COST ESTIMATION AND PRODUCTION EVALUATION FOR HOPPER DREDGES

A Thesis

by

THOMAS ELLIOT HOLLINBERGER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

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Approved by:

Chair of Committee,	Robert Randall
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ABSTRACT

Cost Estimation and Production Evaluation for Hopper Dredges. (May 2010)

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Chair of Advisory Committee: Dr. Robert E. Randall

Dredging projects are expensive government funded projects that are contracted out and competitively bid upon. When planning a trailing suction hopper dredge project or bidding on the request for proposal for such a project, having an accurate cost prediction is essential. This thesis presents a method using fluid transport fundamentals and pump power characteristics to determine a production rate for hopper dredges. With a production rate established, a number of financial inputs are used to determine the cost and duration of a project.

The estimating program is a Microsoft Excel spreadsheet provided with reasonable values for a wide arrange of hopper dredging projects. The spreadsheet allows easy customization for any user with specific knowledge to improve the accuracy of his estimate.

Results from the spreadsheet were found to be satisfactory using the default values and inputs of 8 projects from 1998 to 2009,: The spreadsheet produced an estimate that was an average of a 15.9% difference from the actual contract cost, versus a 15.7% difference for government estimates of the same projects.

ACKNOWLEDGEMENTS

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INTRODUCTION

Dredging, the excavation and placement of seabed material, was a $1 billion annual industry in the United States during 2008 and has grown steadily since the 1960's. Thirty-one (31) % of material dredged in the U.S. is accomplished by self-propelled trailing suction hopper dredges which are uniquely suited for maintaining channels and working in medium to soft materials (NDC 2009). Due to their immense scale, dredging projects are designed and funded based on competitive bidding processes, commonly cost shared by government entities and the US Army Corps of Engineers (USACE) in particular. During the competitive bidding process, a company will bid to undertake the project for a certain amount of money based on an estimate of how much that company thinks it will cost to complete the work. Many companies and even the Corps of Engineers use proprietary estimating software they believe will give a more accurate cost estimate, and thus an advantage in the bidding process. The capability gap still exists, however, for users outside the government-contractor community to easily generate their own dredging project cost estimates when considering new projects, or desiring to understand the scale of work being done.

This thesis follows the style of the Journal of Dredging Engineering.

Objective

This research will develop, test, and validate new software that can be used by the public without access to government or private estimating programs to predict the scope and cost of a hopper dredge project using a number of factors to describe the scope of work for the project as well as external influences on project cost. Dredge production, the rate of material moved, is key to estimating the project duration and thus the associated costs. Production will be determined in this software using fluid mechanics and transport knowledge paired with changeable inputs allowing the user to characterize the equipment in use as well as the material being dredged. This program can be easily distributed because the software is based on the commonly used Microsoft Excel spreadsheet format. The development process is described in the procedures section below, and the completed program will be measured for accuracy against publicly available results from recent USACE projects.

TRAILING SUCTION HOPPER DREDGES

Hopper dredges accounted for 31% of all dredging done for the federal government in 2008 (NDC, 2009). Trailing suction hopper dredges are self propelled vessels that use a trailing arm to move along the sea floor beneath the dredge collecting material as shown in Figure 1. When the vessel moves over the dredge site, the dragarms are lowered from the side until the draghead at the end of the dragarms rests on the sea floor, and centrifugal pumps in either the dragarm, within the hull, or both are energized. At this point the vessel is moving slowly forward and water is flowing into the dragheads and up the dragarms. Once the water flowing into the draghead begins to erode the sediment, the slurry moving up the dragarm achieves a certain threshold of material content and the slurry is then retained in the hopper section of the ship. Though some dragheads are equipped with waterjets or mechanical scrapers to break up harder material they are less common than ones which rely on the erosive flow of water. When slurry in the hopper approaches capacity, typically 750 to 10000 cubic meters (1000 to 13000 cubic yards), some sediment might have settled out of the slurry and cleaner water towards the top of the hopper may be allowed to flow out of a weir so that more slurry can be pumped into the hopper, this is called overflow (Bray et al., 1997). Sometimes, however, sediment will not settle out of the slurry fast enough and pumps are stopped when the hopper nears full capacity to avoid the overflow of sediment back into the water, which depends on the nature of the sediment and can differ from site to site or according to governing regulations.

