay during transit through the locks/dams. These maintenance operations are critical to the waterway system shipping efficiency and safety, which has rich implications to the regional economies and environmental sustainability. Statistics shows about one billion dollars spent annually on dredging. Given the limited fund available each year, how to select dredging projects remains an interesting and significant problem. In the following, both channel dredging and dam/lock repair will be discussed. Without losing generality, readers may conceive the research problem in the context of inland waterway maintenance only.

Channel depth is necessary to safe and efficient shipping. Dredging is the basic means for draft depth maintenance. It removes the sediments from shoaling. Dredging is constantly countered by an effect called shoaling. Shoaling is the result of a complex interaction of three dimensional currents and their spatial variation, bathymetry variation, channel meandering, sediment load, type of sediment material (cohesive or non-cohesive), tributary inflow, tidal interaction [in coastal areas] and weather effects. Without constant dredging, the draft (e.g. the vertical distance from the end of the vessel to the water surface) cannot be maintained and vessel size will be reduced.

Another important waterway maintenance is repair of locks and dams. Locks and dams in the waterway system concerns waiting time of ships and barges go through the channel. In cross a dam or lock, the ship first goes through a chamber in the waterway for transit into the second chamber, which is first raised the water level to the same as the first. The ship moves to the second chamber before it's depleted or increased to the same level as the third one. The ship moves forward in this way until it gets to the next water level before or after the dam/lock. In this way, the ship can smoothly change its level throughout the river. Dams/locks can save water to raise up the depth to allow larger draft for ships in the otherwise shallow river segments (3). Operation failure in the locks and dams causes delay in freight transfer, negatively affecting the waterway system efficiency. An important factor in freight shipping is the integration of modes through a multimodal network,consisting of waterway, railroad, and trucking for efficiency and mobility by taking advantage of the unique advantages of each mode (4)(5).

This paper deals with optimization of the waterway maintenance project selection including dredging and dam/lock repair. The limited waterway maintenance funding partially comes from the Harbor Maintenance Trust Fund. The Corps, as the administrator of maintenance projects, allocates the available fund to maintenance projects in order to maximize the total system benefits, typically measured by increased shipping capacity compared to a do-nothing option. To accomplish that, the Corps conventionally evaluates the candidate projects based on different measures such as cargo tonnage, project ton-miles, and cargo value in dollars (6). Subsequently, the Corps assesses the projects individually and ranks them based on isolated, individual measures. This traditional process does not consider the dependent effect of projects. Therefore, allocating fund in the project-based scenario is not the best approach. The simple rationale is that increased cargo shipping at a selected maintenance project is highly dependent on the increased capacity of the entire freight routes between the interest freight origin and destination. Thus, using a system-based scenario, which can reflect the effects of different projects in collaboratively supporting origin-destination freight shipping is much more realistic. Simply put, all the segments along a path should be dredged to the needed draft in order to sail a large vessel. In other words, the minimum draft along an origin-destination path controls the shipping capacity.

This research aims at developing an operational research model necessary to choose the most rewarding waterway maintenance projects based on cargo shipping efficiency and benefits. As mentioned earlier, different factors should be considered such as the interrelation between projects, dredge scheduling and shoaling effect, the delay in lock and dam (lock and damn operation), and the multimodal connection. A special notion here is about the treatment to the shoaling effect after dredging.

2 Literature

The study problem is multi-faceted concerning dredging, lock and dam system, and multimodal network flow, each of which deserves an independent study. The literature review for this report is therefore categorized into according areas. It is the hope of the investigators that this study will advance the state of the art on this important problem.

Budget allocation is the primary focus of this study. Ford (7) was one of the first who used operation research techniques in the waterway dredging maintenance. He minimized the excavation and material transportation costs in a network which is consisted of disposal and dredging sites. He also considered the benefit by reusing the dredged materials. Linear programming techniques were used to formulate the problem, which allocated dredged materials at each period, to the available sites over the planning horizon, so he did not consider what will happen after that. In other words, the problem was not treated as a multi-stage problem, since storage of the materials at the sites were considered as a simple capacitated lot sizing problem (7)(8). Other scholars such as Hochstein (9), and Lund (10), in contrast, only considered dredging operation on a single route originated from a river (reach), without considering the connectivity.

