CLAMSHELL MECHANICAL DREDGE PRODUCTION AND COST ESTIMATION

A Thesis

by

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ABSTRACT

Mechanical clamshell dredges are a versatile platform for performing dredging operations. The relative mobility, suitability of use for a variety of sediment types, and deep dredging capability result in the use of mechanical clamshell dredges for a variety of dredging projects. Accurate estimates of overall dredging project costs are important for both dredging contractors and entities soliciting dredging projects. This thesis presents a method for determining the production rate and dredging project duration for a mechanical clamshell dredge. The production rate is combined with cost inputs to determine an overall project cost.

The methods and cost inputs are developed with a Microsoft Excel-based estimating program. The program utilizes methodologies for estimating digging production rate and hauling production rate, and utilizes cost inputs from a variety of sources. The program allows for reasonably accurate estimates when limited information about the project or dredge specifics is known. At the same time, the program allows the user to incorporate project-specific knowledge in order to refine the project estimate.

The results of the estimating program are compared with actual winning bids from eight recently completed dredging projects in the United States as well as independent government estimates performed by the United States Army Corps of Engineers. The estimating program generated a mean absolute percentage difference of 23.8% from the winning bids, compared to 33.5% for the government estimates. When compared with a previously developed clamshell dredge estimating program, the mean absolute percentage difference was 14.0%.

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Contributors

Part 1, faculty committee recognition

This work was supervised by a thesis committee consisting of Professor Randall of the Department of Ocean Engineering, Professor Kaihatu of the Department of Civil Engineering and Professor Stössel of the Department of Oceanography.

Part 2, student/collaborator contributions

All work for the thesis was completed independently by the student.

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NOMENCLATURE

$\%_{fill}$	hopper utilization factor
A	area covered from one dredging position
AE	Adair (2004) estimate
B	sediment bulking factor
C	bucket capacity
CDS	Center for Dredging Studies
CE	Center for Dredging Studies (2016) estimate
CEDEP	Cost Engineering Dredge Estimating Program
D	distance to the placement site
d	digging depth
f_a	delay factor for advancing dredge
FY	Fiscal Year
f_h	delay factor for changing hoppers
f_{m-m},	bucket fill factor for mud
f_{m-ls}	bucket fill factor for loose sand
f_{m-cs}	bucket fill factor for compacted sand
f_{m-sc}	bucket fill factor for sand and clay
f_{m-s}	bucket fill factor for stone
f_{m-br}	bucket fill factor for broken rock
GE / IGE / IGCE	Government Estimate / Independent Government Estimate / Independent Government Cost Estimate

H	hopper capacity
h_b	freeboard height of barge
N	number of hoppers
NDC	Navigation Data Center
P_{haul}	hauling production rate per hopper
P_{max}	maximum digging production rate
P_{nom}	nominal digging production rate
T_{cycle}	cycle time; period to complete a dredging cycle
T_{fill}	time required to fill hopper
T_{haul}	time required for hopper to transit to and from placement site
t_a	time required to advance the dredge
t_{close}	time to close clamshell bucket
t_h	time required to change hoppers
t_{open}	time to open clamshell bucket
t_{prep}	time required to prepare hopper for towing
t_{remove}	time required to remove the tug
USACE	United States Army Corps of Engineers
u_{fall}	speed at which clamshell bucket is lowered
u_{raise}	speed at which clamshell bucket is raised
v_{empty}	speed of the hopper when empty
v_{full}	speed of the hopper when filled
WB	Winning Bid

z	thickness of dredged layer
θ_{sw}	Swing angle
ω_{sw}	angular velocity of crane

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INTRODUCTION

Dredging Overview and History

According to Randall (2016), dredging is the removal of bottom sediments from streams, rivers, lakes, coastal waters, and oceans, and the resulting dredged material is then transported by ship, barge, or pipeline to a designated placement site on land or in the water where it is placed. Dredges can be either mechanical or hydraulic. A hydraulic dredge utilizes a mechanism (commonly a drag head or cutter-head) to loosen sediment particles. These loosened particles then mix with the nearby water to form slurry. The slurry is captured by a pump. Using water, the slurry is transported into a hopper, a barge (also referred to as a scow) or transported via pipeline to a placement area. By contrast, a mechanical dredge mechanically excavates the dredged material by closing the clamshell on the bottom sediment, raises the clamshell out of the water and then places the dredged material and some water in a barge (also referred to as a scow or hopper).

Mechanical dredges are classified as dipper, bucket (clamshell), or bucket ladder dredges, depending on the means of excavation, with bucket dredges further classified as either clamshell, dragline, or backhoe, depending on the equipment used. The clamshell dredge is the most common mechanical dredging equipment used in the United States (Randall, 2016). Figure 1 depicts a mechanical clamshell dredge in action.

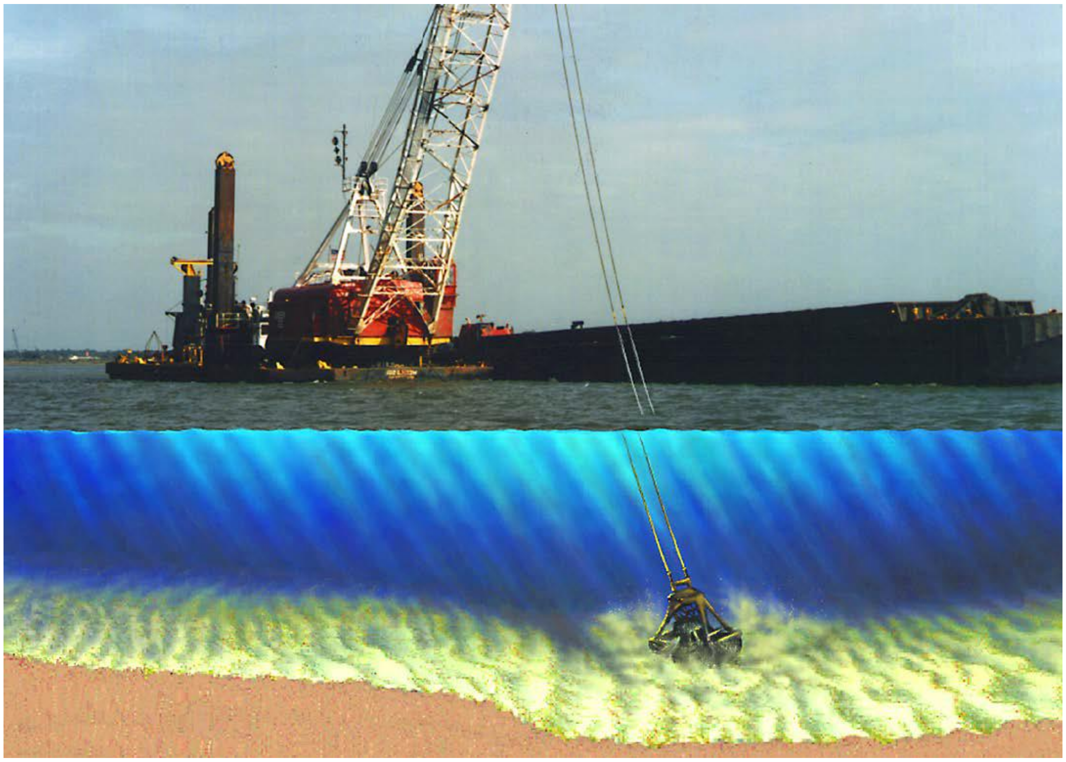

Figure 1: Depiction of a Clamshell Mechanical Dredge (Reprinted from US Army Corps of Engineers (2015))

The mechanical dredge consists of a barge with a crane mounted on it. Most clamshell dredges are not self-propelled, and rely on tugboats for movement. However, in order to minimize the frequency of tugboat usage, most non-propelled dredges will utilize spuds. A spud is a cylindrical or square pile that passes through the top of the dredge, and can be lowered into the channel bottom. The spud allows the dredge to rotate about the point where the spud is lowered. A typical dredge will have three spuds, with one spud located towards the bow, and two towards the stern. The stern spuds are configured so they are symmetric about the centerline. Use of the spuds in conjunction with the ship's anchors allows the dredge to "walk" itself forward without the use of a tugboat (Randall, 2016). Figure 2 is a profile view of a typical clamshell dredge. It depicts the dredge with the crane towards the stern, the deckhouse towards the bow, and spuds located fore and aft.

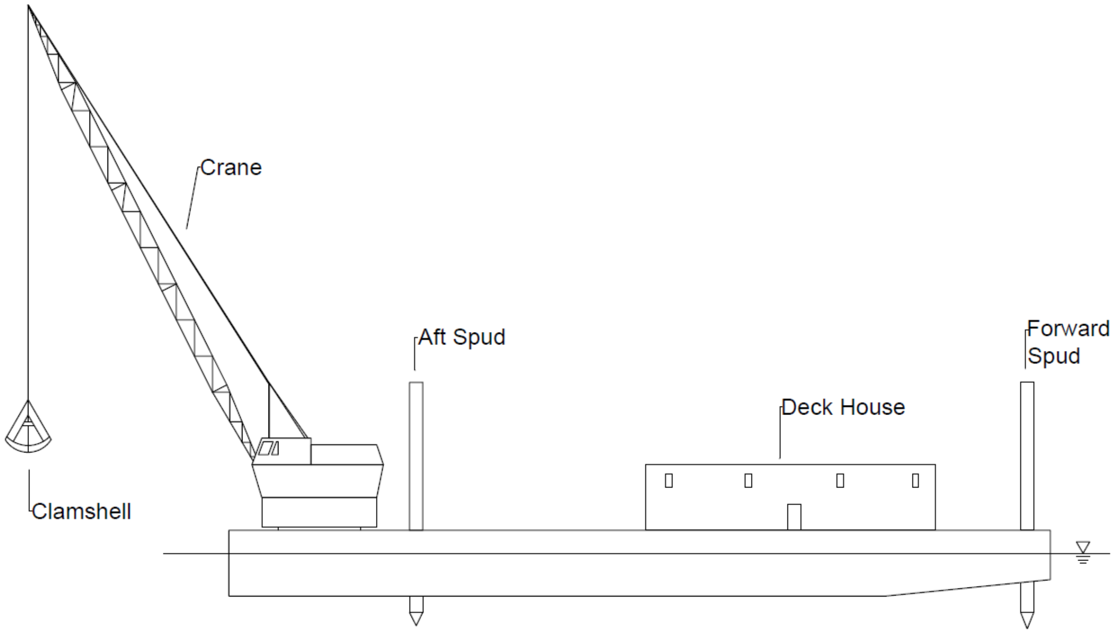

Figure 2: Profile View of a Typical Clamshell Dredge.

The primary purpose of dredging is to maintain navigation channels at proper depths in order to allow the safe passage of vessel traffic through the navigation waterways. According to the United States Army Corps of Engineers (USACE), 89.07% of the volume dredged in the United States in fiscal year 2015 was maintenance dredging (NDC, 2016). Another common objective of dredging projects is to deepen existing navigable waterways. For example, several ports on the East Coast and Gulf Coast of the US have ongoing or planned dredging projects to deepen the existing ports in order to accommodate larger vessel traffic in response to the Panama Canal expansion, and the trend in the shipping industry toward larger cargo vessels (Bhadury, 2016). Dredging projects can also have the objective of land reclamation, such as the Chinese government's recent efforts in the South China Sea (Johnson, 2016), or removal of contaminated sediments.

The history of mechanical dredging traces back thousands of years. The earliest dredging projects relied on manual labor, buckets, and shovels, and was shore-based (Huston, 1970). Later, the buckets and shovels were deployed from vessels, with the removed sediment being loaded onto the vessel, usually a barge, and then placed on shore. Around 1400 AD, vessels were outfitted with scrapers. These scrapers were dragged along the waterway bottom, thus disturbing the sediment. This disturbed sediment was then carried away by natural currents. This method of dredging is known as agitation dredging, and is rarely used today, due to the unpredictability of the dredging sediment's final location, and the adverse environmental impacts. Further improvements in dredging technology led to the bucket ladder. The bucket ladder consisted of a series of buckets attached to a conveyor. This conveyor assembly was lowered into the water, allowing the buckets to scoop sediment from the bottom. The buckets were then emptied into an attached barge or scow. Initially human-powered, the bucket ladder was later modified to utilize horsepower (Huston, 1970).

During the 19th century, mechanical excavation experienced major developments (Bray et al, 1997), leading to the modern derrick barge, which is the typical platform for the modern mechanical dredge. More recent technological developments related to mechanical dredging include the use of the Differential Global Position System (DGPS) to track the bucket position. This allows dredge operators to track the position of the clamshell to accuracies on the order of centimeters, with accuracies of 15 cm in the vertical direction and 10 cm in the horizontal direction attainable (Palermo et al, 2004).

An important term, when discussing dredging projects is production. Production, also known as output, in the context of dredging, is the rate at which in-situ sediment is removed from the bottom, expressed in terms of unit volume per unit time. This definition of production is used throughout the thesis.

Dredging Projects and Estimates

In the United States, most dredging projects are performed by dredging contractors, under the oversight of the US Army Corps of Engineers (USACE). The USACE is also responsible for issuing permits for dredging projects. The Corps of Engineers generally utilizes a competitive bidding process, whereby the government solicits interested contractors to submit a proposal for a particular contract. The Corps of Engineers then evaluates the proposals, and generally selects the lowest reasonable price. Since cost becomes the factor by which the government differentiates between the various offers it receives, a proper understanding of a dredging project's scope of work is crucial. This understanding informs both the contractor's proposal, as well as the independent government cost estimate (IGCE). The IGCE provides the basis for the government to obtain funding for a dredging project prior to awarding a contract, and also is the basis the government uses to determine the reasonableness of a contractor's proposal.

In general, dredging contracts written by the Corps of Engineers consist of two contract line items or work items. The first is a mobilization/demobilization item, and the second is a line item to dredge and dispose a certain in-situ volume of bottom sediment. Contracts will also usually contain one or more option items, which allow for dredging additional volumes of material, environmental monitoring and deployment of environmental controls. The mobilization/demobilization is priced as a single job, while the dredge work item is priced on a per cubic-yard basis. Dredging contracts generally require that the contractor remove 100% of the dredged material identified in the contract specifications, however the contract allows for an over-dredging allowance. The contractor is allowed a certain depth of removal beyond the target dredging depth, whereby the contractor will get paid on a per cubic-yard basis. Figure 3 illustrates this concept, known as a dredging prism. Since the purpose of dredging is primarily the maintenance or deepening of navigation channels, the dredging prism ensures that the desired channel depth is achieved without requiring a level of precision that is not feasible for a dredge to achieve.

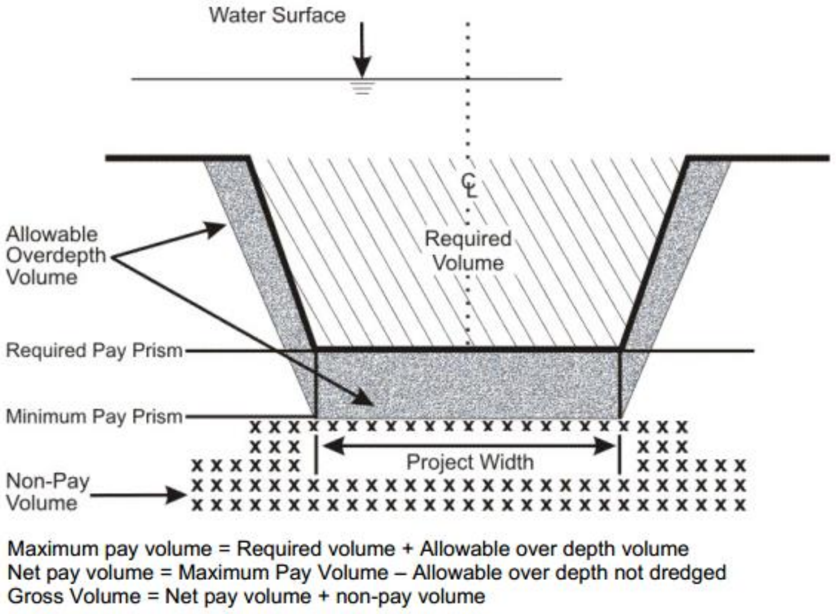

Figure 3: Dredge Prism Illustration (Reprinted from US Army Corps of Engineers (2008))

The US Army Corps of Engineers has its own proprietary program for developing cost estimates for dredging projects, known as the Cost Engineering Dredge Estimating Program (CEDEP) (USACE, 2008). Similarly, contractors have their own proprietary methods for developing cost estimates. Both parties seek to keep their estimating procedures proprietary for differing purposes. In the contractor's case, being able to provide the lowest reasonable price on a proposal allows the contractor to maintain a competitive advantage. The contractor has the best knowledge of its equipment, its production capacities and its costs. Public knowledge of its estimating methods and information would allow potential competitors to undercut that advantage.

Similarly, the Corps of Engineers also has an interest in limiting distribution of CEDEP. The government has limited knowledge regarding the contractor's equipment, production capacities, and costs, and thus must make assumptions when developing its IGCE. If the methodology behind CEDEP was understood by contractors, they could exploit that knowledge to increase their bid costs in areas where their estimate was lower than the government's.

Although the Corps of Engineers usually oversees dredging projects, the project costs are usually shared amongst other entities, or sponsors, typically a state or local government. These sponsors have an interest in estimating a dredging project's cost early on in the planning process, even before the Corps of Engineers conducts their estimate to determine the feasibility of the project and to allocate funding accordingly. The dredging cost and production estimates developed by Texas A&M's Center for Dredging Studies (CDS, 2016) provide a valuable tool for sponsors, serving as a useful estimating tool for predicting production timelines and project costs.

The Mechanical Clamshell Dredge

The clamshell dredge has several advantages over its hydraulic counterparts. A mechanical dredge is well-suited for dredging in areas where maneuverability is restricted. Unlike a hopper dredge, which is self-propelled, a typical clamshell dredge consists of a crane mounted on a barge. The barge can be maneuvered where needed by a tugboat. A barge generally has a shallower draft than a hopper dredge, further improving the clamshell barge's feasibility to work in shallow areas or areas where maneuverability there is limited maneuverability. Mechanical dredges are also useful for projects with deep digging depths. Unlike a hydraulic dredge, whose digging depth is limited by the number of pumps and the length of the discharge piping, a mechanical clamshell dredge is limited by the length of the cable for raising and lowering the clamshell, also known as a grab. Thus, for dredges of comparable size, a mechanical clamshell dredge has superior deep dredging capability (Bray et al, 1997). Another advantage of the clamshell dredge is its potential to limit sediment resuspension with the use of an environmental clamshell bucket, compared to hopper dredging. This is very important when dredging in areas in close proximity to sensitive environmental habitats; areas where strict water quality limits, especially turbidity limits, must be maintained; and when performing environmental dredging.