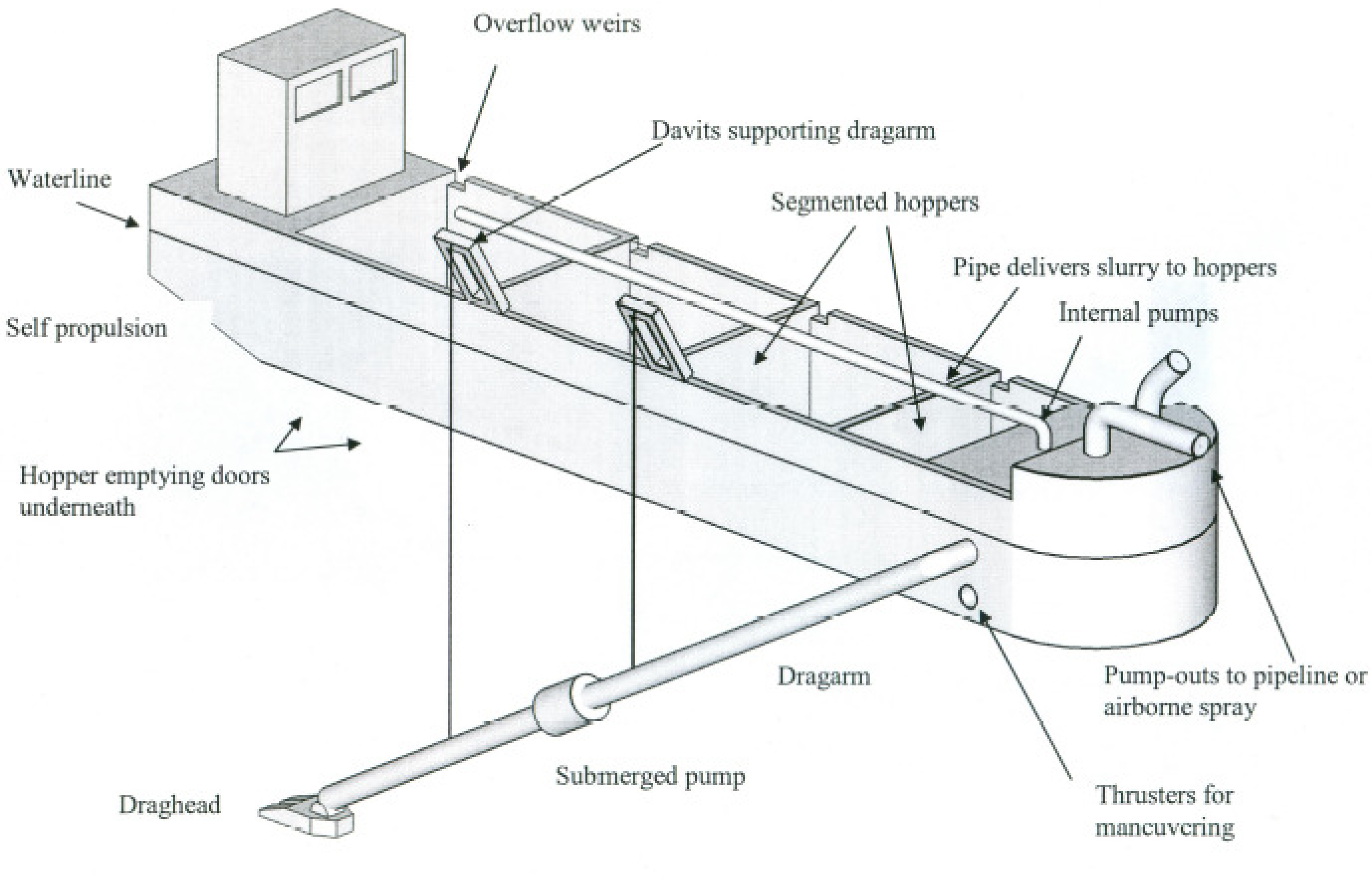

Figure 1. Trailing Suction Hopper Dredge. Note the dragarm lowered for operation.