Mitchell et al. (6) developed a mixed integer programming model to optimize the benefit gained from the dredging operations (11). The benefit was represented by using the historical tonnage flows at each depth of the draft. They developed an all or nothing model which allocated a limited budget to the chosen projects in a waterway network. Some heuristic algorithms were proposed based on sorting. The test results were compared between the algorithms.

Khodakarami et al. (12) proposed partial funding to the dredging projects requested. A project is treated with different dredging depth requests, each depth justifying an according portion of the total requested funding. Only one depth may be granted for each dredging project. For instance, a project which request to dredge 3 ft. will be allowed to dredge from 1 up to 3 ft. This treatment allows a more granular allocation of the limited dredging funds. In other words, the fund will not be devoted solely to the most rewarded projects. It formulated the cost as a linear function of the depth to develop a "continuous" model, and tried to maximize the tonnage flow on routes (13). The modeling technique of this study can be extended to considering commodity groups. However, not the shoaling effect nor the multimodal network is considered.

Some other studies developed reliability models for dredging project selection. For instance, Scully and Mitchell (14) measured the reliability of a channel using a probability term to allocate fund based on keel strike probability. To do so, the uncertainty of all elements were considered to be independent and normally distributed. They considered the probability of having at least zero foot for the net under keel clearance of the dredged location to calculate the reliability. The scope of our study here is totally different in terms of optimally selecting maintenance projects.

Dredging and shoaling are two process critical for the draft evolution. They closely interact with each other. Shoaling happens due to complex water movement processes. This natural phenomenon is expedited after performing a dredging project. A deeper draft due to dredging is likely subject to a faster sedimentation process, more of a shoaling effect. Consequently, dredging a deeper draft will not necessarily result in a larger navigation depth one or more years after the dredging period. The shoaling process is complex. There are some patterns for predicting the shoaling. For instance, dredging an upstream part of a river might increase shoaling at downstream locations. However, there is a lack of data set that describes the actual shoaling process (15). Noteworthy is that the random shoaling behavior is along rather the temporal dimension than over the locations. Ratick and Morehouse Garriga (16) developed a mixed integer programming model in order to maximize the achievable reliability of dredging activities for all locations and all periods. The model found the minimum reliability level achieved across all the time and space horizon. Also, it found the amount of dredged materials, the amount of dredging requirement that is not met (under current solution), and the channel depth for the selected reliability level after performing dredging over each time and location. The costs including the price of renting the utilities and mobilization are considered should be less than the total available annual budget. The number of running equipment and dredging costs were addressed in spatial and time dimensions. The mobilization costs were only considered when the dredging location was changed, not during the process of dredging. Also, the dredged materials were limited to the capacity of the dredging operation at that time. The model allowed the authority to dredge an extra depth to reduce the needs of dredging in the subsequent periods. Also. Target reliability levels for each location and each time span were generated in the Monte Carlo simulation by varying the parameters of a physically based sedimentation model followed by generating a CDF based on the PDF of all depths in time and space horizons. Additionally, the shoaling effect was addressed by considering a change in the reliability of the model in essence of unmet constraints. This study did not examine the shoaling effect as a decision factor in developing the model (16).

Mitchell et al. (11) developed a mixed integer programming model to find the optimal combination of ports and channels for dredging/maintenance to have the maximum tonnage throughput in the waterway system subject to a limited budget. The authors considered network efficiency in this study because in their model, the benefit from each project was highly dependent on the minimum draft of the river sections along the origin-destination path. They formulated the model for 20 years and took the shoaling effect into account. However, random parameters were only added at the end of each period to represent the shoaling effect. In other words, they used the optimal project conditions from the prior year as the condition of the year for project funding, which in our view does not address the shoaling effect satisfactorily. In addition, they limited the sedimentation to be effective up to 3 ft by defining 4 ft as the maximum restored depth through dredging within a single budget period (e.g. year), which is different an assumption from other scholars (15). Further more, Mitchell et al. (11) presumes that the dredging always increases the system capacity; however, the speedy shoaling rate might totally negate this possible benefit. The study showed the required dredging depth for each project each year. Also, the results of GA were validated by a heuristic method based on the average costs (ton/$) (11).