Environmental dredging is the removal of contaminated sediment. The contamination can result from various industrial, agricultural, and municipal processes, and includes substances such as heavy metals, polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAH) (Randall, 2016). While the contaminated sediment removal only accounts for about one percent to four percent of the annual volume of sediments annually dredged from port and ship channels in the United States, these contaminated sediments require specialized handling and disposal (Randall, 2016). As a result, dredging contaminated sediment is significantly more expensive compared to dredging uncontaminated sediment. According to Cushing (1999), environmental dredging costs in the United States range from \$58 to \$2,409 per cubic meter (\$44 to \$1842 per cubic yard). By contrast, uncontaminated sediment removal ranges from \$3 to \$21 per cubic meter (\$2.29 to \$16.06 per cubic yard) (Blazquez et al, 2001).

Mechanical dredging is a preferred method for accomplishing environmental dredging as it extracts less water for a given in-situ sediment volume compared with hydraulic dredging methods. Oftentimes, an environmental dredging project will utilized a specialized bucket that limits sediment resuspension during the dredging process. Some of the features that the environmental bucket includes are overlapping sideplates, rubber seals and an enclosed bucket, all of which minimize sediment resuspension. The environmental bucket also includes a venting system to minimize the amount of water removed during the dredging process, which decreases the amount of contaminated water requiring treatment. Some environmental buckets also utilizes a "level-cut" system that allows for a uniform cut depth, whereas a traditional bucket will remove more material near the center of the cut and leave material at the sides of the cut. This leads to a "pothole" effect, which can result in significant contaminated material being left behind and/or failure to meet cleanup requirements (Bergeron et al, 2000).

The main drawback of a mechanical dredge is its limited production rates. A hydraulic dredge generally can achieve sediment removal at a greater rate than a mechanical dredge. A mechanical dredge is also less conducive for upland disposal, as the dredged material requires re-handling prior to disposal. The re-handling increases the complexity and cost of the dredging process, as more equipment is required, and can also reduce the production rate, thereby further increasing costs.

REVIEW OF LITERATURE

Production and cost estimating methods for dredging projects traditionally have not been readily available to the general public, for reasons explained previously. The Army Corps of Engineers (USACE, 2008) has published guidance for estimating dredging projects as part of overall guidance for civil works estimating. This guidance provides useful information such as factors to consider when developing a cost estimate, a brief general explanation for calculating production rates for mechanical and hydraulic dredges, and also lists some of the costs to consider when developing cost estimates. However, the guidance encourages the reader to consult resources that are not readily available, such as historical dredge project information, including the daily dredge reports, and CEDEP, which is the Corps of Engineers dredge estimating program.

Bray et al (1997) first introduces production and cost estimating techniques that are available to the public, and is useful in quantifying project costs that are not readily available. The authors approach dredge production estimating by identifying the dredge productive unit, dividing it by the appropriate cycle time, and applying applicable modification factors. The authors also provide techniques for calculating production rates for various dredge types, including the mechanical clamshell dredge. The production rate estimate methodology that this thesis uses relies on these techniques.

Additionally, Bray et al (1997) explore the variety of costs one must consider when estimating a dredging project, and provide techniques for calculating these costs, such as mobilization and demobilization, plant capital costs, and plant running costs. Of particular usefulness in developing the cost estimating program were the techniques for estimating fuel and lubricant costs, maintenance and repairs, capital costs of dredges, insurance, overhead, and financial charges (depreciation, amortization, and interest on capital).

The Center for Dredging Studies (CDS) developed the first publicly available general cost estimation program for dredges (Miertschin and Randall, 1998). This estimating program was developed for cutter suction dredges, and later expanded to include hopper dredges, (Belesimo, 2000) and clamshell dredges (Adair and Randall, 2006). Over the past twenty years, the CDS has built upon these estimating programs, with the most recently completed program published by Wowtschuk (2016). The methodology and program functionality first developed by Miertschin and Randall (1998) have influenced the follow-on CDS dredge estimating programs, and this thesis is no exception.

Adair (2004) was the first CDS dredge estimating program developed for clamshell dredges, and uses the techniques from Bray et al (1997) in developing the estimating program. It improves upon the concept of bucket fill factor by applying the work of Bray et al (1997) as well as Emmons (2001) in this area over a wide range of clamshell bucket sizes and sediment types. It also develops regional cost factors based on historical dredging projects and applies inflation-adjustment factors. Follow-on CDS dredging cost estimating programs, have built upon these concepts, including this thesis.

Jones (2013) provides a concise overview on estimating mechanical dredging projects. The author discusses dredging quantity measurements, the various factors to consider when pricing a mechanical dredging job, the different types of costs an estimator must account for, and production rate estimation techniques. The author provides an example scenario that calculates quantity takeoff, equipment costs, labor costs, and production rate. Jones (2013) expands on the concept of a hauling production rate, outlined previously by the Army Corps of Engineers (USACE, 2008), which was particularly useful for incorporating into the production estimating methodology.

Wowtschuk (2016) is the most recent cost estimating program for dredge projects from the CDS, and focuses on trailing suction hopper dredges. Although the methodologies for calculating production rates are different for mechanical and hopper dredges, there are many similarities in cost estimation for both types of dredging projects. Some of the elements from the hopper dredge estimating program that are directly applicable to clamshell dredging include the fuel price estimation method, and improvements to the regional and inflation cost factors. This thesis incorporates the fuel price estimation method, and builds upon the dredging

DEVELOPING A DREDGING COST ESTIMATE

Overview

Developing a cost estimate for a dredging project consists of two parts. The first part is to develop a production estimate. The production estimate determines how long it will take to complete a dredging project, given the equipment being used for the project, the conditions of the sediment being dredged, and the requirements for dredged material placement. Once the production rate is determined, the estimator can then determine the costs associated with the project (Bray et al, 1997).

The first task is to determine the amount of dredged material to remove, also known as takeoff (Jones, 2013). For example, if the scope of work calls for deepening a navigational channel, the estimator calculates the length, width, and depth of the channel deepening to arrive at the total volume of dredged material to remove. After takeoff, the next step is to estimate production rate. For bucket dredging, the production rate will be a function of the bucket size, sediment type, and the cycle time. Cycle time is the time it takes to maneuver the clamshell into position, lower the clamshell, close the clamshell, raise the clamshell, maneuver the clamshell to the scow, and place the material into the scow. Figure 4 provides a flowchart of the dredge cycle for a clamshell dredge. Mechanical dredge production also depends on the number of barges/scows available, the speed at which they are transported from the dredging site to the placement site and back again, as well as the time to prepare the scow for towing, and removing the tow.

These factors collectively comprise the hauling production rate (Jones, 2013). Without an available scow, the dredge is sitting idle. Similarly, the time it takes to prepare a scow for towing, position the new scow for dredging operations, etc., all reduce the productivity of the dredge.

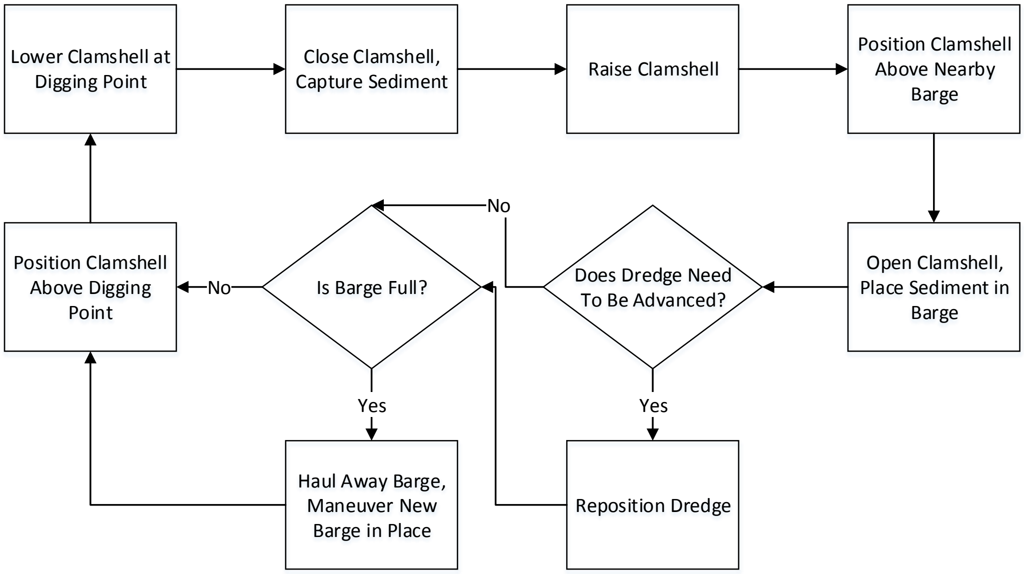

Figure 4: Dredging Cycle Flowchart for Clamshell Dredge

Once the production rate is determined, the project duration can then be calculated by dividing the volume of sediment to be removed by the production. The project duration is then used to determine equipment costs, labor costs, and any material costs. These collectively comprise the direct costs. Some important direct costs that must be accounted for beyond the more apparent production and labor costs include mobilization and demobilization costs, hydrographic surveying, and environmental monitoring. Indirect costs are then estimated as a percentage of the direct costs, and added to the direct costs to determine the total price estimate. Examples of indirect costs include overhead/general and administrative (G&A), profit, and bonding (Jones, 2013).

Production Rate Estimate Methodology

According to Bray et al (1997), the production rate is developed by identifying the basic unit of production, and modifying it for the soil and excavation conditions. Once this is done, the pertinent dredging cycle is identified, and applied to the modified production unit. Finally, reduction factors are applied as needed.

Bucket Capacity

For a mechanical clamshell dredge, the production rate depends primarily on the size of the clamshell bucket being used. Once the clamshell size is known, a bucket fill factor is applied to the volume. With a clamshell dredge, there are actually two modification factors applied. The first factor is a bucket capacity modifier, and is a function of the sediment type being dredged. This factor accounts for the fact that nominal bucket sizes are usually quoted for mud (Bray et al, 1997). Imagine taking a bucket, and filling it with mud, there will be little or no empty space in that bucket. Now take the same bucket, and fill it with large rocks. Even if the bucket were filled by placing the rocks to fit as many as possible, there would still be empty space between the rocks. So although the bucket size is unchanged, the bucket can hold more mud than rock in a single filling, which this factor accounts for.

The second factor is a bucket fill factor, and is a function of the soil type and the bucket capacity. Unlike most other dredges, the digging action depends on the weight of the bucket, and is not powered by the dredge. Both Bray et al (1997) and Emmons (2001) developed bucket fill factors for various bucket sizes and sediment types. However these factors were developed for what are now relatively small bucket sizes. For example, the largest bucket size Bray et al (1997) developed fill factors for was 4 m^3 (5.2 yd^3). In the 15 or 20 years since these factors were developed, the use of larger buckets has become standard practice in the dredging industry, and bucket capacities of 10 to 15 m^3 (13.1 to 19.6 yd^3) are now common, and the use of even larger buckets is not unusual.

To account for the increase in bucket sizes, Adair (2004) developed a method to take the data from Emmons (2001) and Bray et al (1997), and fit it into an exponential curve. Adair's method thus accounted for the fact that bucket fills become more efficient at larger capacities due to the additional bucket weight, but still maintained the accuracy of the factors for smaller bucket sizes.

Adair (2004) presents bucket fill factors for six different sediment classifications: mud, loose sand, compact sand, sand and clay, stones, and broken rocks. Mud refers to fine sediments such as silts and clays, with a particle size of less than 0.075 mm (0.003 in), sands refer to particle sizes of 0.075 mm to 4.75 mm (0.003 in to 0.187 in), stones and broken rocks are particles larger than 4.75 mm (0.187 in) (Briaud, 2013). Stones refer to gravel-sized particles up to cobble-sized particles, and broken rocks refer to cobble-sized particles. According to the Uniform Soil Classification System (USACE, 1960), gravels are defined as particle sizes of 4.76 mm to 76.2 mm (0.187 in to 3 in), and cobbles are defined as particles larger than 76.2 mm (3 in). The distinction between loose and compacted sands is indicative of whether the sediment has been previously loaded, with the compacted sand indicating loading (Adair, 2005). This thesis uses the work of Adair (2004) for determining bucket fill factors.

Adair (2004) provides the following curves for estimating the bucket fill factor for each of the six sediment types. The curves are shown as equations (1) through (6) below,

$$f_{m-\,m} = \ 0.0474 * ln(C) + 0.7255 \tag{1}$$

$$f_{m-ls} = 0.0614 * ln(C) + 0.6607 \tag{2}$$

$$\mathrm{f}_{m-ls} = 0.0933 * ln(\mathrm{C}) + 0.5517 \tag{3}$$

$$f_{m-sc} \ = \ 0.1228 * ln(C) + 0.4214 \tag{4}$$

$$f_{m-s} = 0.1443 * ln(C) + 0.25 \tag{5}$$

$$f_{m-br} = 0.1443 * ln(C) + 0.1 \tag{6}$$

where C is the bucket capacity in cubic meters, and $f_{m\text{-}m}$, $f_{m\text{-}ls}$, $f_{m\text{-}cs}$, $f_{m\text{-}sc}$, $f_{m\text{-}s}$, and $f_{m\text{-}br}$ are the bucket fill factors for mud, loose sand, compacted sand, sand and clay, stone, and broken rock, respectively.

Cycle Time

Once the modified bucket capacity is obtained, the capacity is divided by the dredging cycle time. For a mechanical clamshell dredge, the dredging cycle consists of six steps (Bray et al, 1997): swinging the clamshell to the mark (the point above where digging will occur), lowering the clamshell, closing the clamshell, raising the clamshell, swinging to discharge point (usually a hopper barge), and discharging the dredged material into the hopper. The swing (both to mark and to discharge) is a function of the swing speed and swing angle, the raising and lowering of the clamshell is a function of the crane winch's speed and the digging depth, and closing and opening of the clamshell is a function of the sediment type being dredged. The cycle time is expressed in the form of an equation:

$$T_{cycle} = 2\left(\theta_{sw}/\omega_{sw}\right) + t_{close} + t_{open} + u_{fall}(d + h_b) + u_{raise}(d + h_b) \tag{7}$$

where T_{cycle} is the cycle time, θ_{sw} is the swing angle or angle the crane has to swing between the mark and the discharge, ω_{sw} is the angular velocity of the crane as it rotates between the mark and the barge, t_{close} is the time to close the bucket, t_{open} is the time to open the bucket, u_{fall} is the speed at which the bucket is lowered, u_{raise} is the speed at which the bucket is raised, d is the digging depth, and h_b is the freeboard height of the barge.

For the purposes of constructing the production estimate, constant default values are used. However, the user can modify the values if needed. For example, the speed for raising and lowering the bucket is assumed to be 1 m/s (3.3 ft/s). However, for an environmental dredging project, the speed at which the bucket is raised and lowered may be reduced to 0.3 m/s (1 ft/s) in order to minimize sediment resuspension. Similarly, the bucket opening or closing time can be adjusted based on the bucket size.

Digging Production Rate

Once the modified bucket capacity and cycle time are calculated, the bucket capacity is divided by the cycle time to obtain a nominal digging production rate. The nominal digging production rate represents the output the uninterrupted clamshell dredge would achieve. However, a dredge does not operate uninterrupted. The dredge can only dig a certain area before it must advance to dig the adjacent area. Additionally, once the dredge material fills up the hopper, the filled hopper must be transported to the disposal site, and a new hopper must be put in place for the dredging operation to continue.

To account for the delays in advancing the dredge Bray et al (1997) defines the following delay factor:

$$f_a = \frac{1}{1 + \frac{t_a P_{nom}}{Az}} \tag{8}$$

where f_a is the delay factor for advancing, t_a is the time to advance the dredge, P_{nom} is the nominal digging production rate, A is the area covered from one dredging position, and z is the thickness of the dredged layer.

Similarly, the delay factor for changing hoppers is:

$$f_h = \frac{1}{1 + \frac{t_h f_a P_{nom} B}{H}} \tag{9}$$

where f_h is the delay factor for changing hoppers, t_h is the time required to change hoppers, B is the sediment bulking factor, and H is the hopper capacity. The remaining variables are the same as in equation (8). Once the delay factors are calculated, they are multiplied by the nominal digging production rate and the result is the maximum digging production rate (P_{max}).

$$P_{max} = f_a f_h P_{nom} \tag{10}$$

The maximum digging production rate represents the average hourly output in ideal circumstances, i.e. 100% efficient crew and machinery. Since this is not realistic, a further reduction must be applied to develop an average digging production rate that can be used for the estimate. Bray et al (1997) define further delay factors that account for bad weather, passing vessel traffic, crew and management efficiency, and mechanical breakdowns. Since these factors can vary widely from project to project, an overall delay factor of 85% is used for this thesis. That is, the actual digging production rate used for developing the cost estimate is 85% of the maximum digging production rate.

Hauling Production Rate

It is important to note that usually the production rate is limited by the bucket capacity and the cycle time. However, if the disposal site is a very long distance from the dredging site, the barge availability can become the limiting factor for production rate. This situation is undesirable as the dredge, an expensive piece of equipment to acquire and operate, is sitting idle, while waiting for an available barge. To avoid this situation, it is important to ensure that a sufficient number of barges are available for the project. The software includes a check to ensure that the production rate is limited by the digging rate, and adjusts the number of barges to ensure the number of barges is sufficient for the dredge's production rate, or notifies the user to manually increase the number of barges required.

The time required to fill the hopper can be calculated using the following equation:

$$T_{fill} = \frac{H * \%_{fill}}{B * P_{nom}}$$

(11)

Where T_{fill} is the time required to fill the hopper, H is the hopper capacity, $\%_{fill}$ is a hopper utilization factor, B is the bulking factor, and P_{nom} is the nominal digging production rate. Once the hopper is filled, it must be transported to the placement site. Equation (12) allows for the calculation of the time required to transport the hopper to the placement site:

$$T_{haul} = t_{prep} + D/v_{full} + t_{empty} + D/v_{empty} + t_{remove} \tag{12}$$

Where T_{haul} is the time required for the hopper to transit to and from the placement site, t_{prep} is the time required to prepare the hopper for tow, D is the distance to the placement site, v_{full} is the speed of the hopper when filled, v_{empty} is the speed of the hopper when empty, and t_{remove} is the time required to remove the tug.

The hauling production rate is the hopper capacity divided by the sum of the time required to fill the hopper and the time required for the hopper to transit to and from the placement site, or:

$$P_{haul} = \frac{H}{T_{fill} + T_{haul}}$$

(13)

where P_{haul} is the hauling production rate per hopper, and the remaining variables are the same as in previous equations (11) and (12).