When the hopper is full, the dredge lifts the dragarms off the seabed, secures its pumps, and sails to the designated placement area. The dredge empties its hopper at the placement area, normally through the doors of various types in the hull, though some dredges are a split-hull design where the vessel is comprised of two hull sections that are hinged along the centerline and are split apart by hydraulic power in a clamshell manner to open the underside of the hull and quickly unload the hopper. Hopper dredges are also equipped with discharge pipes allowing them to pump their hopper content into a pipeline or to discharge the contents through the air (called rainbowing) to a beach area if the material is being used for a beneficial project such as beach nourishment or the creation of artificial habitats. With an empty hopper, the dredge sails back to the dredging site and repeats the cycle of sail, load, sail, unload shown in Figure 2.

Hopper dredges are ideally suited to maintenance dredging, that is the removal of accumulated material from navigation channels that have been previously dredged. This suitability is due to the erosive action of the dreagheads which is especially effective on less hard materials. Another unique aspect of the hopper dredge is its self-propulsion which allows easy navigation, maneuvering, and traffic avoidance, and also eliminates most of the mobilization/demobilization costs associated with other dredges such as cutter-suction or mechanical bucket or dipper-types that usually require tow service to arrive at a project, and miscellaneous support vessels during operation.

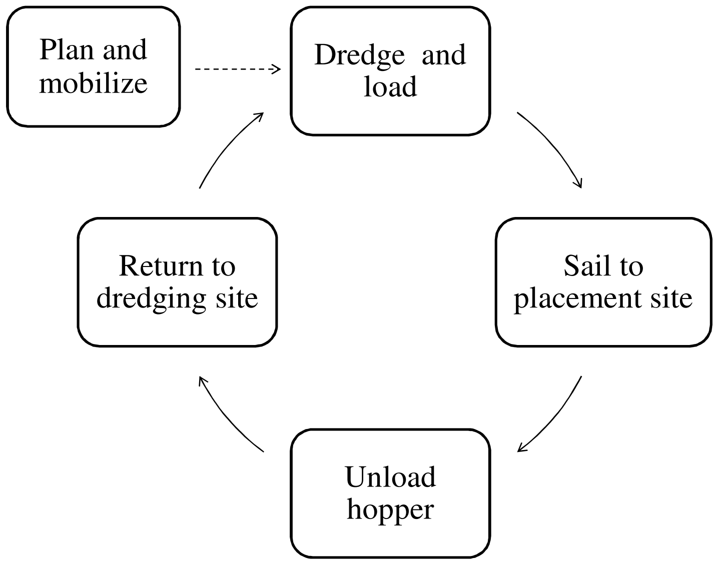

Figure 2. Trailing Suction Hopper Dredge Operation Cycle.

REVIEW OF LITERATURE

A review of prior work in this field is broken down into two areas: The study of hydraulic transport fundamentals related to dredging, and development of previous dredge project estimating schemes. Hydraulic transport fundamentals are used to estimate the rate that a hopper dredge with a given equipment configuration can carry out work. Hydraulic transport studies feed into prior project estimating work, as will be shown, by generally being the core limitation on how fast a project will be completed.