Ahadi et al. (17) developed a two-stage stochastic model, based on GA and mixed integer programming, for optimizing the cargo value through the inland waterway system. To keep the problem tractable, they considered only the important O-D pairs since about 85% of the total tonnage was on about 20% of O-D pairs. In that study, A set of discrete scenarios were generated to represent the shoaling possibilities across the waterway network. Those scenarios were able to reflect correlation of shoaling on different inland waterway sections due to correlated weather and other conditions. However, the lock and dam effect was not considered in that study.

Lock and dam maintenance is another important aspect of the waterway system.The delay at the locks can disrupt commodity transport. Wang and Schonfeld (18) optimized the rehabilitation of locks in an interdependent environment by using the genetic algorithm (GA). They considered shipping delay in each lock and dam project. The developed model was not computationally efficient, and a schedule was found based on simulation. However, the dredging of waterway and repair at lock/dams should be treated in an integrated manner in the mathematical framework to have a generalized waterway maintenance model. By and large, delay occurs in the general transportation network. Wilson et al. (19) analytically considered the delay costs by considering the entry into the rivers, import ports, and export ports, crops transfer between production and export zones. A multimodal network was developed comprising truck, rail, and barges. The delay was also considered in a synchromodal freight multimodal transport system. Behdani et al. (20)

developed a similar multimodal network incorporating these freight modes. It specifically considers costs of shipping,waiting, and late delivery (20).

This study may be considered a typical example of multimodal transportation network, but is more at the strategic level of planning (21). A distinct feature of our work here is its unique consideration of the waterway system maintenance. While in the context of the waterway system maintenance, the special treatment to the shoaling effect appears still a relatively new area. Much remains to be further examined in the near future.

This research follows our earlier effort along the line of modeling the shoaling effect for dredging project selection, Khodakarami et al. (12) developed a two-stage model. The first stage chose the dredging projects and the depth of the dredging for each project, and the second stage decided on assigning the budget based on the occurrence of shoaling. In other words, by knowing the expected depth of the projects, the throughput maximization problem is solved by choosing the most beneficial projects. The problem was modeled in a deterministic and probabilistic approach (based on SAA method) by assuming dredging happening in the first year and shoaling effect happening in the next year. In other words, the sum of the system benefit over the first year and the expected benefit over the second year is maximized (12). However, the effect of locks and dams and the network connectivity had not been considered in the model. Within a similar context, Ahadi et al. (17) uses a set of scenarios of shoaling in its developed optimization model, but it is not on a multimodal freight network.

3 Problem Definition

The main objective of this section is to develop a mathematical model for budget allocation in the context of a multimodal network involving waterways, considering the maintenance activities, such as dredging, shoaling rate, and lock and dam repair. Note that unscheduled delays at locks and dams due to lack of repair as well as impact of dredging (shoaling) on the waterway capacity should be addressed. Some detailed description is provided below to facilitate reading.

- **Dredging**: Performing dredging increases the throughput of the system, allows larger vessels and decreases the number of vessels needed to carry the cargo. The decrease in numbers of vessels reduce the total costs of transporting goods, which shows its effectiveness in the objective function. Also, the increase in throughput allows higher tonnage to be passed through the channel, which could put a strain on the land side link capacity.

- **Shoaling**: The probabilistic behavior of shoaling should be modeled in a stochastic way. Tentatively for now, a two-stage deterministic proxy method is proposed, in which the dredging depth will be selected to minimize the expected value of total cost at the end of the second stage. In other words, the depth in the second stage is known, and the optimal decision will be made based on that.

- **Lock and dam**: The delay at locks and dams is random, which means that by improving lock and dams, there is still a chance for having the delay. To address this issue, the probability of occurrence of failure should be obtained for each improvement in the system.To linearize the interaction of delay and repair improvement, the mean reduced delay for each given repair improvement is assumed known, which by intuitive observation shows a decreasing rate of return with repair.

In summary, for providing an acceptable and efficient level of maintenance service of the waterway system, continuous maintenance of waterway elements is necessary. To optimally allocate the available budget to different decisions, a minimization problem formulation is proposed.

4 Methodological Approach

A mixed integer model is developed to minimize total maintenance cost, including waterway dredging and lock/dam repair. The cost considered comes from both stages. Again, partial dredging such as dredging 2 feet as the decision for a 9 feet dredging request has accordingly $\frac{2}{9}$ of the total requested dredging cost for the initial 9-ft project. In the following, the notations, the objective function, variables, the parameters, and the constraints are explained.