To ensure that the dredge is not idle, the digging production rate should be less than the total hopper production rate, or:

$$P_{max} < N * P_{haul} \tag{14}$$

where P_{max} is the maximum digging production rate and N is the number of hoppers. To fully utilize the dredge, at least two hoppers will be needed. If the time required to fill the hopper is less than the hauling time, then N should be increased by one.

Cost Estimate Methodology

Overview

Once the production rate is known, the project length can be determined. The project length is a necessary component for determining how much a project will cost. Many of the costs associated with a dredging project can be estimated as a cost per day. Multiply these costs by the project length to obtain the total "recurring" costs. Then add any non-recurring costs, such as mobilization and demobilization, apply the appropriate inflation and location factors, and the result is a total dredging project cost estimate.

The costs considered when developing the cost estimate program for this thesis were mobilization and demobilization costs; the capital cost of the dredge; the cost of renting and operating workboats, tugs, and barges; fuel and lubricant costs; labor costs; maintenance and repair costs; depreciation, overhead, insurance and bonding costs. Once all of these costs were developed, a reasonable profit is applied. For the purposes of the estimating program, a default profit of 10% is assumed.

After the total cost is developed, a yearly index is applied to the total, to account for inflation. A location factor is also developed to account for the variations in costs from location to location, such as wage rates, equipment rental costs, and fuel costs.

Mobilization and Demobilization Costs

Mobilization costs are very difficult to predict. There are many factors that vary based on the contractor, the job location, and the specifics of the dredging project. Since most clamshell dredges are not self-propelled, they need to be transported to and from the job site, and may require set-up and tear down. There is also the cost of transporting personnel to and from the job site, as well as lost revenue during this time when the dredge could otherwise be employed. Due to the variability of mobilization costs, this program developed a default value for dredging mobilization and demobilization, based on a review of eight recent clamshell dredging projects. The default value is a percentage of the winning bid value that was for non-mobilization/demobilization costs. It was determined by taking the value of the mobilization/demobilization contract line item and dividing it by the total remaining contract value (i.e. total contract value minus the mobilization and demobilization costs). This process was applied for each of the eight contracts, and the median value of the results, 10.2%, was used. As a comparison, a similar process was conducted for government estimates. The government estimates had a median value of 12.2% of the remaining contract value.

Overall, of the eight projects compared, the mobilization/demobilization cost percentage yielded mostly consistent results. Four of the projects had government estimates and winning bids for mobilization/demobilization percentages within 2% (e.g.

winning bid had mobilization/demobilization costs as 10.2% of remaining project cost, government estimate had mobilization/demobilization costs as 8.4% of remaining project costs), three ranging from 2-10%, two ranging from 10-15%, and one instance where the difference was greater than 15%.

This process revealed that significant variances can occur between government estimates for mobilization and demobilization costs, and the contractor's winning bids. For example, on the one project discussed above that had the greatest variation in mobilization and demobilization costs, the winning contractor's bid breakdown had mobilization/demobilization costs as 60% of the winning bid, or one and a half times the cost for the dredging work. This is contrasted with a government estimate of mobilization/demobilization costs of approximately 33% of the total government estimate, or 50% of the dredging work estimate.

Dredge Capital Costs

One of the most important costs to determine is the capital cost of dredges. The capital cost is the basis for developing maintenance costs, insurance costs, and depreciation costs associated with dredging equipment. Unfortunately, there is very little publicly available data on the capital costs of dredges in general, and clamshell dredges are no exception. As with the cost estimating techniques, the dredging industry considers capital costs proprietary information. However, Bray et al (1997) provide some insight into the capital costs of clamshell dredges, and presents capital costs for different sizes and varieties of dredging plants, in order to provide an indication of the average relative costs.

The data that Bray et al (1997) present thus becomes the starting point for developing the capital cost estimate for a clamshell dredge. Bray et al (1997) provide cost data for clamshell dredges based on bucket capacity, with the largest bucket size being 1000 L, or 1 m^3 (1.3 yd^3). The information is presented in 1996 Dutch guilders. It was necessary to convert the price from Dutch guilders to US dollars (USD), and then convert the price to current values. To convert from guilders to dollars, all of the daily exchange rates for 1996 were obtained from historical exchange rates (Federal Reserve Statistical Release, 1999), and an average exchange rate for 1996 of 1.69 guilders per dollar was developed.

The conversion process required selecting an appropriate cost index, since there are many different indices that could be used. For example, Adair (2004) and Wowtschuk (2016) use cost indices from RS Means to adjust costs for each year. After considering RS Means, cost index data from the Army Corps of Engineers (2016), the consumer price index (CPI) and the producer price index (PPI), the PPI was selected as the best for calculating the capital cost of dredges for the current year, specifically the index for shipbuilding and repair (BLS, 2016). This index was selected over the other indices for several reasons. The PPI was selected because it tracks the output of US producers. Furthermore, it includes an index specifically for shipbuilding and construction, which is the type of cost being considered.

The CPI was not selected because its primary purpose is to track household consumption (BLS, 2017), rather than production output. Similarly, RS Means and USACE cost indices were decided against because they primarily track civil works projects (USACE, 2016) and heavy construction projects (RS Means, 2015). In this case the intent is to measure price changes as they relate to shipbuilding costs in particular, not construction projects in general.

The Producer Price Index (PPI), published and maintained by the Bureau of Labor Statistics, provides a listing of the various sub-indices that comprise the overall PPI. This listing was used to locate the data for the shipbuilding and repair sub-index. The sub-index selected was “Non-propelled ships, new construction,” with a series ID of PCU3366113366111 (BLS, 2016). To convert the index values to an inflation rate (E), the following formula was used:

$$E = \frac{I_{new} - I_{old}}{I_{old}} * 100\% \tag{15}$$

where E is the inflation rate, I_{new} is the current index value, and I_{old} is the index value for 1996. For current and old index values, the average index values for the years 1996 and 2015 were used. For 1996, BLS (2016) only reported the sub-index from July through December.

After developing the exchange and inflation rates, they were applied to the capital cost data from Bray et al (1997) as follows:

$$CC_\$ = CC_f * \frac{1 + E}{X} \tag{16}$$

where $CC_\$$ is the current capital cost in dollars, C_f is the capital cost value from Bray et al (1997) in 1996 Dutch guilders, X is the exchange rate in terms of guilders per dollar, and E is the inflation rate. Based on this formula, a capital cost of approximately $14.5 million was obtained for a clamshell dredge.

Since the capital cost data based on bucket size had an upper limit of 1 m$^{3 (}$1.3 yd^3), extrapolating the capital cost based on the bucket size was considered. However, the data that Bray et al (1997) present indicates a linear cost trend, so that extrapolating the bucket size to 7.65 m^3 (10 yd^3) to account for the increase in bucket sizes led to a capital cost increase by a factor of 7.65. This resulted in the associated costs also increasing by a factor of 7.65, and led to cost estimates that were too high, so extrapolation was not used to determine the capital cost.

Fuel and Lubricants

The cost of fuel and lubricants is a very large portion of the operating costs for a dredging project. The process for determining the fuel and lubricant costs of a dredging project is based on the installed horsepower of the dredge, a time-weighted average of horsepower usage, the operating hours per day, a conversion factor that equates horsepower usage to fuel consumption, and the price of diesel fuel (Bray et al, 1997). A default installed horsepower value was established by using an average value of installed horsepower as reported in a recent directory of dredges (Richardson, 2016), and a fuel consumption rate of 0.182 L/hr (0.0481 gal/hr) per installed horsepower was adopted from Bray et al (1997). The diesel prices used were an 18-month average of diesel fuel prices from the United States Department of Energy's Energy Information Administration (EIA). Lubricant costs were assumed to be ten percent of fuel costs (Bray et al, 1997). The result is the daily fuel and lubricant costs.

The method for determining an average installed horsepower relied on listings of bucket clamshell dredges in the United States as published in World Dredging, Mining & Construction (Richardson, 2016). The publication listed 141 bucket clamshell and grab dredges in the United States, but only 58 of the dredges had the dredge's power listed. A distribution plot of the 58 dredges, sorted by bucket size, is contained in Figure 5. Based on Figure 5, dredge horsepower is only moderately correlated to bucket size. Also, for two dredges with the same bucket size, their installed horsepower can vary greatly. For example, there are three dredges listed with bucket sizes of 10.7 m^3 (14 yd^3) yet each dredge has an installed horsepower of 500, 1000, and 1500 HP, respectively. This data shows that developing fuel consumption estimates based on bucket size can be misleading.

Taking the mean or median installed horsepower value of the listed dredges from Richardson (2016) is another alternative, but would also under-represent larger dredges, which would tend to be the dredges completing the types of projects the program is attempting to estimate. Figure 5 shows that a majority of the dredges represented are small, both on the basis of bucket size and installed power. Furthermore, a significant number of the smallest dredges listed are owned by state agencies, such as the NY Department of Transportation and the Ohio Department of Natural Resources (Richardson, 2016). Of the 16 dredges with bucket sizes of 1.1 m^3 (1.5 yd^3) or less, 13 were owned by these two state agencies. It is reasonable to conclude that based on the small size of these dredges and their ownership, the USACE would not utilize them for its dredging projects. Additionally, a government agency will utilize an interagency agreement, not a contract, to obtain services from another government agreement. As a result, even if the USACE entered into an agreement for a state agency to perform dredging work, it would not appear in the NDC's dredging dictionary, so comparing its costs to the contracted projects would be difficult to perform.

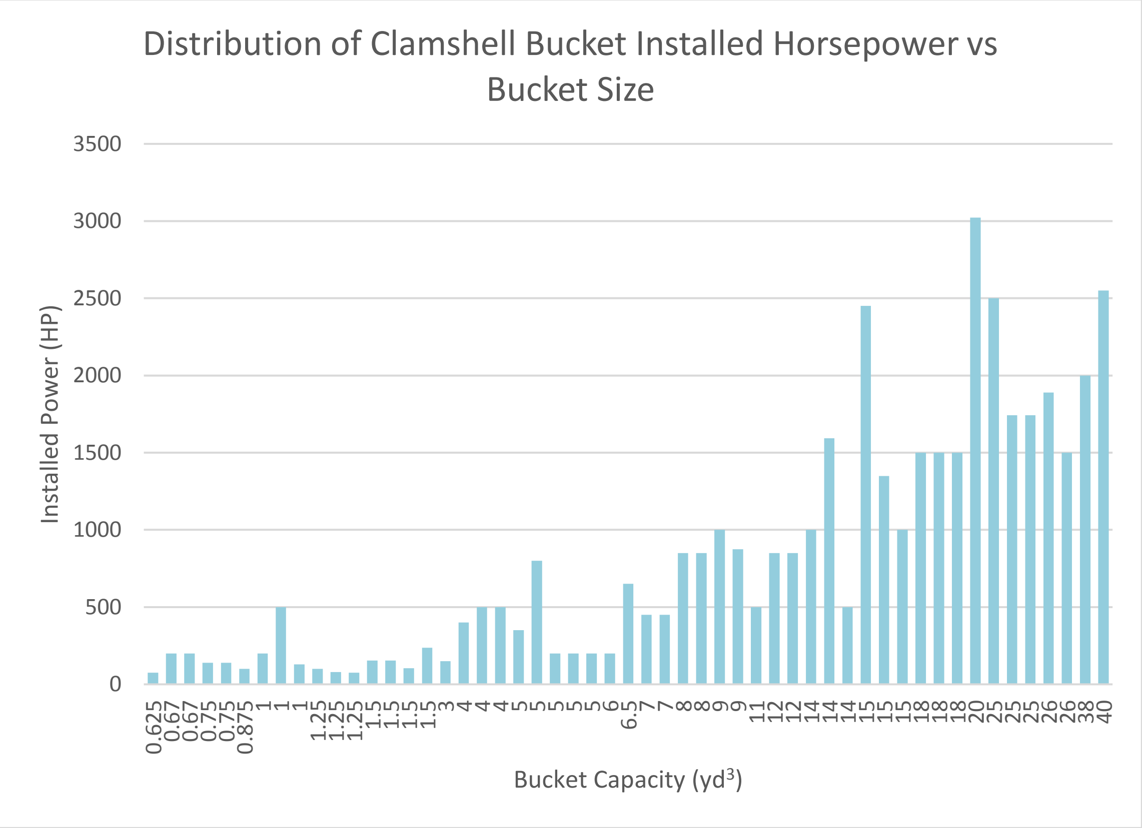

Figure 5: Installed Horsepower vs Bucket Size

Since the correlation between bucket size and installed horsepower is weak, and the data available on the whole over-represents smaller dredges, an alternate method was used. The dredging dictionary (NDC, 2016) lists the winning contractor for each project. Looking at dredging projects completed over the past 5 years, a list of contractors who completed 5 or more projects was compiled. While there were over 10 companies that met this requirement, only 3 of them had available horsepower data. The three companies were Great Lakes Dredge and Dock Company, Manson Construction Company, and Weeks Marine, Incorporated. As a result, the average installed horsepower was determined by taking the average installed horsepower of these companies' clamshell dredges. This resulted in an average installed horsepower of 2038 HP, which became the default value for the estimating program.

Labor

Labor is another significant portion of a dredge's operating costs. Typical crew sizes for a mechanical clamshell dredge were obtained from Adair (2004) and RS Means (2015). Both sources consider a dredge crew to consist of a foreman, 2 laborers, a crane operator, an oiler, and a light equipment operator. Since the typical clamshell dredge is not propelled, this program also considers the labor costs associated with tugs and workboats. A project is assumed to have a single tugboat crewed by a vessel captain and a deckhand (laborer), and a single small workboat has a small workboat crewed by two laborers. Hourly wage rates were obtained from RS Means Heavy Construction Index (2015). For each hourly rate, a job-specific workman's compensation rate is applied to the "bare" wage rates, as well as an additional 18% "wage overhead" rate to account for items such as payroll taxes, unemployment insurance, risk insurance, and public liability costs. The result is a "burdened" hourly rate, which is then multiplied by the number of hours worked per day to develop a daily labor cost.

Support Equipment

In addition to the dredge, a mechanical dredging project requires hoppers for placing the dredged material excavated by the dredge, a tugboat to transport hoppers to and from the disposal site, and a workboat to maneuver the dredge. It is assumed that a dredging contractor would rent this equipment. Rental rates for this equipment were obtained from RS Means Heavy Construction Index (2015). The rental rates assume maintenance and operation costs only, labor is not included in the rates, hence the reason for accounting for tugboat and workboat operators in the *Labor* section.

Maintenance and Repairs

Maintenance and repair costs are based on the capital cost of the dredge (Bray et al, 1997). Bray et al develop two repair factors, one for minor repairs, known as running maintenance, and one for major repairs, such as dry-dock, equipment overhaul, or other types of depot-level maintenance. For a non-propelled clamshell dredge, the running repair cost per operating day is 0.000130 of the capital cost (Bray et al, 1997). The major repair cost per operating day is 0.000250 of the capital cost (Bray et al, 1997).

Depreciation and Insurance

Bray et al (1997) recommends an average annual insurance premium of 2.5% of the insured value of the dredging plant. For the purposes of this estimating program, the insured value is assumed to be the same as the capital cost of the dredge. The annual insurance cost is then divided by the number of working days per year to obtain a daily insurance cost to use in a project estimate.

Overhead and Bonding

Bray et al (1997) recommends an overhead rate of 9% of the project costs outlined above. Belesimo (2000) recommends a bond of 1.0 to 1.5% of the same costs. This estimating program combines overhead and bonding into a total rate of 10% of project operating costs.

Cost Factors

After obtaining a total cost, cost factors are applied to the total to account for pricing differences based on location, and any inflation or deflation that occurs when projects from different years are compared. The location factors are published by the USACE, and vary based on the year and state selected. For projects in 2015 or later, the 2015 location factors are used, since 2015 is the most recent year for which USACE location index data is available. For projects prior to 2002, the 2002 set of location indices are used, as the historical location indices are only reported from 2002 up to the most recent data available (USACE, 2016).

For inflation factors, the USACE also publishes cost indices for civil works projects. The publication consists of past historical information, as well as estimated indices for future years, based on Office of Management and Budget projections (USACE, 2016).

The USACE cost factors were used because they are intended for estimating costs for civil works projects that the USACE oversees, which includes dredging projects. The other advantage is that the future inflation rates are based on a more informed assumption, rather than assuming a constant inflation rate as previous dredge estimating programs have (Wowtschuk, 2016 and Adair, 2005).

A note when using the cost and location indices: the USACE publishes the data based on fiscal year, not calendar year. The US government fiscal year begins on the 01 October preceding the calendar year. For example, Fiscal year 2017 began on October 1, 2016.

THE DREDGE ESTIMATING PROGRAM

Using the Production and Cost Estimate methodologies described in the previous sections, an Excel-based dredge estimating program was developed. The program consists of 10 separate worksheets, corresponding to different aspects of the production and cost estimating process. The program is constructed with the expectation that the user may only have limited information regarding a dredging project. The program allows a user to obtain a reasonably accurate cost estimate with only the dredged volume, average digging depth, project location, and project year known. However, the program does allow the user the flexibility to modify default values and add additional information if desired based on job-specific knowledge. Examples include modifying equipment-specific characteristics such as, bucket size, swing speed, hopper size, and fuel consumption, or project-specific characteristics such as sediment type, distance to placement site, prevailing labor rates, and fuel prices.

How to Use the Program

The first tab allows the user to enter the required input values, which are the volume of sediment to be dredged, the project location, and project year. A dropdown menu is provided to select the project year through 2027, and another dropdown menu allows the user to select any of the 50 United States plus the District of Columbia for the project location. The user can also select the national average, which corresponds to a location factor of 1.0. The input page also contains a summary of the overall project cost estimate, the estimated time to complete the project, and also computes the estimated cost on a per cubic yard basis, by taking the total cost and dividing it by the volume of sediment to be dredged. Additionally, the inputs page lists the default values used throughout the program, thus easily allowing the user to modify values based on project-specific information available.

Default Values

The accuracy of the cost estimate will depend in large part on the user's ability to obtain project-specific information. In addition to the input values described in the previous section, other important parameters include the sediment type and bucket size. Also, any project-specific costs, if known, should be accounted for in the estimating process.

Bucket Size

The program is constructed such that the bucket size varies based on the amount of dredged material being excavated. For projects with a volume of less than 76,455 m^3 (100,000 yd^3), a bucket size of 4.5 m^3 (6 yd^3) is used. The bucket size increases to 7.65 m^3 (10 yd^3) for project volumes from 76,455 m^3 up to 191,139 m^3 (100,000 to 250,000 yd^3). For project volumes greater than or equal to 191,139 m^3 (250,000 yd^3), the default bucket size is 11.5 m^3 (15 yd^3).