A number of reports have been produced with the primary objective of estimating cutter suction dredge costs, and though these deal with another type of dredge, they present a solid approach to the hydraulic transport question and also to associated costs. Belesimo (2000) addressed production by cutter suction and hopper dredges using hydraulic transport fundamentals to establish an optimal slurry flow rate for various equipment configurations working in a material with known characteristics. The production rate of a dredge was estimated by

$$P = Q \times AC_V \times 0.297 \tag{1}$$

where P is the production rate in cubic yards per hour, Q is the pumped flowrate in gallons per minute as determined by operator and must be higher than a critical flowrate, AC_V is the average concentration by volume of solids being pumped. The critical flowrate is dictated by the pipe size, material grain size, and specific gravity of both the solid and fluid as explained in the hopper dredge production section. The production rate in Equation 1 is occurring only while the hopper dredge is loading, and the operator may stop loading when the hopper is full of a slurry mixture or continue to pump while sediment in the slurry settles in the hopper and the volume of material in each load increases. Belesimo's estimation program yielded dredge project estimates with an average difference between estimate and actual bid of 17.3%, compared to government prepared estimates which yielded a 16.2% difference from the actual bids, indicating that his estimation system was highly competitive with that used by the Corps of Engineers themselves.

Bray et al (1997) present a production estimating system based on a plot of typical hopper dredge loading characteristics and a series of modifiers that account for dredged material properties and the layout of the project. Bray et al. present a bulking factor (B) for hopper dredges to characterize how much of the hopper capacity will be filled by actual material after the loading cycle defined as the dredged volume / in situ volume and given in Table 1.

Table 1. Selected Bulking Factors. (Bray et al., 1997)

Soil type	Bulking factor, B
Gravel, loose	1.10
Sand, hardpacked	1.25-1.35
Sand, medium soft to hard	1.15-1.25
Sand, soft	1.05-1.15
Silts, freshly deposited	1.00-1.10
Silts, consolidated	1.10-1.40
Clay, medium soft to hard	1.10-1.15
Clay, soft	1.00-1.10
Sand/gravel/clay mixtures	1.15-1.35

Randall et al. (1998) lay the groundwork for cost estimating of cutter suction dredge work on the Texas Gulf Intracoastal Waterway and present the use of pipeline transport fundamentals and cost engineering over long pumping distances. This work stresses the importance of an accurate production estimate when preparing a project, and identifies cost components applicable to all dredging projects.

Randall (2004) gives a formula for determining the production rate of cutter suction dredges similar to Equation (1), but with the addition of a dredge cycle efficiency factor to account for the walking movement of those dredges. Randall (2004) covers associated costs such as supplies, crew, maintenance and more, and calculates costs for major repairs, insurance and depreciation as portions of the capital cost of the dredge being used. Miertschin (1997) developed a cost estimate system for cutter suction dredges, and presented the use of dimensionless pump characteristics to enable a more accurate, scalable estimate for the use of different sized dredge equipment. This work was continued by Miertschin and Randall (1998) with the use of dimensionless pump characteristics for one model of dredge pump in lieu of individual tables for pump generated head at specified horsepower levels.

Wilson et al. (2006) present a method for determining the hydraulic gradient i_m (that is, head loss due to friction in a unit length of pipe) of the slurry being transported in a pipe, explained in the hopper dredge production estimate section. Wilson et al. use many inputs such as the Moody friction factor of the flow, the inner diameter of the pipe, the mean velocity of the mixture, relative density of the solid in the mixture, mean velocity of the fluid at which 50% of the solid particles are suspended by the flow, a parameter of the particle size, and the delivered concentration of solids. Wilson et al. provide solutions for all of these variables and also offer modifications to account for non-horizontal orientations of the pipe in question.

The USACE Engineer Instruction 01D010 (USACE, 1997) mandates the use of the Corps of Engineers Dredge Estimate Program (CEDEP) or other industry developed software to determine production rates for Corps project estimates in the absence of historical production data. EI 01D010 also provides definitions for project parameters and includes a lists of monthly costs, fixed costs, and pay items to be considered during a dredging operation.