4.1 Notations

In general, the sub- or superscripts below used in the later notations are defined as follows.

i	*Waterway segment i, such as elements of a route,the route,the lock and dam.*
k	*k foot of dredging.*
$1, 2$	*Showing the stochastic behaviors in the first and second stage.*

4.2 Objective function

$$\min \sum_{i} C^{i}_{max,1} + C^{i}_{max,2} \tag{1}$$

4.3 Decision variables

Dredging

$$d_i^k = \begin{cases} 0, & \text{otherwise} \\ 1, & \textit{if segment } i \textit{ is dredged for } k \textit{ feet} \end{cases} \tag{2}$$

$$x_{i,1}^k = \begin{cases} 0, & \text{otherwise} \\ 1, & \textit{if all the segments along route } i \textit{ are dredged for } k \textit{ feet or deeper} \\ & \textit{at the first stage.} \end{cases} \tag{3}$$

$$x_{i,2}^k = \begin{cases} 0, & \text{otherwise} \\ 1, & \textit{if all the segments along route } i \textit{ are kept for } k \textit{ feet or deeper} \\ & \textit{at the second stage.} \end{cases}$$

Lock and dam

l_i *the amount of improvement on lock i.*
y_i *the linear approximation of mean reduced delay on lock i.*

Costs

$C^i_{max,1}$ *the maximum cost on route i at stage one.*
$C^i_{max,2}$ *the maximum cost on route i at stage two.*

4.4 Parameters

Dredging

C_i^d *cost of one foot dredging on segment i.*
B_i^k *added tonnage to the draft k of segment i.*

Trips and connectivity

N_i^k *the number of trips that should be done on route i with draft k to meet all the demand.*
P_i^k *the proportion of the tonnage on route i that is attributable to the OD k.*
a_p *the capacity on land side route p.*
C_i^t *the average cost of trip per mile on route i.*

Sets

$L(m)$	*the set of all connected land side routes.*
R	*the set of all waterway routes.*
OD	*the set of all origin-destination pairs*
$R(i)$	*the set of alternative (water) routes serving an OD i.*
S	*the set of all segments.*
$S(i)$	*the set of all segments on route i.*

Lock and dam

Cl_i	*cost of a unit of maintenance on lock i.*
V	*cost of one hour delay.*
a_j	*the start value at the start of each linearized piece (j=0, 10 20, 50).* * 50 is the maximum theoretical improvement scale.*

Numbers

M	*the Big M.*
U	*an upper bound of delay on all locks.*

4.5 Constraints

1. ***Total budget***

$$\sum_k \sum_i d_i^k C_i^{d,k} + \sum_i l_i C_i^l \leq B$$

2. ***One dredging depth for each segment***

$$\sum_k d_i^k \leq 1 \qquad (\forall i \in S)$$

3. ***One depth for each route***

$$\sum_k x_{i,1}^k \leq 1 \qquad (\forall i \in R)$$
$$\sum_k x_{i,2}^k \leq 1 \qquad (\forall i \in R)$$

4. ***Choosing the segment of a route***

$$\sum_k k x_{i,1}^k \leq \sum_k k d_j^k \qquad (\forall i \in R, j \in S(i))$$
$$\sum_k k x_{i,2}^k \leq \sum_k E(k) d_j^k \qquad (\forall i \in R, j \in S(i))$$

5. ***Trips and connectivity***

$$\sum_{i \in R(m)} \sum_{k} x_{i,1}^{k} B_i^k P_i^m \leq D_m \qquad (\forall m \in OD)$$

$$\sum_{i \in R(m)} \sum_{k} x_{i,2}^{k} B_i^k P_i^m \leq D_m \qquad (\forall m \in OD)$$

$$\sum_{k} \left\{ x_{i,l}^{k} N_i^k C_i^t + \sum_{j \in S(i)} (U - y_j) N_i^k V + (x_{i,1}^{k} - 1) M \right\} \leq C_{max,1}^{i} \qquad (\forall i \in R)$$

$$\sum_{k} \left\{ x_{i,2}^{k} N_i^k C_i^t + \sum_{j \in S(i)} (U - y_j) N_i^k V + (x_{i,2}^{k} - 1) M \right\} \leq C_{max,2}^{i} \qquad (\forall i \in R)$$