The variation in default bucket size corresponds with the smallest one-third, median one-third, and largest one-third of dredging projects on the basis of volume. According to the dredging dictionary (NDC, 2016), from fiscal year (FY) 2012 to FY 2016 there were two-hundred and twelve bucket dredging projects with estimated volumes listed. Seventy of these projects had volumes of less than 76,455 m^3 (100,000 yd^3), sixty-four project volumes ranged from 76,455 m^3 to 191,139 m^3 (100,000 to 250,000 yd^3), and the remaining seventy-eight projects had volumes greater than or equal to 191,139 m^3 (250,000 yd^3). The default bucket sizes selected therefore provide a reasonable means of differentiating between small, mid-size, and large dredging projects. Alternately, the user can input a unique bucket size if the information is known.

Sediment Type

The program allows the user to select the soil type for the project. As discussed in the Production Rate Estimate Methodology section, the sediment type affects the production calculations, specifically bucket fill factor and the bucket capacity modifier. Using the information presented by Adair (2004), the user can select from six different sediment types for developing the cost estimate. The different soil types are summarized in Table 1.

Table 1: Sediment Types

1	mud
2	loose sand
3	compact sand
4	sand and clay
5	stone
6	broken rock

The program assumes a default sediment type of sand and clay. The default sediment type is typical for maintenance dredging projects (Herbich, 2000). The user can modify the sediment type if historical data or a site investigation indicates a different sediment type is present.

Cycle Time Parameters

The default values for cycle time parameters are based on the values from Adair (2004). Table 2 provides a summary of the default values used for the production estimates.

Table 2: Default Values for Cycle Time Calculation

Cycle Time Inputs		
Swing Angle (θ_{sw})	120	degrees
Swing Speed (ω_{sw})	21	degrees/sec
Fall Velocity (u_{fall})	1	m/s
Grab Time (t_{close})	1	s
Lift Velocity (u_{raise})	1	m/s
Empty Time (t_{open})	2.6	s
Barge Freeboard height (h_b)	2	m

Delay Factors

The default delay factors were the same as those selected by Adair (2004). Table 3 presents the default values used.

Table 3: Default Values for Calculating Delay Factors

Delay Inputs		
time to advance dredge (t_a)	0.33	hr
time to change hopper (t_h)	0.25	hr
Area Dredged in single position (A)	1142.7	m^2
Cut Depth (z)	2	m
Hopper Capacity (H)	3440	m^3

Additional Costs

The estimating program affords the user the opportunity to account for additional project-specific costs such as rock or debris removal, government-directed standby time, or environmental monitoring. The program uses a default value of zero for these costs, since they are not included in every dredging project.

RESULTS

Comparison Methodology

After developing the production and cost estimates using the methodology explained previously, the next step was to compare the results of the estimating program to recently completed dredging projects.

As stated earlier, the US Army Corps of Engineers (USACE) oversees most dredging projects in the United States. USACE maintains the Navigation Data Center (NDC), which includes data on past, present, and future dredging contracts such as planned project timelines, solicitation schedules, and listings of awarded dredging contracts. The listing of awarded dredging contracts is known as the dredging dictionary, and contains information such as the type of dredge used, the amount of material estimated to be dredged, the disposal method, the government estimate, the winning bid and contractor, actual cost and volume removal, and project dates. The most important information obtained from the dredging dictionary is the estimated material to be dredged, as this is an input for the cost estimate, as well as the winning bid and government cost estimates, in order to compare the results. The NDC also maintains bid abstracts for most of the dredging projects. The bid abstracts contains a breakdown of the dredging costs by contract line item, and provides the government estimate, winning bid, and bids from other contractors for each line item.

Another important input to the program is the average digging depth. After selecting projects for comparison, the digging depth was determined using project information regarding channel layout and channel depths available through the USACE district websites and correlated with navigation charts that are available from the National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey (OCS, 2017). The dredging dictionary provides a latitude/longitude location for each dredging project, which can be used to correlate the project location to a particular navigation chart. Navigational charts, especially harbor charts, provide accurate channel depth information and were used to develop average channel lengths when the data were not available from the USACE district websites. The navigation channel depths recorded in harbor charts are based on USACE hydrographic surveys. An average of the depths listed on the harbor chart corresponding to the project location was used.

Overview of Selected Projects

Eight recent dredging projects were selected from the NDC's dredging dictionary. These projects were selected based on availability of corresponding bid abstracts and completeness of information contained in the dredging dictionary. In order to keep the analysis relevant to dredging production costs, the selection process focused on projects that did not include job-unique line items in the bid abstracts, such as turbidity monitoring, dredged material inspectors, standby time, and debris removal.

Also, for consistency in the evaluation method, projects with open-water disposal were selected.

Barcelona Harbor

Barcelona Harbor is located on Lake Erie, in New York State. The project depth is 3 m (10 ft) for the entrance channel, and 2.4 m (8 ft) for the inner harbor (OCS, 2016). An average digging depth of 2.7 m (9 ft) was used for the project input. The project took place in FY 2014. The estimated dredging volume was 54,283m^3 (71,000 yd^3). Table 4 summarizes the project information.

Table 4: Barcelona Harbor Project Information

Location (State)	New York
Year	2014
Average Digging Depth, m (ft)	3 (9)
Volume, m^3 (yd^3)	54,283 (71,000)

Erie Harbor

Erie Harbor is located on Lake Erie, in Pennsylvania. The project depth ranges from 8.5-8.8 m (28-29 ft) for the entrance channel, and 5.5-8.5 m (18-28 ft) for the inner harbor (OCS, 2016). An average digging depth of 7.6 m (25 ft) was used for the project input. The project took place in FY 2014. The estimated dredging volume was 191,139 m^3 (250,000 yd^3). Table 5 summarizes the project information.

Table 5: Erie Harbor Project Information

Location (State)	Pennsylvania
Year	2014
Average Digging Depth, m (ft)	7.6 (25)
Volume, m^3 (yd^3)	191,139 (250,000)

Fairport Harbor

Fairport Harbor is located on Lake Erie, in Ohio. The project depth ranges from 7.6 m (25 ft) at the approach channel, harbor channel and mooring area, down to 6.4 m (21 ft) at the landward end of the navigation channel, with an 8.8 m (18 ft) deep turning basin (OCS, 2016). An average digging depth of 7.3 m (24 ft) was used for the project input. The project took place in FY 2014. The estimated dredging volume was 229,366 m^3 (300,000 yd^3). Table 6 summarizes the project information.

Table 6: Fairport Harbor Project Information

Location (State)	Ohio
Year	2014
Average Depth, m (ft)	7.3 (24)
Volume, m^3 (yd^3)	229,366 (300,000)

Huron Harbor

Huron Harbor is located on Lake Erie, in Ohio. The project depth ranges from 8.8 m (29 ft) at the approach channel and entrance channel, to 8.2 m (27 ft) at the end of the navigation channel, with a 6.4 m (21 ft) deep turning basin (OCS, 2016). An average digging depth of 8.5 m (28 ft) was used for the project input. The project took place in FY 2014. The estimated dredging volume was 210,253 m^3 (275,000 yd^3). Table 7 summarizes the project information.

Table 7: Huron Harbor Project Information

Location (State)	Ohio
Year	2014
Average Depth, m (ft)	8.5 (28)
Volume, m^3 (yd^3)	210,253 (275,000)

Lorain Harbor

Lorain Harbor is located on Lake Erie, in Ohio. The project consists of the Lorain Harbor Channel, and the Black River Channel (OCS, 2016). The project depth ranges from 8.5-8.8 m (28-29 ft) in the Lorain Harbor Channel, and 8.2-8.5 m (27-28 ft) in the Black River Channel (OCS, 2016). An average digging depth of 8.5 m (28 ft) was used for the project input. The project took place in FY 2014. The estimated dredging volume was 126,151 m^3 (165,000 yd^3). Table 8 summarizes the project information.

Table 8: Lorain Harbor Project Information

Location (State)	Ohio
Year	2014
Average Depth, m (ft)	8.5 (28)
Volume, m^3 (yd^3)	126,151 (165,000)

Toledo – Maumee River

Toledo, OH, is connected to Lake Erie by means of the Maumee River and Maumee Bay. This project was for maintenance dredging of the Maumee River portion of the channel. The project depth ranges from 8.5-8.8 m (28-29 ft) in the Lorain Harbor Channel, and 8.2-8.5 m (27-28 ft) in the Black River Channel (OCS, 2016). An average digging depth of 8.5 m (28 ft) was used for the project input. The project took place in FY 2014. The estimated dredging volume was 76,455 m^3 (100,000 yd^3). Table 9 summarizes the project information.

Table 9: Toledo-Maumee River Project Information

Location (State)	Ohio
Year	2014
Average Depth, m (ft)	8.5 (28)
Volume, m^3 (yd^3)	76,455 (100,000)

Coos Bay Upriver Dredging

Coos Bay is located on the Oregon Coast, and connects the Coos River to the Pacific Ocean. The Coos River navigation channel consists largely of the portion transiting Coos Bay. This portion is the deepest portion of the channel, and has a project depth 14.3 m (47 ft) from the entrance to river mile 1. From river kilometer (1.9 (mile 1) to river kilometer 27.8 (mile 15) the channel depth is 11.3 m (37 ft). There are two smaller navigation channels adjoining the main portion transiting Coos Bay. These smaller portions consist of the South Slough channel and the Isthmus Slough channel. The South Slough channel extends from Coos Bay to Charleston, and is located near the Pacific Ocean entrance to Coos Bay, with a length of 975 m (3,200 ft), and a depth of 5.2 m (17 ft). The Isthmus Slough channel extends from Coos Bay to Millington, with a length of 3.7 km (two miles), and a depth of 6.7 m (22 ft) (USACE Portland District, 2017). For the purposes of determining the average digging depth of this project, the dredging area was assumed to cover the 11.3 m (37ft) deep portion of the channel, the South Slough Channel, and the Isthmus Slough channel. A channel length-averaged depth was computed, using the following method:

$$d_{average} = \frac{\sum(d_{channel} * L_{channel})}{\sum L_{channel}} \tag{17}$$

where $d_{average}$ is the average channel depth, $d_{channel}$ the depth of each channel segment, and $L_{channel}$ the length of each channel segment. For this project, the average depth was computed to be 10.7 m (35 ft). The project took place in FY 2015. The estimated dredging volume was 198,784 m^3 (260,000 yd^3). Table 10 summarizes the project information.

Table 10: Coos Bay Upriver Dredging Project Information

Location (State)	Oregon
Year	2015
Average Depth, m (ft)	10.7 (35)
Volume, m^3 (yd^3)	198,784 (260,000)

Suisun Bay

Suisun Bay is located in the San Francisco Bay area. The navigation channel is roughly oriented west-east. It is extends from Carquinez Strait at Martinez to its eastern terminus at the mouth of the San Joaquin River. The project depth is 10.7 m (35 ft) for the entire length of the channel (OCS, 2016). The project took place in FY 2015. The estimated dredging volume was 133,797 m^3 (175,000 yd^3). Table 11 summarizes the project information.

Table 11: Suisun Bay Project Information

Location (State)	California
Year	2015
Average Depth, m (ft)	10.7 (35)
Volume, m^3 (yd^3)	133,797 (175,000)

Cost Comparison with Recent Dredging Projects

For each project, the required inputs for each project (volume of material to dredge, average dredging depth, project location, and year) were entered on the inputs page. Once entered, the estimating program generated an estimated project cost. The project cost from the estimating program was then compared against the winning bid for that project, and the government's independent cost estimate. Additionally, the government estimate was compared to the winning bid. In addition to comparing the differences between the winning bids and the various estimates on a per-project basis, the total estimates, i.e. the sum of all of the projects were compared. Additionally, the mean absolute percent error, or the average of the absolute values for the percentages above or below the winning bid, was determined for each estimating method. Table 12 presents the results. Negative values indicate that the estimate was less than the winning bid. For the last column of Table 12, a negative value indicates the Paparis estimate was less than the government estimate.

Table 12: Total Project Cost Comparison, Recent Dredging Projects.

Project	Winning Bid (WB)	Government Estimate (GE)	Paparis Estimate (PE)	GE vs WB	PE vs WB	PE vs GE
Barcelona Harbor	$602,200	$552,050	$647,861	-8.3%	7.6%	17.4%
Erie Harbor	$868,980	$1,330,700	$1,123,416	53.1%	29.3%	-15.6%
Fairport Harbor	$1,640,000	$1,846,500	$1,231,146	12.6%	-24.9%	-33.3%
Huron Harbor	$1,165,150	$1,231,800	$1,192,673	5.7%	2.4%	-3.2%
Lorain Harbor	$773,200	$1,310,050	$1,041,344	69.4%	34.7%	-20.5%
Toledo - Maumee River	$436,700	$736,600	$632,245	68.7%	44.8%	-14.2%
Coos Bay Upriver Dredging	$2,862,160	$3,824,852	$1,761,572	33.6%	-38.5%	-53.9%
Suisun Bay	$1,769,330	$2,158,825	$1,456,005	22.0%	-17.7%	-32.6%
Total	$10,117,720	$12,991,377	$9,086,262	28.4%	-10.2%	-30.1%
Mean Absolute Percent Error				34.2%	25.0%	23.8%

For the eight projects, three of the Paparis estimates were within 20 percent of the winning bid, two were between 20 and 30 percent of the winning bid, two were between 30 and 40 percent of the winning bid, and one project was between 40 and 50 percent of the winning bid. By contrast, three government estimates, were within 20 percent of the winning bid, one was between 20 and 30 percent, one was between 30 and 40 percent, and the remaining three varied from the winning bid by greater than 50%. Table 12 also indicates that the Paparis estimate was closer to the winning bid for six of the eight projects compared, with the exceptions being the Fairport Harbor and Coos Bay Upriver Dredging projects.

The results show that the government estimates are consistently higher than the winning bid, with the government overestimating the contractor's bid on seven of the eight projects. The government may intentionally use a more conservative estimate. The Anti-Deficiency Act prevents government officials from obligating or expending government funds that are not appropriated for that purpose (U.S. Code, 2006). Because the appropriations process is quite lengthy, and requires planning well in advance of when the estimate may be completed, it is difficult to obtain additional funds after Congress appropriates funding. Therefore the USACE has an interest in ensuring it can adequately support its missions, and using overly conservative estimates is a way to ensure adequate funding is available.

The estimating methods outlined in this paper, referred to as the Paparis estimate, yields lower estimates compared to the government estimate. In seven of the eight instances, the government estimate was higher than the Paparis estimate. In four of the eight projects, the Paparis estimate was lower than the winning bid. The Paparis estimates showed the greatest variations from the winning bids on the Lorain Harbor, Maumee River, and Coos Bay Upriver Dredging projects. Figure 6 is a bar chart comparing the winning bid to the government estimate and Paparis estimate for each of the eight projects.

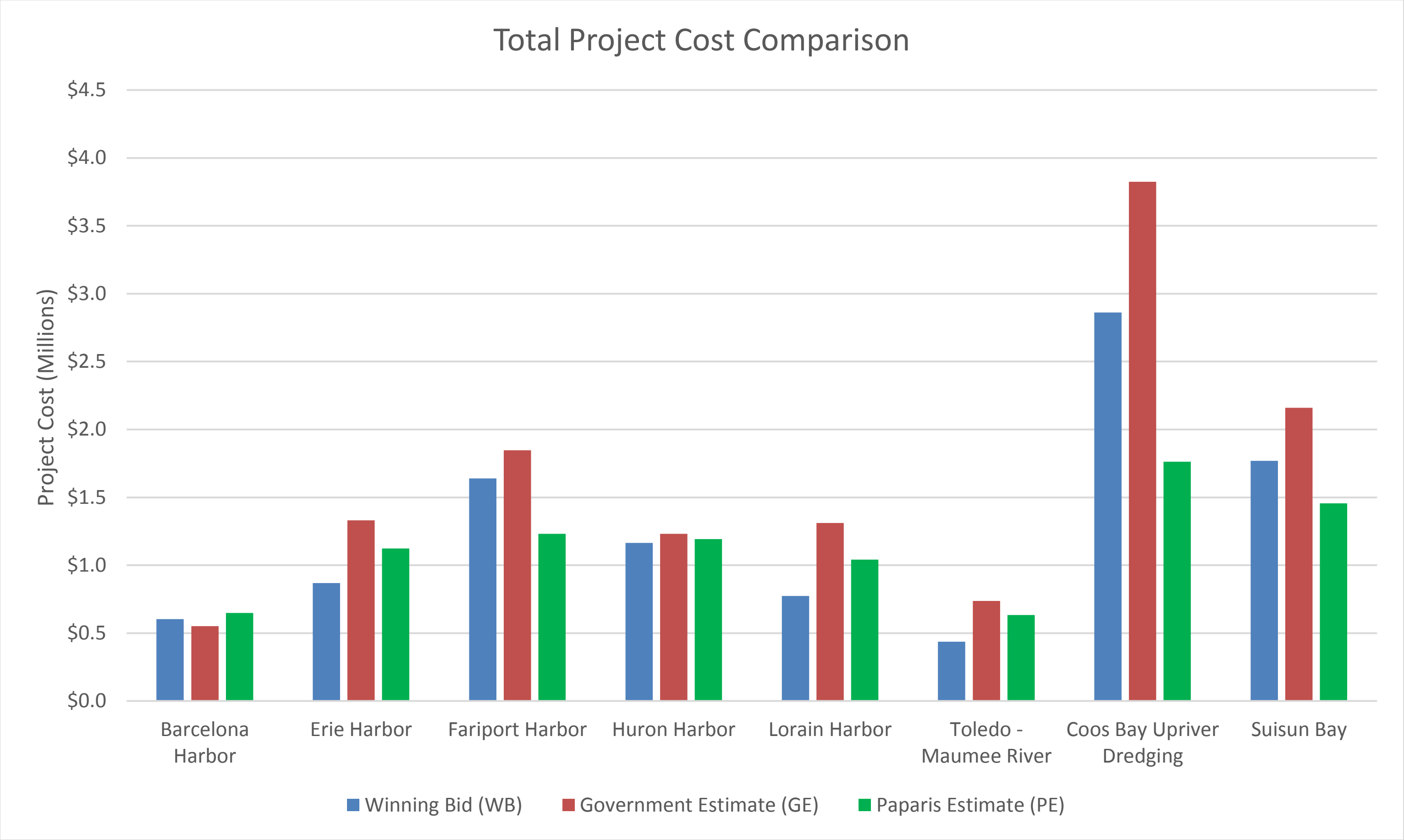

Figure 6: Total Project Cost Comparison

After comparing the total project cost estimates to the winning bids, the estimates were compared on a production costs basis. For the purposes of this analysis, production costs were defined as the costs associated with contract line items on the bid abstracts that were dredging and placement-related. This excluded mobilization/demobilization costs, and in the instance of the Coos Bay Upriver Dredging Project, a line item for government-directed standby time. The results are shown in Table 13.