For application to different locations, and to make the program applicable in future years, RS Means (2009) publishes quarterly Construction Cost Indices. These publications describe the changes in local construction markets, providing a good reference for labor, material and consumable costs, and also account for regional cost differences in the United States which can help provide more accurate overall project cost trends. The RS Means Heavy Construction index also provides a method to advance the capital costs of hopper dredges from a known baseline as discussed in the cost estimate section.

Randall and Koo (2003) discuss beneficial uses of dredged material, focusing on beach nourishment projects. This work provides valuable insight into the unit costs related to dredging and placement of material using hopper dredges along with other means. Randall and Koo (2003) also demonstrate an effective way to compare multiple scenarios when looking to determine optimal arrangements and costs.

HOPPER DREDGE PRODUCTION ESTIMATE

Hydraulic Transport

Hydraulic transport deals with the movement of materials suspended in a liquid. In the context of dredging, hydraulic transport defines the movement of dredged sediment, mixed with water into a slurry, by the flow of water through a system of pumps and piping into the hopper of a trailing suction hopper dredge. The flow rate of the slurry through the system is found by locating the balance point where energy provided by pumps is equal to the loss of energy resulting from the configuration of piping and properties of the slurry. The description of hydraulic transport concepts used in this hopper dredge production estimate is broken down into four components: power supplied by the pumps, energy lost to travel through the system, critical velocity which must be exceeded, and net positive suction head, or NPSH which must be positive to prevent cavitation and allow pumps to function properly.

Pump Power

Trailing suction hopper dredges use centrifugal pumps to move slurry by introducing energy in the form of higher pressure into the system. Centrifugal pumps create that high pressure by propelling slurry through a rotating impeller into the casing shell and down the piping system as demonstrated in Figure 3. The pump impeller rotates at a high speed, thrusting the fluid away from the center of the impeller and out towards the pump casing. When the fluid exits the impeller, it enters the casing where the velocity of the fluid decreases as it is no longer moved by the impeller. Following Bernoulli's principle, the decrease in velocity causes energy to be converted from kinetic energy (velocity) to static energy (pressure). When the fluid exits the pump casing through piping with a similar diameter as the inlet, continuity dictates that volume flowrates at the inlet and discharge must match. Pipes with similar cross-sectional areas on both the supply and discharge sides of the pump mean that the discharge velocity must match the entrance velocity.

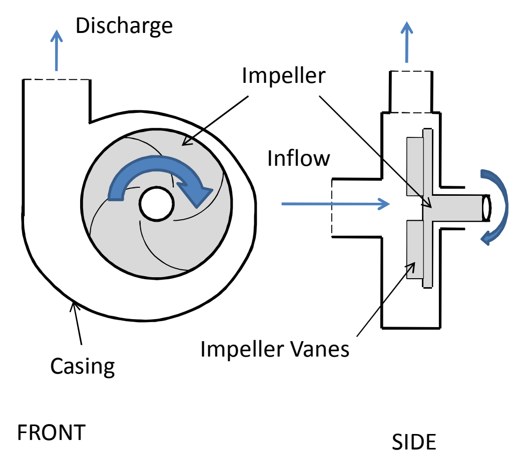

Figure 3. Representative Centrifugal Pump.

With similar velocities at the pump entrance and exit, the energy introduced through the impeller is found in the form of increased pressure at the discharge which drives flow downstream, away from the pump exit (Munson et al., 2002). The pressure, or head, developed by a pump is the difference in pressure from inlet to outlet and can be described by Equation 2 where H_p is the head developed by the pump, H_d is the head at the pump discharge, and H_s is the head at the pump suction side.

$$H_p = H_d - H_s \tag{2}$$

H_d and H_s are defined by Equations 3 and 4 where subscripts indicate either discharge (d) or suction (s), and P is the pressure, γ is the specific weight of the fluid, V is fluid velocity, g is gravitational acceleration, and z is the elevation of the suction or discharge.