6. ***Linearization of costs in the lock and dams***

$$y_i = \sum_j w_{ij} f(a_i) \qquad (\forall i \in locks)$$

$$l_i = \sum_j w_{ij} a_j \qquad (\forall i \in locks)$$

$$\sum_j w_{ij} = 1 \qquad (\forall i \in locks)$$

$$Cl_i = \begin{cases} 12,000 \\ 0.622 l_i^2 + 12.6 l_i + 1,216 \end{cases} \qquad (\forall i \in locks)$$

7. ***Binary and non-negativity***

$$x_{i,1}^{k}, x_{i,2}^{k}, d_i^k : binary \qquad (\forall i \in R)$$

$$l_i, C_{max,1}^{i}, C_{max,2}^{i} \leq 1 \qquad (\forall i \in R)$$

The model tries to minimize the cost of dredging and the cost of delay at the locks and dams using a deterministic model. The constraints are written in different blocks for clarity. The first block is limiting the total costs of dredging, and lock and dam maintenance to the available budget. The second block shows that each segment should have one depth of dredging. The third block dictates one and only one depth of dredging for each section of the waterway. The fourth block prescribes that each route should have one maximum effective depth of dredging at the first and second stages, respectively. It should be mentioned that the expected remaining draft after shoaling is considered in the second stage. The first constraint in the fifth block makes demand of each OD flow satisfied. The second and third constraints in the fifth block prescribe the total cost for each stage, which is to be minimized. The cost of each route is calculated based on the number of trips using the route with selected draft, and the delay at all the lock and dams along the route.

The sixth block is about constraints regarding linearization of locks and dams' maintenance costs. This cost is originally formulated based on a non-linear function of the mean reduced delay (y_i), which should be linearized to be solved by the software. So, a piecewise linearization method is utilized to quantify the amount of improvement gained over the different mean reduced delay by using multiple linear functions. In other words, five sections are created (which are shown by j in the model), and the value of the function is determined at the borders($f(a_j)$). It should be mentioned that the cost of improvement at each lock and dam is formulated in two scenarios, based on a linear function, and a non-linear function with the initial cost.

4.6 Data and parameters' description

The developed model is applied to the Ohio River basin. The Ohio River plays an important role in the waterway system of the United States. It connects six states of Illinois, Indiana, Kentucky, Ohio, West Virginia, and Pennsylvania. The major cargo shipped through the Ohio River Basin is coal for the rich reserve in this area. In addition, petroleum, chemicals, and grains are shipped through this basin (22). The developed model in this study applies to the main stem of the Ohio River, which has about 700 miles and consists of 21 lock and dams. The main stem in this study is divided into 51 segments. Figure 1 shows the geographic layout of the river while Figure 2 illustrates the topological connectivity of its components including the river sections, the highway and railway serving to the freight ODs. Khodakrami (13) provides partially explanation to the data used in this study. For space and time, we do not provide detailed discussion about the data here.

In addition to the parameters and sets as described in the notations earlier, needed data includes the number of vessels on each route for different draft depth. The change in the number of vessels used for carrying the cargo at each draft depth is calculated by having the tonnage carried through the routes at each draft, and the average load factor of the vessel for each draft.

To consider the connectivity between the land side links and the waterway network, all the major land side ODs and the major highways and railroads that connect to the waterway are considered. The portion of cargo that is carried through each route is prepared. The available capacities of land side modes are also estimated.

Moreover, to measure the delay at each lock and dam, the amount of improvement and the associated reduced delays are estimated by assuming a non-linear function. A power function is used to quantify the effect of one unit of improvement on the reduced delay.