Table 13: Production Cost Comparison Results, Recent Dredging Projects

Project	Winning Bid (WB)	Government Estimate (GE)	Paparis Estimate (PE)	GE vs WB	PE vs WB	PE vs GE
Barcelona Harbor	$508,500	$465,450	$587,896	-8.5%	15.6%	26.3%
Erie Harbor	$832,000	$1,186,000	$1,019,433	42.5%	22.5%	-14.0%
Fairport Harbor	$1,559,000	$1,739,000	$1,117,193	11.5%	-28.3%	-35.8%
Huron Harbor	$1,135,000	$1,141,000	$1,082,281	0.5%	-4.6%	-5.1%
Lorain Harbor	$701,500	$1,208,750	$944,959	72.3%	34.7%	-21.8%
Toledo - Maumee River	$398,000	$679,500	$573,725	70.7%	44.2%	-15.6%
Coos Bay Upriver Dredging	$2,114,500	$3,115,100	$1,598,523	47.3%	-24.4%	-48.7%
Suisun Bay	$978,900	$1,258,825	$1,321,239	28.6%	35.0%	5.0%
Total	$8,227,400	$10,793,625	$8,245,247	31.2%	0.2%	-23.6%
Mean Absolute Percent Error				35.3%	26.2%	21.5%

The production cost comparison yielded interesting results. When individual project estimates were compared, the production cost estimates tended to yield results that varied further from the winning bids. For the Paparis program estimates, five of the eight project estimates had the absolute percent error increase. As a result, this increased the mean absolute percent error from 25.0% to 26.8%. On the other hand, the sum of all of the Paparis program estimates yielded a result that was less than 2% of the all of the winning bids. Looking at Table 13, the government estimates were closer to the winning bid on four of the eight projects, compared to only two of eight projects when considering total project costs (Table 12). This indicates that the government tends to do a better job of estimating production costs compared to estimating total project cost, although the relative accuracy of each estimating program remained the same, as the mean absolute percent error values only increased by 1.1 or 1.2 percent.

Compared with Table 12, the variation of the Paparis estimate from the winning bid did not change by more than 10 percent for six of the eight projects. The two exceptions were the Coos Bay Upriver Dredging and Suisun Bay projects.

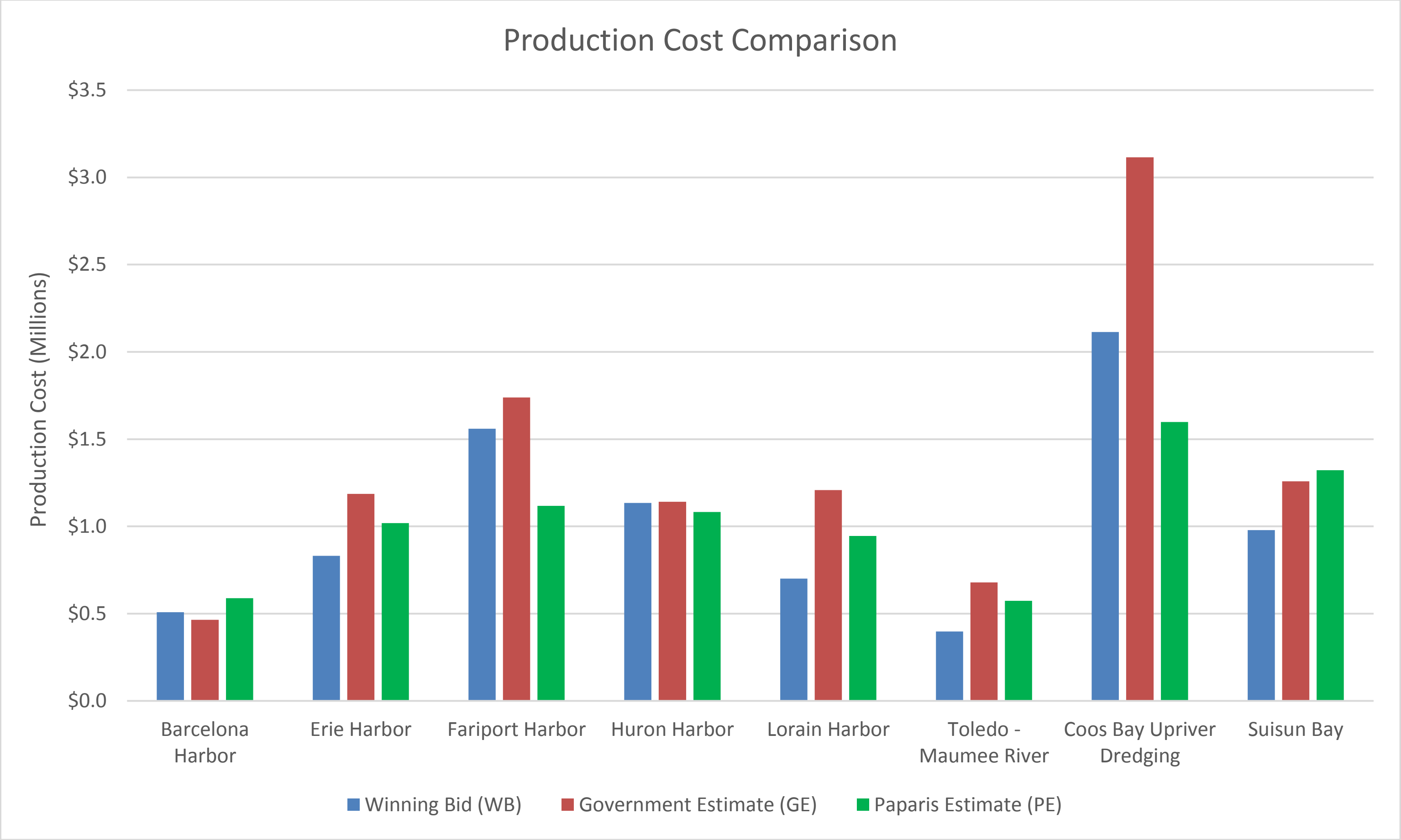

Figure 7: Production Cost Comparison

Figure 7 provides a bar chart comparing the winning bid, government estimate and Paparis estimate of the production costs for the eight projects. The most significant differences in the total cost vs production cost estimates came from the Coos Bay and Suisun Bay projects. These projects had the largest mobilization and demobilization costs. For the Coos Bay project, the mobilization and demobilization costs were 25% of the entire bid. For the Suisun Bay project, the mobilization and demobilization cost was 45% of the entire bid. The result was that the Paparis program estimate went from underestimating the entire project cost by over 40% to underestimating the project cost by less than 30%. On the Suisun Bay project, the Paparis program estimate underestimated the total project cost by nearly 20%, while overestimating production costs by 33.3%.

The Paparis program production estimates were more in-line with the government estimates, as shown by the significant reductions of the total variation and the mean percent error. For five of the eight projects, the degree of variation between Paparis program estimates and government estimates was reduced.

Comparison with Adair (2004) and CDS (2016)

In addition to comparing the estimating program with recently completed dredging projects, the estimating program was tested using dredging projects selected by Adair (2004) for comparison with his dredging program. For the five dredging projects that Adair (2004) selected, the winning bid was compared with the government estimate, the Adair (2004) estimate, the winning estimate, the Paparis estimate, and the estimate using the most recent estimating program available from the Center for Dredging Studies (CDS, 2016).

The five projects that Adair selected were Erie Harbor (1998), Coos Bay (1995), Coos Bay (1997), Fernandina Harbor (1994) and Wando River (1994). Unfortunately, with the exception of the Coos Bay (1997) project, the inputs that Adair (2004) used were not available in the thesis. Therefore, the inputs were obtained using information available from the dredging dictionary (NDC, 2016), and navigational charts (OCS, 2016), similar to the methods used for determining inputs for the recently completed dredging projects. For the five projects selected, the dredging volume and project year were obtained from the dredging dictionary. The dredging dictionary provides a latitude and longitude position for the project, which was correlated with navigational charts (OCS, 2016) to determine the project location. The digging depth was obtained from navigational charts. The digging depth for Erie Harbor (1995) was assumed to be 7.62 m (25 ft), the same as the digging depth for the more recent Erie Harbor project analyzed. The digging depth selected for the Coos Bay project was 10.7 m (37 ft). Initially, the depth for the Coos Bay (1995) project was assumed to be the same as the depth for the Coos Bay (1997) project, however this led to variances greater than 35% for both the Paparis and CDS (2016) estimates. Since the project name is listed in the dredging dictionary as “Coos Bay River Mile 12 to 15” (NDC, 2016), this would indicate that the dredging project occurred in the upriver portion of the navigation channel. The upriver portion of the channel has a project depth of 11.2 m (37 ft) (OCS, 2016), whereas the depth of 14.6 m (48 ft) used by Adair (2004) for estimating the Coos Bay (1997) project corresponds with the project depth for the portion of the navigation channel near the entrance (USACE Portland District, 2017).

The remaining values were set to each program's respective default values. One important difference to note is that Adair (2004) and the CDS (2016) estimating programs assume loose sand as the default sediment type, while the Paparis estimating program assumes a default sediment type of sand and clay. Table 14 summarizes the inputs for each project.

Table 14: Summary of Project Inputs for Comparison with Adair (2004) and CDS (2016)

Project	Year	Location	Estimated Volume (cy)	Digging Depth (ft)
Erie Harbor	1998	Pennsylvania	100,000	25
Coos Bay	1995	Oregon	600,000	37
Coos Bay	1997	Oregon	796,200	48
Fernandina Harbor	1994	Florida	770,000	32
Wando River	1994	South Carolina	970,000	45

The project information was inputted into both the Paparis and CDS (2016) programs, with the results shown in Table 15.

Table 15: Total Project Cost Comparison with Adair (2004) and CDS (2016)

Project	Gov't Estimate (GE)	Winning Bid (WB)	Adair (2004) Estimate (AE)	Paparis Estimate (PE)	CDS (2016) Estimate (CE)	GE vs WB	AE vs WB	PE vs WB	CDS vs WB
Erie Harbor (1998)	$357,000	$324,500	$476,000	$406,289	$496,344	10.02%	46.69%	25.20%	52.96%
Coos Bay (1995)	$1,692,000	$1,490,000	$1,667,000	$1,753,883	$1,802,960	13.56%	11.88%	17.71%	21.00%
Coos Bay (1997)	$3,614,920	$2,939,114	$2,244,314	$2,758,545	$3,131,454	22.99%	-23.64%	-6.14%	6.54%
Fernandina Harbor (1994)	$2,502,470	$1,479,820	$1,590,000	$1,575,631	$1,895,363	69.11%	7.45%	6.47%	28.08%
Wando River (1994)	$3,907,500	$2,360,000	$2,038,000	$2,185,989	$2,769,349	65.57%	-13.64%	-7.37%	17.35%
Totals	$12,073,890	$8,593,434	$8,015,314	$8,937,572	$10,354,476	40.50%	-6.73%	1.01%	17.48%
Mean Absolute Percent Error						36.96%	18.34%	10.65%	23.90%

Based on the results provided in Table 15, the Paparis estimate was closer to the winning bid than the results obtained by Adair (2004) on four out of the five projects analyzed. The mean absolute percent error for the Paparis estimates was 10.65%, compared to 18.34% for Adair (2004). When taking the summation of the projects and comparing the totals, the Paparis estimate total is 1.01% higher than the winning bid. These results indicate that the Paparis estimating program can yield accurate results for recent dredging projects as well as older projects, and that the Paparis estimating program provides useful results over a range of project types. Figure 8 provides a bar chart that compares the variation between the winning bid and the various estimates.

Similar to the recent projects analyzed, Figure 8 indicates the tendency of government estimates to overestimate the total project cost. The government estimates were all greater than the winning bids for each of the five projects. This is especially noticeable on the Fernandina Harbor and Wando River projects, where the government estimates exceeded the winning bids by greater than 50%. Figure 8 also indicates that the CDS (2016) program also consistently provided conservative estimates, however the CDS (2016) estimates tended to be closer to the winning bid than the government estimates.

The biggest advantage of the CDS (2016) program, as indicated in Figure 8 is that it does not under-predict project costs on larger projects, while the Paparis and Adair (2004) estimates both under-predicted the total cost for the Coos Bay (1997) and Wando River projects, the CDS (2016). These were the two largest projects that Adair (2004) selected, as seen in Table 13.

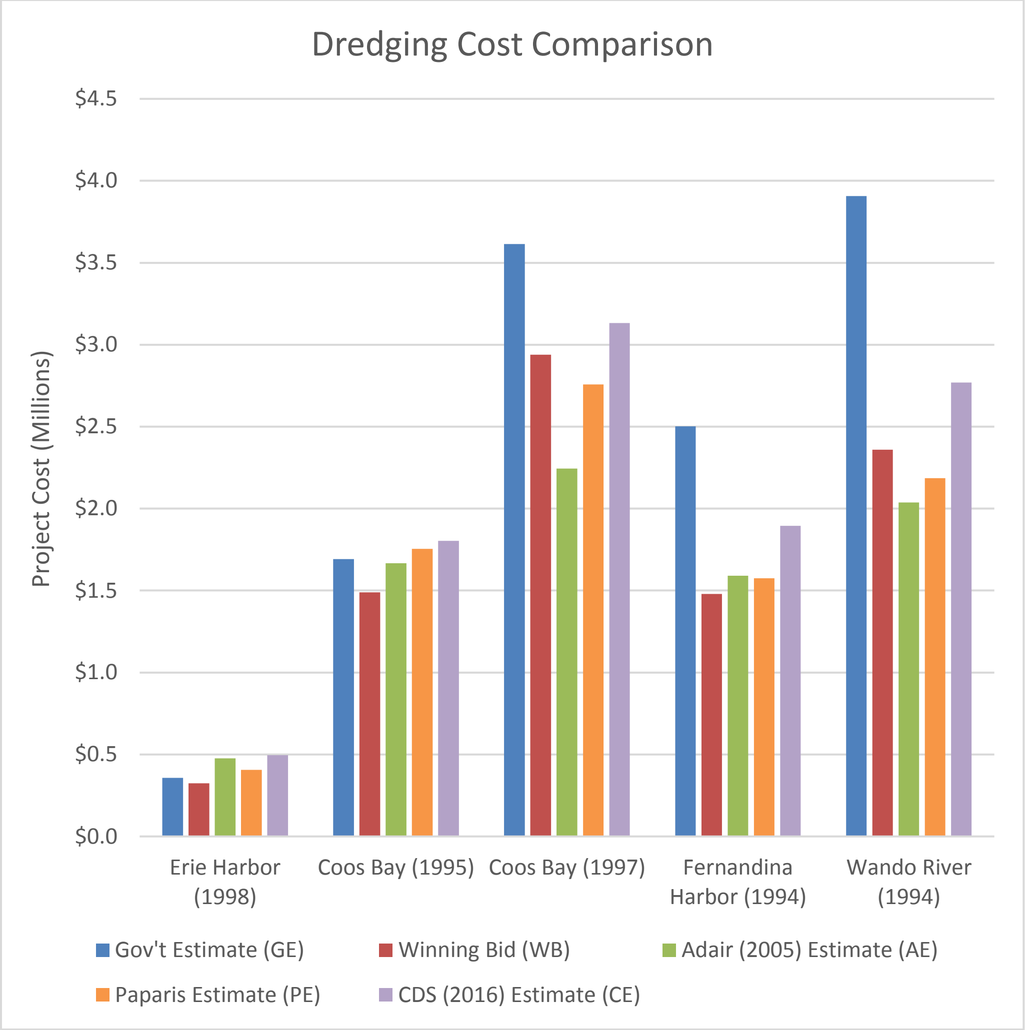

Figure 8: Project Cost Comparisons with Adair (2004) and CDS (2016)

Sensitivity Analysis

In order to demonstrate how certain project variables can influence the overall cost estimate, a sensitivity analysis was performed. The sensitivity analysis consisted of varying a single project parameter, while holding the remaining project parameters constant for a test project. The resultant total project cost is then compared to the changing parameter. The test project consisted of a theoretical dredging project for 382,277 m^3 (500,000 yd^3) of material to be dredged. The location factor was set to 1.0 by selecting the "national average" location in the program. The year selected was 2015, thus ensuring that the cost inflation factor was 1.0. The default depth was 7.6 m (25 ft), and the default sediment type was sand and clay. The sensitivity analysis explored the effect on project cost when sediment type, bucket size, digging depth, and planned operating time were varied.

The first parameter considered was the sediment type. The program was run for each of the six sediment types that the program allows the use to choose from: mud, loose sand, compact sand, sand and clay, stones, and broken rock. The results are shown in Figure 9.

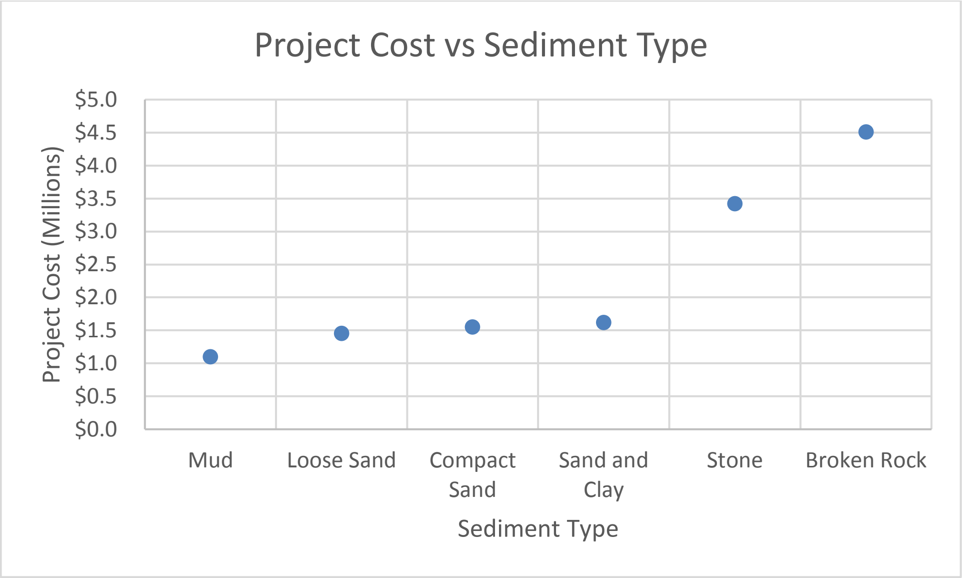

Figure 9: Sensitivity Analysis, Impact on Total Project Cost Due to Variation in Sediment Type.