$$H_d = \frac{P_d}{\gamma} + \frac{V_d^2}{2g} + z_d \tag{3}$$

$$H_s = \frac{P_s}{\gamma} + \frac{V_s^2}{2g} + z_s \tag{4}$$

Manufactured pumps are described by a 'pump curve' similar to that shown in Figure 4 that plots the head created by a pump at various flow rates, speeds (RPM), power levels (Hp), or efficiency percentages. Each model of centrifugal pump has a pump curve of this type, and they are used in this estimating program to define the head put into the system by the pump (H_p). Equations 3 and 4 can be combined to yield the modified Bernoulli Equation, or, the energy equation, given by Equation 5 with the addition of system losses denoted by H_f and H_m

$$\frac{P_s}{\gamma} + \frac{V_s^2}{2g} + z_s + H_p = \frac{P_d}{\gamma} + \frac{V_d^2}{2g} + z_d + H_f + H_m \tag{5}$$

For the suction hopper dredge arrangement, P_s is the pressure due to the depth of water at the draghead, V_s is assumed to be zero outside the draghead, and z_s is defined as zero, using the seafloor as the vertical reference. P_d is zero because there is no system pressure at the discharge of the piping system into the hopper, and the assumption is made that the water level in the hopper will be roughly the same as sea level. V_d is the velocity of slurry at the discharge point into the hopper, this velocity head term is small incomparison to the other terms in this equation (on the order of 6-10 ft for many hopper dredge applications) and is assumed to be negligible. Z_d is the elevation of the piping system discharge in the hopper compared to the seafloor and is assumed to the project depth. Losses are divided into major and minor losses where major losses refer to energy lost due to friction (H_f in Equation 5) throughout the pipe flow and minor losses (H_m) result from changes in geometry in the piping such as turns, elbows and valves as further described by Munson et al. (2002) and other fluids textbooks.