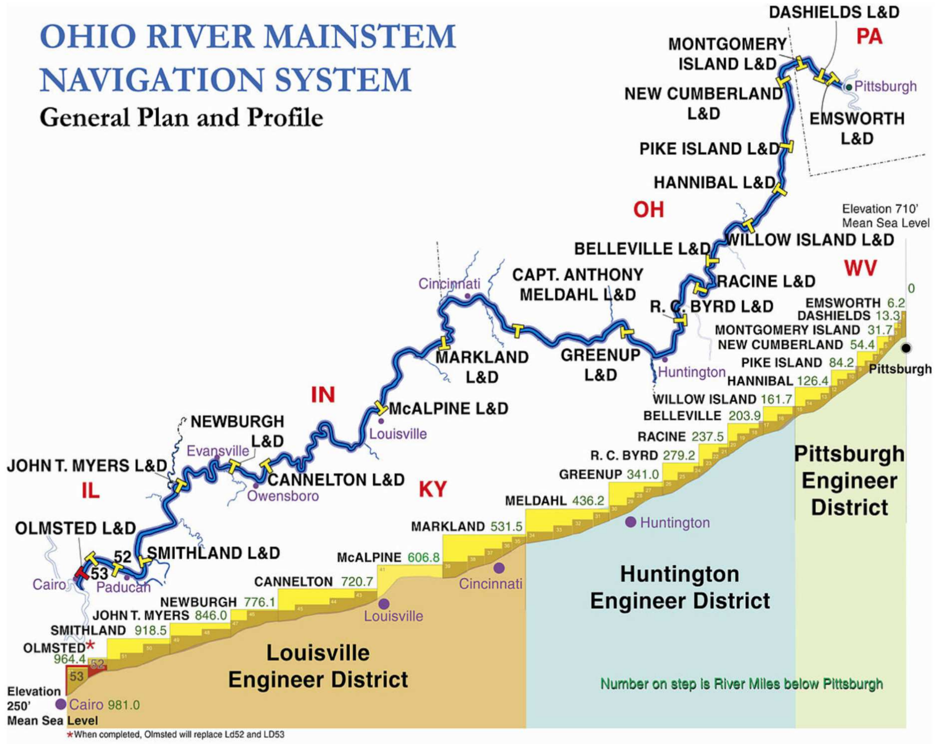

Figure 1: The Ohio River Corridor

The costs of improvement at each lock and dam is formulated in two scenarios, based on a linear function, and a non-linear function with the initial cost, as shown in in the constraints of the formulation earlier. It should be mentioned that different parameters for the C_i^t and V are tested to assess their importance to the robustness of the optimal solution. The mixed integer linear programming model is be solved with `Cplex`.

5 Results and Findings

The model is tested with multiple combinations of C_i^t and V. The tests show that the solutions are not sensitive to these parameters. Thus, the model is solved by changing the total amount of available budget into five different scenarios, each having an amount allocated to the locks and dams. Table 1 summarizes the test results.

In Table 1, budget scenario is for the fraction of the total budget to satisfy all the maintenance requests that is available. For example, 1.0 means a budget that satisfies all the maintenance requests. A value of 0.2 means only 20 percent of the total requested budget is available. The column for the available budget is the total budget that can be budgeted for the maintenance. Its last number is the total budgeted requested for the year. Upper from it, it is the product between the 'budget scenario' value and the last