Figure 9 indicates that the project cost will increase significantly if the project requires stone or broken rock removal. This is because stone and broken rock significantly reduce the capacity modifier and the fill factor for the clamshell bucket (Adair, 2005). By effectively reducing the bucket's capacity, the change in sediment type decreases the production rate, which leads to a longer project timeline. Since most project costs are calculated on a rate basis (e.g. cost per day), the result is an increased project cost. For this reason, dredging projects will include a separate line item for rock removal (NDC, 2013)

Since stone and broken rock can have such a significant impact on the overall project, the sensitivity analysis is shown in Figure 10 with the stone and broken rock sediment types omitted.

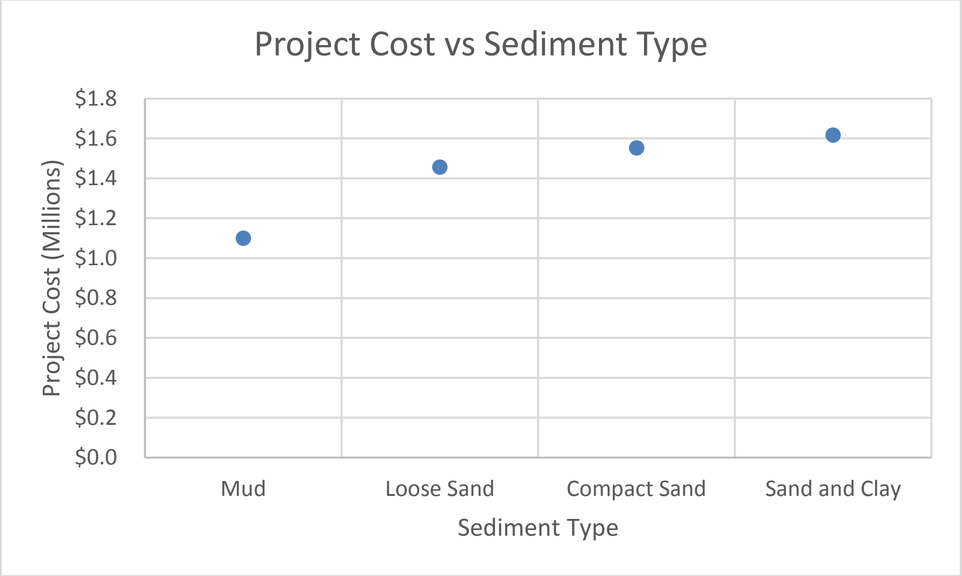

Figure 10: Sensitivity Analysis, Impact on Total Project Cost Due to Variation in Sediment Type, Stones and Broken Rock excluded.

While the effect on project cost is less significant when broken stone and rocks are omitted, the sediment type can still have a significant effect on the project cost. If a sediment type other than the default input of sand and clay is selected, the project cost is reduced, with the maximum reduction for a situation where the sediment type is pure mud.

For the bucket size comparison, Figure 11 shows the impact on total project cost due to varying the bucket size. For this comparison, the bucket size was varied from 1.53 m^3 to 19.1 m^3 (2 yd^3 to 25 yd^3) at 0.76 m^3 (l yd^3) increments, and from 19.1 m^3 to 38.2 m^3 (25yd^3 to 50 yd^3) using 3.8 m^3 (5 yd^3) increments.

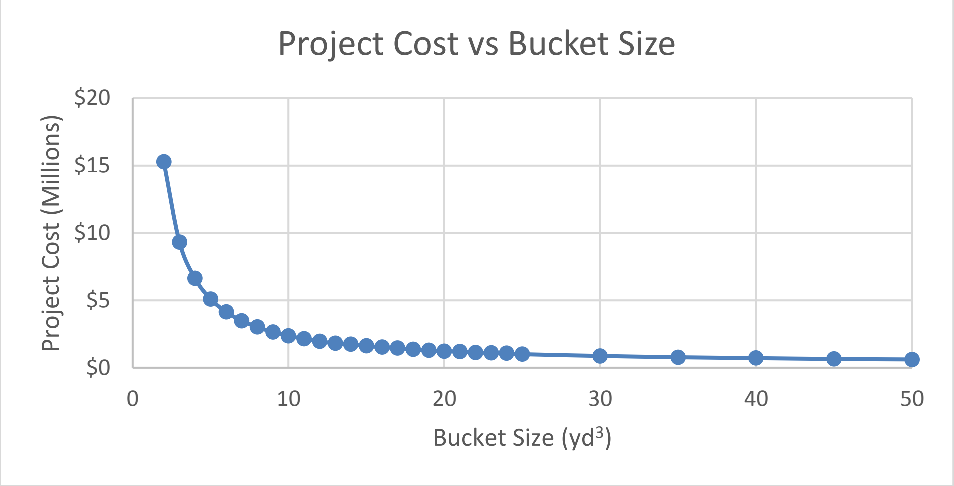

Figure 11: Sensitivity Analysis, Impact on Total Project Cost Due to Variation in Bucket Size.

As Figure 11 shows, the project cost is especially sensitive to smaller bucket sizes. The project cost varied from almost $15 million for a 1.53 m^3 (2 yd^3) bucket to as little as $615,000 for a 38.2 m^3 (50 yd^3) bucket. To further illustrate the effect smaller bucket sizes have on project costs, Figure 12 shows the relationship between bucket size and project costs for buckets from 1.53 m^3 to 3.82 m^3 (2 yd^3 to 5 yd^3), and Figure 13 shows the relationship between bucket size and project cost for buckets from 3.82 m^3 to 38.2 m^3 (5 yd^3 to 50 yd^3).

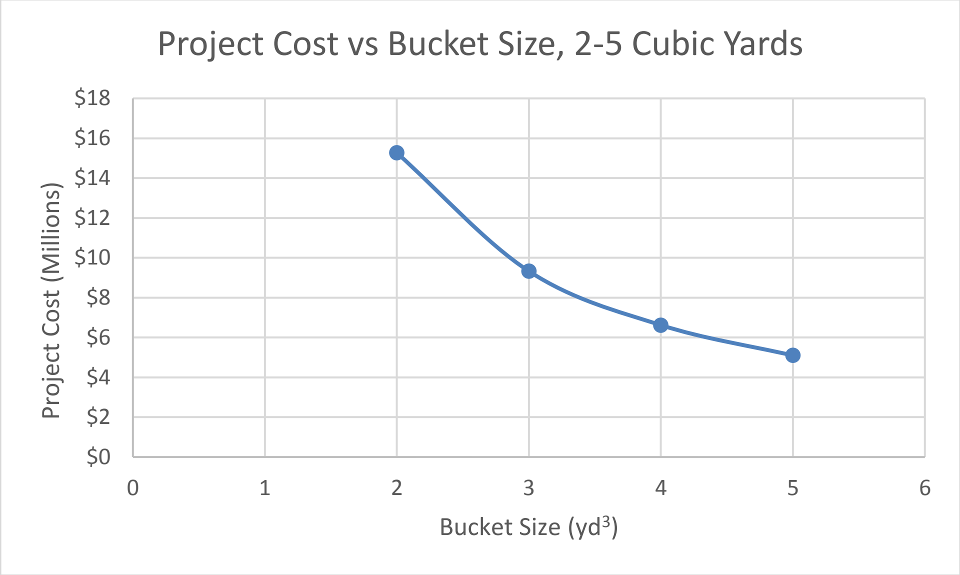

Figure 12: Project Cost vs Bucket Size, 2 to 5 Cubic Yard Bucket Size

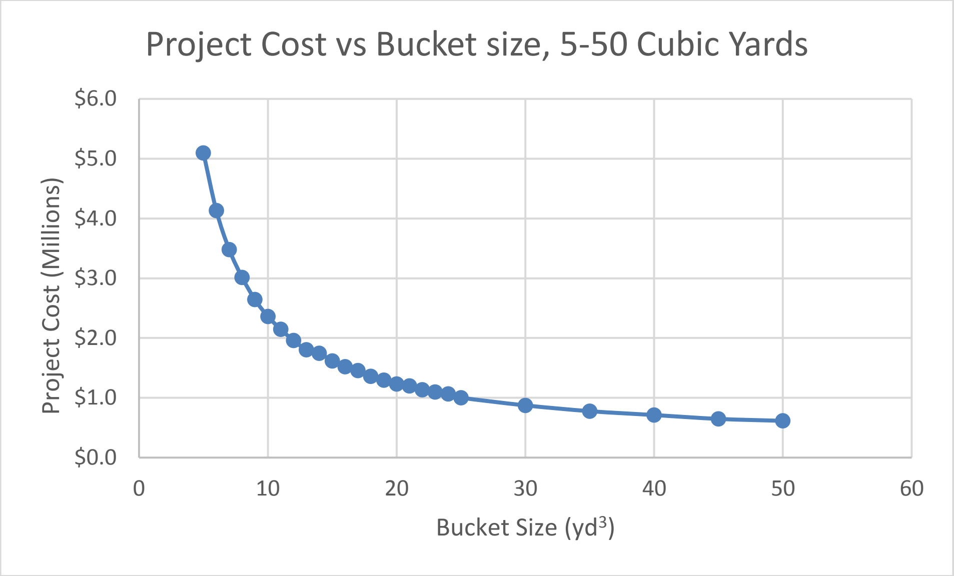

Figure 13: Project Cost vs Bucket Size, 5 to 50 Cubic Yard Bucket Size

The reason for the dramatic cost increase for the smallest bucket size is due primarily to the bucket fill factors. As seen in equations (1) through (6), the bucket fill factors are logarithmic functions of bucket size. The result is that the bucket fill factor changes the most for the smallest bucket sizes, with the increases becoming less as the bucket size increases. While the bucket size itself does impact the production rate, the fill factor effects dominate the sensitivity analysis. This can be seen in Figure 14, which reproduces the bucket fill factor curve for the sand and clay sediment type. For bucket sizes from 1 m^3 to 5 m^3 (1.3yd^3 to 6.5 yd^3) the fill factor increases by almost 50%, from 5 m^3 to 10 m^3 (6.5 yd^3 to 13.1 yd^3) the fill factor increases by only 17%, and from 10 m^3 to 15 m^3 (13.1 yd^3 to 19.6 yd^3) the fill factor increases by 7%.

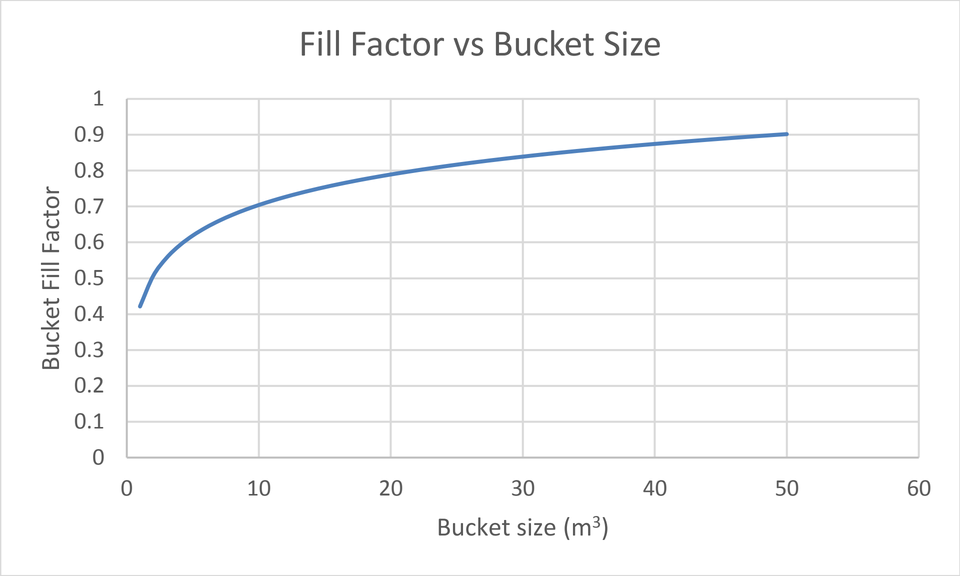

Figure 14: Bucket Fill Factor vs Bucket Size, Sand and Clay Sediment Type

The next parameter analyzed was the digging depth. The digging depth was varied in 1.52 m (5 ft) increments from 1.52 m to 16.8 m (5 ft to 55 ft). The results are shown in Figure 15.

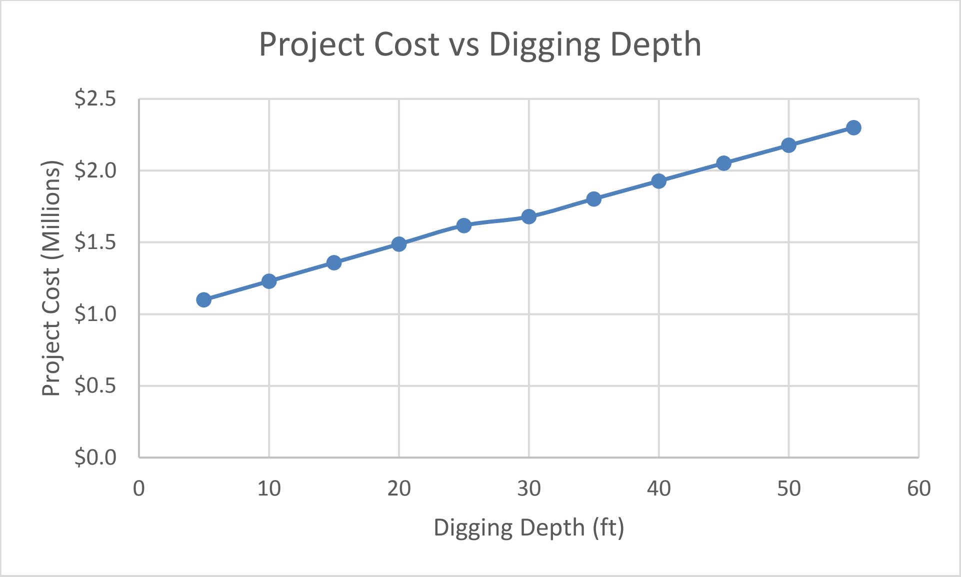

Figure 15: Sensitivity Analysis, Impact on Total Project Cost Due to Variation in Digging Depth.

Figure 15 shows a linear relationship between the digging depth and the project cost. The impact on project cost is because the increased digging depth increases the cycle time. The increased cycle time thus decreases the dredge's productivity and increases the project time, thus increasing the project cost. The apparent outlier at the 7.62 m (25 ft) digging depth is likely due to the fact that the estimating program rounds the project time up to the next day, e.g. if the project is estimated to take 15.1 days to complete, the program rounds up to 16 days. This is significant because most of the project costs are based on a daily rate. Thus, it is possible for a slight variation in the digging depth to have no impact on the project cost.

The final parameter analyzed was estimated planned operating hours per day. The program default is set at 16 hours, or a double-shift. This value was varied in two-hour increments from 8 hours to 24 hours. The results are shown in Figure 16.

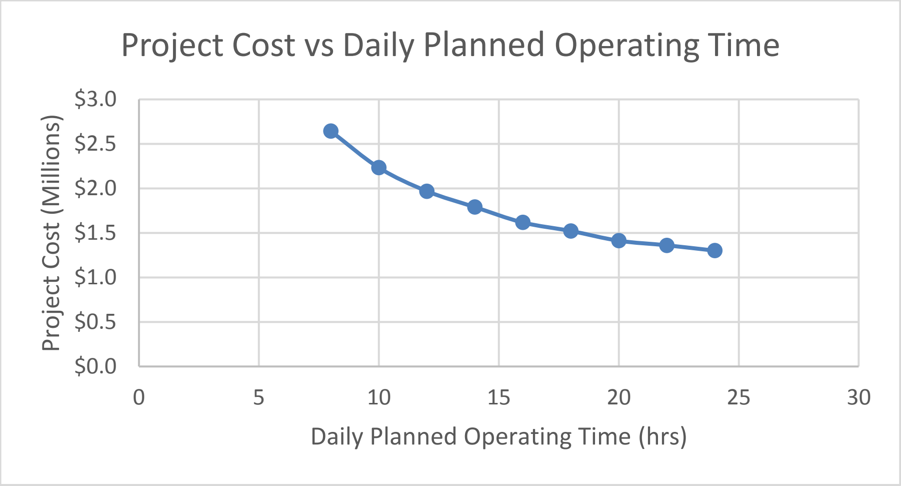

Figure 16: Sensitivity Analysis, Impact on Total Project Cost Due to Variation in Daily Planned Operating Time.

Figure 16 indicates that increasing the Daily planned operating time from a single eight-hour shift to a double-shift reduces the project cost by approximately 38%, while increasing to a continuous operating schedule results in a project cost reduction of 50%. It is important to note that such an increase may reduce the dredging crew’s productivity and thus the effective operating time. A continuous operating schedule would require performing dredging operations during nighttime, which adds to an evolution’s overall complexity, and results in less favorable working conditions. Since the analysis performed was a univariate sensitivity analysis, the potential reduction in operating efficiency was not considered.

CONCLUSION AND RECOMMENDATIONS

This thesis provides the methodology for estimating the production and cost of a mechanical clamshell dredging project. The methodology was used to develop a readily available, Microsoft Excel-based program for estimating mechanical clamshell dredging costs.

The program improves upon a previous estimating program developed by Adair (2004), and also incorporates and expands upon cost estimating techniques from Wowtschuk (2016). With the expectation of limited project data being known, the program allows the user to develop a reasonably accurate cost estimate, while still allowing the user to incorporate project- and equipment-specific information when available.

The production rate is calculated using the production rate methodology proposed by Bray et al (1997), and is based on bucket size, sediment type, and cycle time. This production rate is further reduced by delay factors, which are vary based on dredging area, depth of dredging cut, hopper and tugboat characteristics, and disposal site characteristics. This production rate is used to determine the estimated project duration, which largely determines the project’s costs, by combining the production rate estimate with assumptions regarding operating cost rates.

The estimating program resulted in a mean absolute percent error of 23.8% when total project costs were compared between the winning bid and the estimating program, compared to a mean absolute percent error of 33.5% between the winning bid and the government estimate. When mobilization/demobilization costs and any other costs not related to the dredging and placement of sediment were excluded, and only dredging production costs were considered, the result was a mean absolute percent error of 26.8% between the winning bid and the estimating program, compared to a mean absolute percent error of 35.3% between the winning bid and the government estimate. This indicates that the estimating program developed cost estimates that were closer to the winning bid than the government estimate. However, the estimating program tended to underestimate project costs. While the degree of under-estimation decreased from 12.1% to 1.9% when only production costs were considered, it is generally better to over-estimate rather than under-estimate a project's costs when developing cost estimates.

Overall, the accuracy of the program indicates it can reasonably predict mechanical clamshell dredging projects for open water disposal. As with any cost estimate, the more information that is known about a dredging project and can be incorporated into the estimate, the more accurate the results. As shown in the sensitivity analysis, a clamshell dredge estimate is particularly sensitive to the bucket size. Hence, the decision to incorporate different default bucket sizes into the estimating program's architecture. Having project data on bucket sizes used when comparing results would most likely reduce the variations between the project estimate and the winning bids. It would also help to reduce the level of uncertainty associated with the program's estimates.

The capital cost data, and thus its dependent parameters, would benefit from more recent cost information that accounts for cost increases in dredge construction due to increased bucket sizes and improved technology that may be incorporated in new dredge construction. However, the paucity of capital cost information available to users outside of the dredging industry is likely to persist, and thus the data from Bray et al (1997) provides the best means of quantifying these costs. In addition, fuel consumption estimates can be improved by comparing the consumption rate of diesel engines installed on dredges to the values over the values provided by Bray et al (1997)

The functionality of the estimating program can be improved by developing an estimation methodology for clamshell dredging projects that place the dredged sediment in an upland placement area, in addition to the open water placement estimating methods used in this thesis. The program functionality can also be expanded by incorporating the production and cost estimating techniques from Bray et al (1997) for backhoe mechanical dredges to further improve the versatility of the estimating program.

An additional improvement to the estimating program would be a refinement of the mobilization and demobilization cost estimate methodology. This estimating program adopts a one-size-fits-all approach by estimating theses costs as a percentage of the production costs. Further analysis of dredging projects may reveal correlation between project size or certain project characteristics and mobilization costs.

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APPENDIX A

USER’S GUIDE

This guide serves as a walkthrough for the user to understand the mechanical clamshell production and cost estimation program. It will explain to the user all of the steps required to develop an estimate, including acquiring the data inputs required to use the dredging program, highlight default settings within the program, and explain the calculation, process, and the accompanying results. This guide will walk the user through the estimating process used for the Suisun Bay project estimate in this thesis.

Finding the Required Project Inputs

The program is designed to allow the user to generate a reasonable cost estimate with limited information. There are four inputs that the user must obtain in order to use the program: volume to be dredged, average digging depth, project year, and project location (state). To obtain project volumes, it is recommended that the user obtain volumes from the dredging dictionary. The dredging dictionary contains a wealth of dredging project information dating as far back as 1990. The information contained in the dredging dictionary includes estimated dredging volumes, dredge types and disposal methods used, government estimates, winning bids, project dates, contractor information, and actual project information. As of the writing of this user guide, the NDC maintains its dredging dictionary here: http://www.navigationdatacenter.us/db/dredging/xls/dredging.xlsx.

If historical project information is not available for the location of the dredging project the user is trying to estimate, an alternative method is to calculate the dredging prisms for the project. The user can do this using channel project dimensions listed on navigational charts. Navigational charts are maintained by NOAA's Office of Coast Survey (OCS). OCS has a useful chart locator tool here that will easily allow the user to identify the specific navigational chart required. The locator tool can be found here: http://www.charts.noaa.gov/InteractiveCatalog/nrnc.shtml.

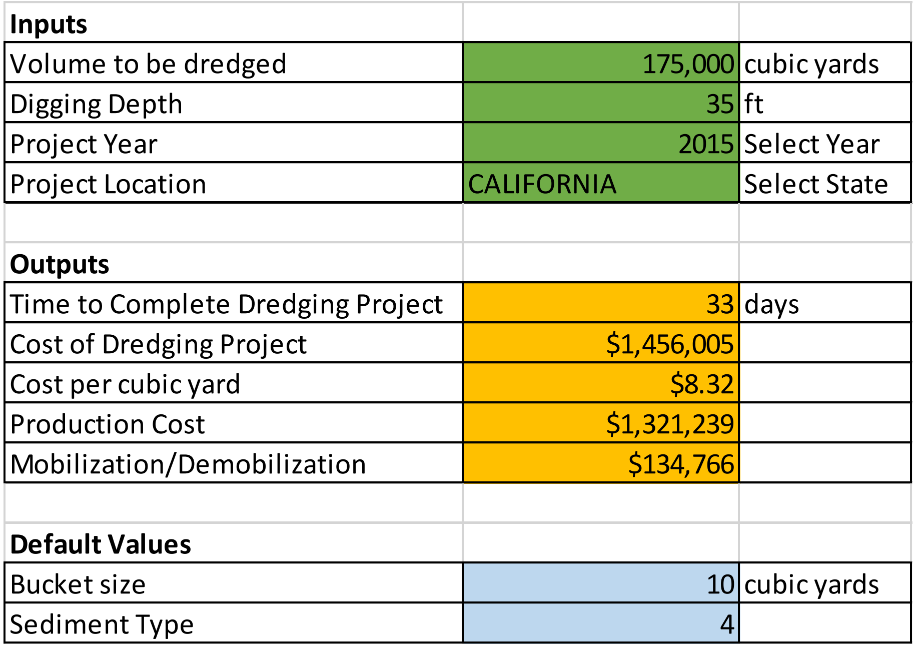
The user will likely have to estimate the vertical dimension of the prism, assuming hydrographic survey information is not available. Another source of channel dimension information is the cognizant USACE district website. Many of the USACE districts maintain hydrographic surveys for navigation channels within their area of responsibility. This survey data will provide the user with information needed to make a more informed dredging volume calculation. The various USACE district websites can be accessed via this link: http://www.usace.army.mil/Locations.aspx.

The average digging depth can be obtained from either navigational charts or the local USACE district website. Project year and project location are self-explanatory.

Entering Required Project Inputs

The "Inputs" sheet is shown in Table A-1. The user enters the required data in the appropriate cell. For ease of use, the program has color-coded cells throughout to help differentiate between inputs, default values, calculated values, and tabulated values. Required inputs are green, default values are blue, calculated values are orange, and values that are tabulated or obtained from other portions of the program are yellow.

Table A-1: Estimating Program Input Sheet



Inputs		
Volume to be dredged	175,000	cubic yards
Digging Depth	35	ft
Project Year	2015	Select Year
Project Location	CALIFORNIA	Select State
Outputs		
Time to Complete Dredging Project	33	days
Cost of Dredging Project	$1,456,005	
Cost per cubic yard	$8.32	
Production Cost	$1,321,239	
Mobilization/Demobilization	$134,766	
Default Values		
Bucket size	10	cubic yards
Sediment Type	4	

For project year and location, the program has dropdown menus. For project volumes and digging depth, it is important to provide the inputs in cubic yards and ft, respectively.

The inputs sheet also summarizes the project outputs, thus easily allowing the user to obtain the results. Below the "Outputs" section is the "Default Values" section. This section contains the default values that can have the biggest influence on the overall estimate, and as such are values that the user would want to adjust if project-specific information is available. For bucket size, the program will automatically adjust the bucket size based on the volume to be dredged. Projects with less than 76,455 m^3 (100,000 yd^3) have a default bucket size of 4.59 m^3 (6 yd^3), projects between 76,455 m^3 (100,000 yd^3) and 191,139 m^3 (250,000 yd^3) assume a default bucket size of 7.65 m^3 (10 yd^3), and projects greater than 191,139 m^3 (250,000 yd^3) assume a bucket size of 11.5 m^3 (15 yd^3).

For sediment type, the user selects from a number from 1 to 6, with each number corresponding to a sediment type. The legend, shown in Table A-2, is near the dropdown menu. The default value assumes a sand and clay sediment type.

Table A-2: Sediment Type Legend

Sediment Types	
1	mud
2	loose sand
3	compact sand
4	sand and clay
5	stone
6	broken rock

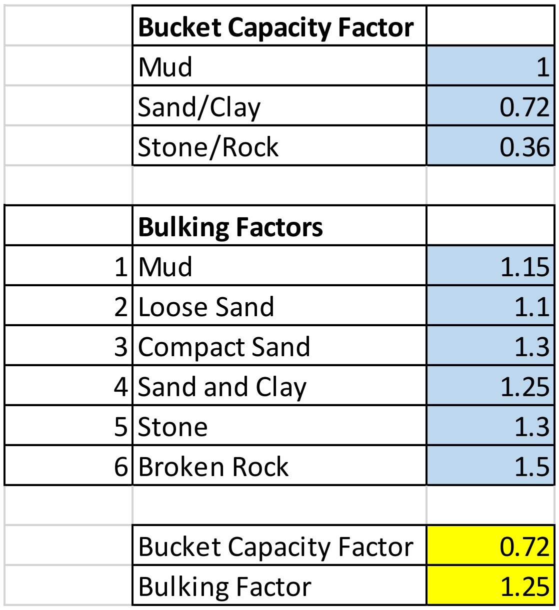
Bucket Capacity, Bulking, and Bucket Fill Factors

The next sheet in the program is the "Fill and Bulking Factors" sheet. It provides the bucket capacity factors, bulking factors, and calculates the bucket fill factors. The first portion of the sheet is shown in Table A-3. The default values for these factors were obtained from Bray et al (1997). The values at the bottom of Table A-3 are the bucket capacity factor and bulking factor value used for the production calculations, and correspond to the sediment type selected.

Table A-4 shows the fill factor portion of the sheet, which is for calculating the bucket fill factor. The bucket fill factors are a function of the bucket size, and are calculated using the curves from Adair (2004). The fill factor value at the bottom of

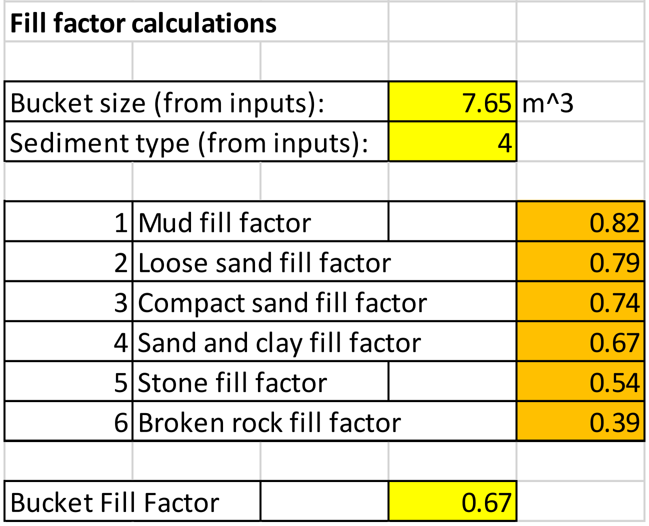
Table A-4 corresponds to the sediment type selected and is used for the production calculation.

Table A-3: Bucket Capacity Factor and Bulking Factor



	Bucket Capacity Factor	
	Mud	1
	Sand/Clay	0.72
	Stone/Rock	0.36
	Bulking Factors	
1	Mud	1.15
2	Loose Sand	1.1
3	Compact Sand	1.3
4	Sand and Clay	1.25
5	Stone	1.3
6	Broken Rock	1.5
	Bucket Capacity Factor	0.72
	Bulking Factor	1.25

Table A-4: Fill Factor Calculations



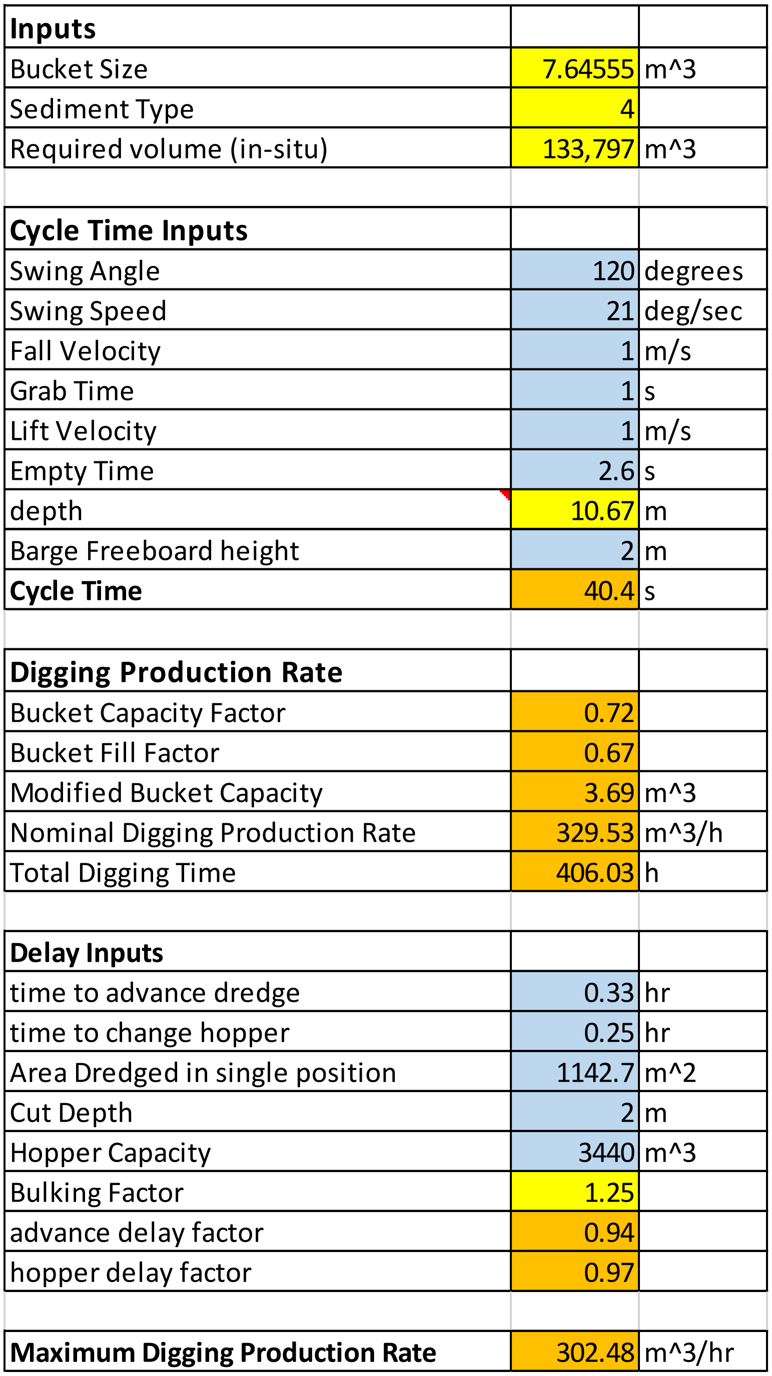
Fill factor calculations			
Bucket size (from inputs):		7.65	m^3
Sediment type (from inputs):		4	
1	Mud fill factor		0.82
2	Loose sand fill factor		0.79
3	Compact sand fill factor		0.74
4	Sand and clay fill factor		0.67
5	Stone fill factor		0.54
6	Broken rock fill factor		0.39
Bucket Fill Factor		0.67	

Production

The production sheet develops the production estimate for the project. It consists of determining the maximum production rate, or digging production rate. The program also determines the productivity of the scows, or a hauling production rate, to ensure the estimate has an adequate number of scows to support the digging production rate. The default values for this sheet were obtained from Adair (2004). Although the inputs page requires inputs in US customary units, the production calculations require SI units. The reason for this difference is to allow the user to easily enter data obtained from the NDC, OCS, and/or the local district, since all of this information is provided in US customary units. The digging production rate portion of the production calculations is shown in Table A-5.

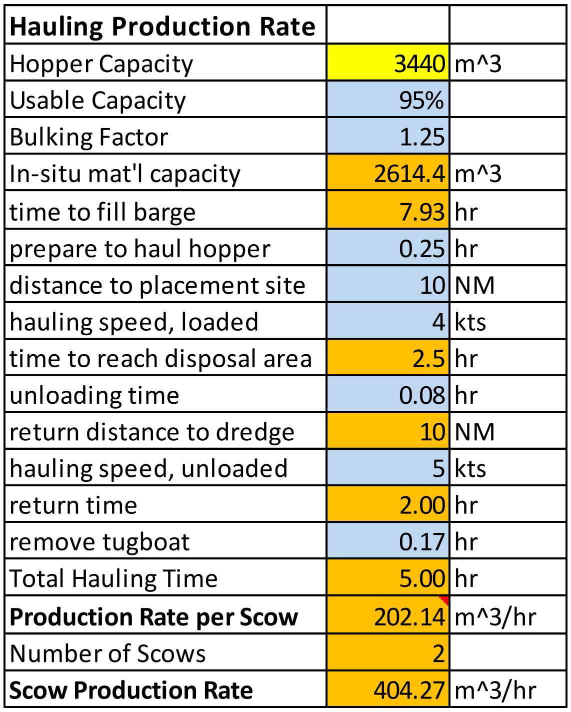
The next portion of the production sheet is the hauling production rate calculation, shown in Table A-6. The hauling production rate calculation ensures the estimate has enough scows to keep the dredge from sitting idle. The number of scows is used later in the cost estimate portion. If the placement area for the project is quite far, the project may require a greater number of scows than usual. At a minimum, two scows will be required. If more than 3 scows are required, the program will prompt the user to manually input the number of scows. The user will not be able to calculate costs until the hauling production rate is less than the digging production rate. The default values for the hauling production calculation were selected based on the author's experience.