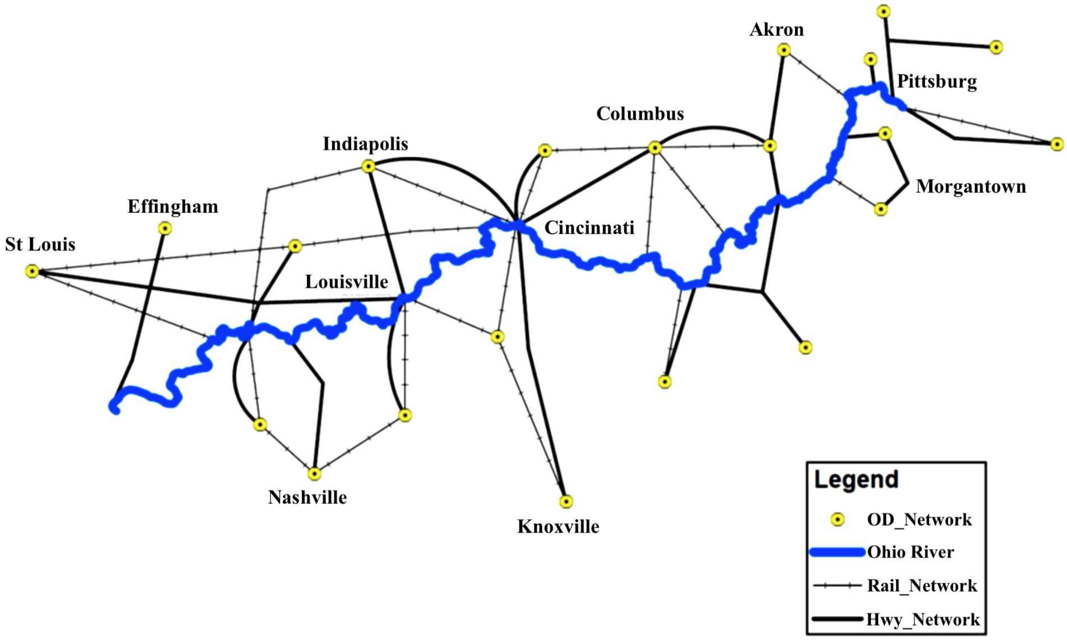

Figure 2: Schematic view of the Ohio River in the developed model

Table 1: The optimal results of the model

Budget scenario	Available budget ($)	Objective function ($)	Allocated budget to lock ($)	Lock's fund allocated (%)	Improvement of OBJ (%)	Optimal gap (%)
Linear costs maintenance function						
0.2	473,813	94,706,653	7,862	1.66	27.45	0.5
0.4	947,626	78,905,067	453,154	47.82	6.19	0.5
0.6	1,421,439	74,927,125	897,552	63.14	0.83	0.5
0.8	1,895,252	74,625,598	1,260,000	66.48	0.43	0.4
1	2,369,065	74,307,763	1,260,000	53.19	0.00	0.0
Non-linear costs maintenance function						
0.2	473,813	135,603,533	0	0.00	24.39	1.0
0.4	947,626	126,828,910	392,838	41.45	16.34	1.2
0.6	1,421,439	119,684,094	894,076	62.90	9.79	0.6
0.8	1,895,252	113,768,892	1,366,405	72.10	4.36	0.5
1	2,369,065	109,015,375	1,845,179	77.89	0.00	0.5

(largest) available budget in the column. The optimality gap is the parameter setup in the Cplex. 0.5% means that the final Cplex solution could have an optimality gap up to 0.5%.

By defining the different budget level and the linear locks' maintenance function, the allocated budget for maintaining lock and dams system varies. It shows that a small portion of the budget is assigned to locks and dams when the total available budget is very low; however, by increasing the available budget, the fund mainly goes for the maintenance of locks and dams. Table 1 shows the trend of allocating budget for locks and dams in different budget scenarios. The table shows that the change in budget allocation to the locks and dams has a steep slope at the beginning, while by increasing the budget, the slope gradually decreases. In addition, when considering the non-linear maintenance costs, the results show that by increasing the total lock/dam maintenance budget, the cost of the system increases significantly and benefits from the dredging operation could not merely compensate the system costs beyond a certain threshold.

6 Recommendations and Conclusion

The United States waterway system carries a significant percentage of the national freight. Two different maintenance operations are performed annually to rehabilitate the waterway system and keep it functional: dredging which removes sediments in the waterway to restore the lost navigational draft depth, and locks and dams repair due to the aging and deterioration of them. Different maintenance project requests different budget to perform the maintenance. All the projects together are subject to a limited budget. This study attempts to solve this special knapsack problem considering the budget constraints, system randomness, and network connectivity to minimize the costs of operations in order to choose the most beneficial projects. The network connectivity defines in this case the inter-dependencies between projects on different segments of the waterway, which is a distinct feature of this research problem. The random-behavior of shoaling, which occurs after performing the dredging in year one, also defines the research problem by adding this unique dimension.

A multimodal network formulation is developed as a deterministic means to solve this essentially stochastic problem. A piece-wise linearization is used for the cost of delay at locks and dams. By using the data from the Ohio River basin network, the model is solved with Cplex. The results show that the optimal solution is not dependant on the perceived value of time in vessel delay at locks and dams, nor on the costs of vessels. It shows a clear preference to locks and dams repair over dredging operations in the optimal allocation of the maintenance budget.

Note that the model and case study are illustrative. For practical implementation, more detailed work would be needed such as addition of Ohio River Tributaries, such as ones connected to Morgantown and Nashville. The same model still applies.

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