Table A-5: Digging Production Rate Calculations



Inputs		
Bucket Size	7.64555	m^3
Sediment Type	4	
Required volume (in-situ)	133,797	m^3
Cycle Time Inputs		
Swing Angle	120	degrees
Swing Speed	21	deg/sec
Fall Velocity	1	m/s
Grab Time	1	s
Lift Velocity	1	m/s
Empty Time	2.6	s
depth	10.67	m
Barge Freeboard height	2	m
Cycle Time	40.4	s
Digging Production Rate		
Bucket Capacity Factor	0.72	
Bucket Fill Factor	0.67	
Modified Bucket Capacity	3.69	m^3
Nominal Digging Production Rate	329.53	m^3/h
Total Digging Time	406.03	h
Delay Inputs		
time to advance dredge	0.33	hr
time to change hopper	0.25	hr
Area Dredged in single position	1142.7	m^2
Cut Depth	2	m
Hopper Capacity	3440	m^3
Bulking Factor	1.25	
advance delay factor	0.94	
hopper delay factor	0.97	
Maximum Digging Production Rate	302.48	m^3/hr

Table A-6: Hauling Production Calculations

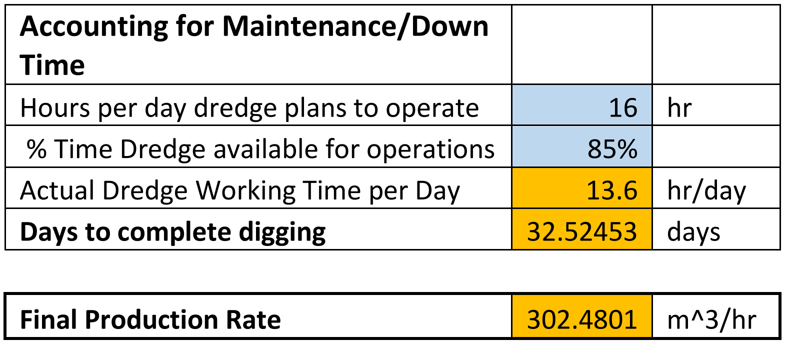


Hauling Production Rate		
Hopper Capacity	3440	m^3
Usable Capacity	95%	
Bulking Factor	1.25	
In-situ mat'l capacity	2614.4	m^3
time to fill barge	7.93	hr
prepare to haul hopper	0.25	hr
distance to placement site	10	NM
hauling speed, loaded	4	kts
time to reach disposal area	2.5	hr
unloading time	0.08	hr
return distance to dredge	10	NM
hauling speed, unloaded	5	kts
return time	2.00	hr
remove tugboat	0.17	hr
Total Hauling Time	5.00	hr
Production Rate per Scow	202.14	m^3/hr
Number of Scows	2	
Scow Production Rate	404.27	m^3/hr

The final portion of the production sheet is the project duration calculation, shown in Table A-7. The program determines the project duration based on the hours per day the dredge plans to operate, and percentage of time the dredge is available for operations. In this case, a 16 hour (double-shift) working day was selected, and it is expected that the dredge is available for operations during 85% of that time. The 85% is intended as a default value, however the user can adjust for project-specific disruptions such as frequent vessel traffic, dredge crew and management skill, or other project conditions (Bray et al, 1997). If the number of scows inputted for the project is insufficient, the program will return an error for the “days to complete digging” value.

At this point the user has completed the production estimate and is ready to progress to the cost estimate.

Table A-7: Project Duration and Final Production Rate Calculations



Accounting for Maintenance/Down Time		
Hours per day dredge plans to operate	16	hr
% Time Dredge available for operations	85%	
Actual Dredge Working Time per Day	13.6	hr/day
Days to complete digging	32.52453	days

Final Production Rate	302.4801	m^3/hr

Costs

The next sheet is the "Costs" sheet, which develops a daily cost for the project, then develops the total production cost based on the project duration calculated in the "Production" sheet. The production cost is used to calculate the mobilization and demobilization costs, which is added to the production cost to obtain the total project cost. Table A-8 shows the cost calculations.

The first part of the cost calculations is the daily cost, with the first line item being the fuel cost. The fuel cost is calculated based on the horsepower of the dredging plant. See the "Fuel" section of this user guide for more detail on how the fuel costs were calculated. The lubricant costs are assumed to be 10% of fuel costs and are the next daily line item. Minor repairs, major repairs, insurance, and depreciation are the next line items, and are calculated based on the capital cost of the dredge. See the

“Capital Cost” section of this user guide for more detail. The crew and labor calculation is detailed in the “Labor” section of this guide, and the equipment rental details are also included in the “Capital Cost” section.

Once the daily cost line items are known, they are added together to develop a daily project cost. To this subtotal, the overhead and bonding rates are applied and added to the subtotal. To this new total (“Daily total w/ovhd and bonding”), the profit rate is applied. The profit is added to the project total, and the result is the Total Daily Cost. Default values for overhead, bonding, and profit are 8.5%, 1.5%, and 10% respectively, and can be modified by the user.

The total daily cost is multiplied by the project duration calculated in the “Production” sheet and rounded up to the next day. For example, if the project duration is 29.1 days the project duration is rounded up to thirty days. In the case of the Suisun Bay estimate, Table A-7 indicates the project duration was estimated to be 32.5 days, so that is rounded up to 33 days for the purpose of production costs. The result is the total production cost. The next line in the cost sheet shows the total production cost with the year and location factor applied.

Table A-8: Cost Calculations

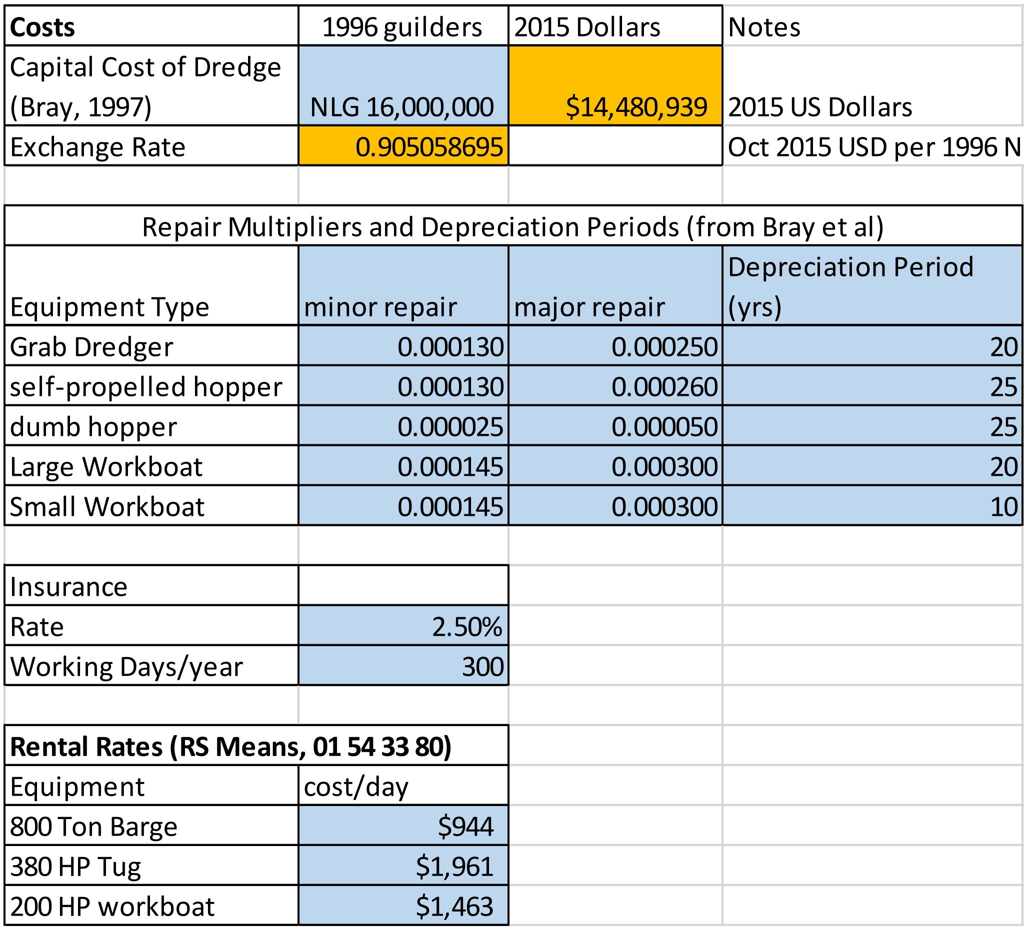
Daily Costs		2015 Dollars	Notes
	Fuel	$4,297	cost per day
	Lubricants	$430	cost per day (10% of fuel cost)
	Minor Repairs	$1,883	cost per day
	Major Repairs	$3,620	cost per day
	Insurance	$1,207	cost per day
	Depreciation	$2,413	cost per day
	Crew and Labor	$8,880	cost per day
	Equipment Rentals	$5,312	cost per day
Subtotal		$28,041	cost per day
Overhead and Bonding			
	Overhead Rate	8.5%	
	Bonding Rate	1.5%	
	Ovhd and Bonding	$2,804	
Daily Total w/ Ovhd & Bonding		$30,846	
Profit			
	Profit Rate	10%	
Profit		$3,085	Calculated after total w/Ovhd & Bonding
Total Daily Cost		$33,930	
Total Production Cost		$1,119,694	
Adjusted Production Cost		$1,321,239	
Mobilization & Demobilization			
	Mob/Demob Rate	10.2%	
Mob/Demob		$114,209	
Adjusted Mob/Demob		$134,766	Percentage of Production Cost
Total Project Cost		$1,233,902	
Year Factor		1.00	
	Year-Adjusted Cost	$1,233,902	
Location Factor		1.18	
	Location-Adjusted Cost	$1,456,005	Includes year adjustment
Additional Costs			
	Rock/Debris Removal	$0	
	Government-Directed Standby Time	$0	
	Environmental Monitoring	$0	
	Other Project-Specific Costs	$0	
Total Adjusted Project Cost		**$1,456,005**	

The next portion is the mobilization/demobilization costs. This program determines the mobilization/demobilization costs as a percentage of the total production cost. The default value is 10.2%, however the user can adjust this value as desired. Alternately, the user can enter a mobilization/demobilization cost if known. The program calculates the mobilization and demobilization costs with the year and location factors included as well ("Adjusted Mob/Demob"). After the mobilization and demobilization costs are determined, they are added to the total production costs. The project year adjustment factor is first applied, and then the location adjustment factor, with the "total adjusted project cost" representing the cost estimate output.

Capital Cost

Table A-9 shows the capital costs portion of the cost estimate, which is located on the "Costs" spreadsheet. The capital cost of dredge, repair multipliers, depreciation periods, and insurance rates come from Bray et al (1997), the working days per year from Wowtschuk (2016), and the rental rates from RS Means (2015).

Table A-9: Capital Costs



Costs	1996 guilders	2015 Dollars	Notes
Capital Cost of Dredge (Bray, 1997)	NLG 16,000,000	$14,480,939	2015 US Dollars
Exchange Rate	0.905058695		Oct 2015 USD per 1996 N

Repair Multipliers and Depreciation Periods (from Bray et al)			
Equipment Type	minor repair	major repair	Depreciation Period (yrs)
Grab Dredger	0.000130	0.000250	20
self-propelled hopper	0.000130	0.000260	25
dumb hopper	0.000025	0.000050	25
Large Workboat	0.000145	0.000300	20
Small Workboat	0.000145	0.000300	10

Insurance	
Rate	2.50%
Working Days/year	300

Rental Rates (RS Means, 01 54 33 80)	
Equipment	cost/day
800 Ton Barge	$944
380 HP Tug	$1,961
200 HP workboat	$1,463

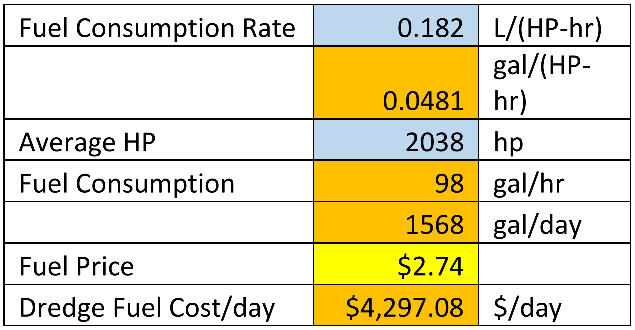
The capital cost calculation is explained in the "Dredge Capital Costs" section of the thesis. The repair multipliers represent a daily rate for major and minor repairs. By default, the program utilizes the repair multipliers and depreciation period for a grab dredge. The repair multipliers for hoppers and workboats are included if the user wants to treat these items as owned, and not rented. Capital costs for these items would be required to utilize this method.

This portion also includes the rental rates for support equipment. The number in the heading correlates to the section of RS Means (2015) where the rental rate data was obtained from, allowing the user to update the data in the future.

Fuel

Table A-10 shows the fuel consumption and cost calculations used for the cost estimate. The fuel estimate is based on a consumption rate of 0.182 L (0.0481 gal) per hour per horsepower of installed power from Bray et al (1997). After converting the consumption rate to gallons, it is multiplied by the installed horsepower to determine the hourly fuel consumption. The hourly rate is then multiplied by the number of hours per day the dredge plans to operate (from the "Production" sheet) to determine the daily consumption rate. The daily consumption rate is then multiplied by the fuel price per gallon to determine the daily fuel cost.

Table A-10: Fuel Calculations



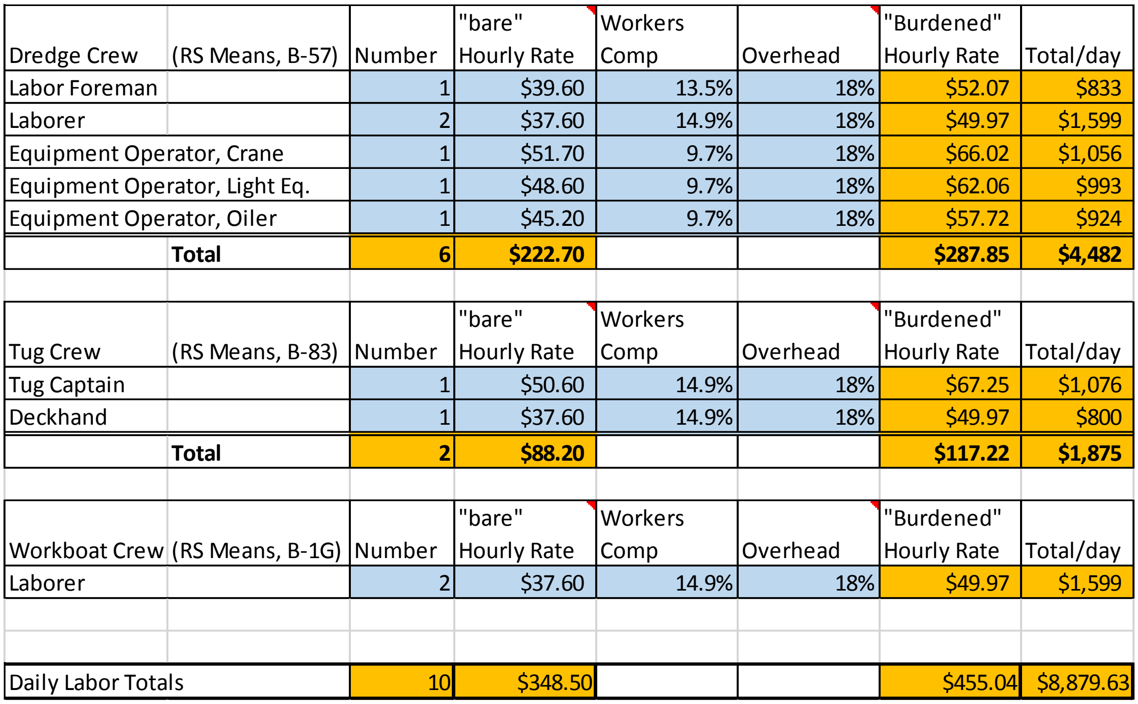
Fuel Consumption Rate	0.182	L/(HP-hr)
	0.0481	gal/(HP-hr)
Average HP	2038	hp
Fuel Consumption	98	gal/hr
	1568	gal/day
Fuel Price	$2.74	
Dredge Fuel Cost/day	$4,297.08	$/day

The price per gallon was obtained from the US Energy Administration (EIA) website here: http://www.eia.gov/petroleum/gasdiesel/. The program uses an 18-month average of monthly U.S. on-highway diesel fuel prices. EIA reports national prices as well as regional prices. The program utilizes the 18-month average of regional fuel prices for the fuel calculation. The location selected on the “Inputs” sheet determines the regional average used.

Labor

The “Labor” sheet is shown in Table A-11. To estimate labor costs, a “bare” hourly labor rate was determined from RS Mean (2015) for each job type. The bare labor rate includes fringe benefits such as paid vacation, health insurance training, etc., but excludes legally required benefits such as unemployment insurance, and workman’s compensation. After the bare labor rate is established, a trade-specific workman’s compensation rate is applied to the bare labor rate, as well as a flat overhead rate, also from RS Means (2015). The overhead is intended to capture employer costs such as Social Security/Medicare withholding (FICA), unemployment insurance, and any risk insurance or public liability costs. The program uses a default overhead rate of 18%. Applying the workman’s compensation and overhead percentages to the bare labor rate yields the burdened hourly rate for each job type. This burdened hourly rate is multiplied by the planned operating hours per day (from the “Production” sheet), and the number of laborers per job type. This process is repeated for each job type, and the totals summed to obtain the total daily labor cost.

Table A-11: Labor Calculations



Dredge Crew	(RS Means, B-57)	Number	"bare" Hourly Rate	Workers Comp	Overhead	"Burdened" Hourly Rate	Total/day
Labor Foreman		1	$39.60	13.5%	18%	$52.07	$833
Laborer		2	$37.60	14.9%	18%	$49.97	$1,599
Equipment Operator, Crane		1	$51.70	9.7%	18%	$66.02	$1,056
Equipment Operator, Light Eq.		1	$48.60	9.7%	18%	$62.06	$993
Equipment Operator, Oiler		1	$45.20	9.7%	18%	$57.72	$924
	Total	**6**	**$222.70**			**$287.85**	**$4,482**
Tug Crew	(RS Means, B-83)	Number	"bare" Hourly Rate	Workers Comp	Overhead	"Burdened" Hourly Rate	Total/day
Tug Captain		1	$50.60	14.9%	18%	$67.25	$1,076
Deckhand		1	$37.60	14.9%	18%	$49.97	$800
	Total	**2**	**$88.20**			**$117.22**	**$1,875**
Workboat Crew	(RS Means, B-1G)	Number	"bare" Hourly Rate	Workers Comp	Overhead	"Burdened" Hourly Rate	Total/day
Laborer		2	$37.60	14.9%	18%	$49.97	$1,599
Daily Labor Totals		10	$348.50			$455.04	$8,879.63

Miscellaneous

The remaining sheets are the tables for the year and location adjustment factors, and the exchange rate calculation for the capital cost. This section of the user guide provides guidance if the user wishes to update information for year and location factors, however, it is only recommended to do so if the user has some familiarity with editing dropdown menus, If functions (including nested If functions), Match Functions, and Lookup Functions.

The annual cost index uses a Lookup function based on the year selected on the "Inputs" sheet. For the year adjustment factor, the user can simply update the "Index" values in column I of the "Annual Cost Index" sheet as updated USACE (2016) data becomes available. If the user wishes to add an additional year, the user can do this by adding additional rows to the sheet, adding the year and index, copying the formulas for factor and percent increase/decrease from an already entered row, updating the Lookup function, and updating the dropdown menu to include the new year(s).

The location factor is more complex, as it requires both a year and a location input. It also uses a Lookup function, but it depends on a Match function to allow the Lookup function to determine the factor based on two variables. The Match function uses an If function with a nested If function to account for the limited location factor data relative to the year indices. Future location indices can be added to the right of the 2015 column. Careful modification of the Match function, Lookup function, and dropdown menus is required to incorporate new location factor data.

The final sheet is the “Capital Cost” sheet, and contains the data used to calculate the exchange rate and inflation rates used to calculate the dredge capital cost in the “Costs” sheet.