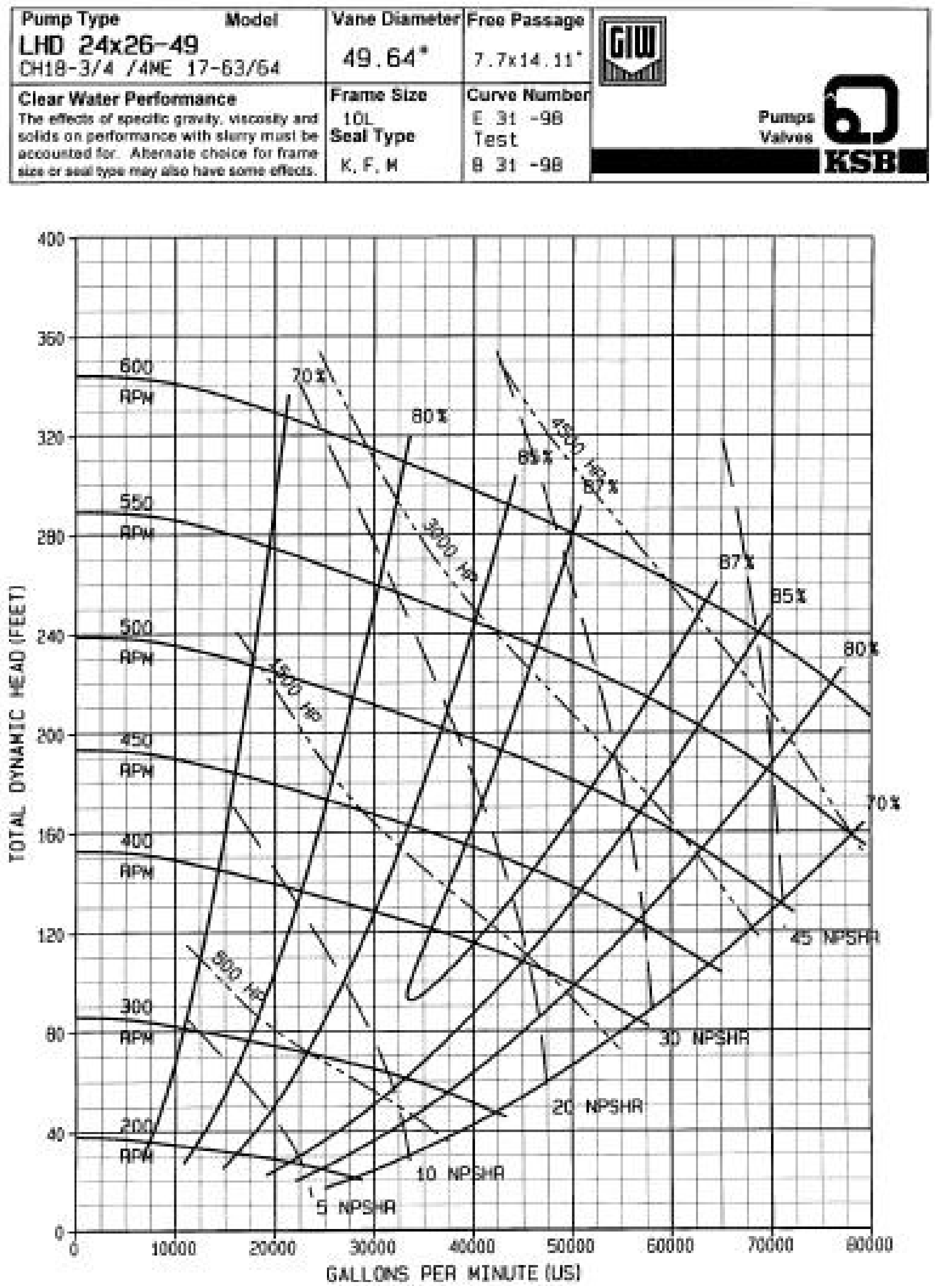

Figure 4. Centrifugal Pump Curve. (GIW, 1998)

System Losses

Energy lost during transport through the piping system can be observed as a drop in pressure along lengths of pipe, also known as a pressure gradient. This change in pressure is due to losses from pipe geometry or friction effects, known as minor or major losses respectively. Minor losses result from system configuration and are found in pipe elbows and valves in particular. These minor loses are characterized by a loss coefficient K_L used in Equation 6 given by Munson et al. (2002).

$$h_L = K_L \frac{V^2}{2g} \tag{6}$$

Where h_L is the head loss, V is the fluid velocity, and g is gravitational acceleration in any consistent system of units. Values of K_L for configurations found in a trailing suction hopper dredge are given in Table 2, based on values from Munson et al. (2002) and Randall (2009)

Table 2. Loss Coefficients for Common Dredge Components.

	Component	K_L
Elbows		
	Regular 90°, flanged	0.3
	Long radius 90°, flanged	0.2
	Long radius 45°, flanged	0.2
	Return bend, 180°, flanged	0.2
Valves		
	Gate valve, full open	0.15
	Ball valve, full open	0.05
Inlets, D is pipe diameter, r is entrance fillet radius		
	Pipe intake, no face	0.8
	r/D = 0, no fillet	0.5
	r/D = 0.05	0.2
	r/D = 0.1	0.1
	r/D = 0.25	0.04
Other fittings		
	Ball joint, straight	0.1
	Ball joint, medium cocked	0.4-0.6
	Ball joint, Fully cocked (17°)	0.9
	Swivel, stern	1.0
	End section, discharge	1.0

Major losses are due to frictional interaction between the slurry and pipe walls during transportation along the pipe. Wilson et al. (2006) provide a method for determining head loss for heterogeneous slurry flow found in hopper dredging in both horizontal and inclined applications. For horizontal flow found inside the trailing suction hopper dredge itself where slurry is distributed to the hoppers, Wilson et al. (2006) present a method for determining the hydraulic gradient i_m (that is, head loss due to friction in a unit length of pipe, in m/m or ft/ft) based on flow and material properties

$$i_m = \frac{f_w}{2gD} V_m^2 + 0.22(S_s - 1)V_{50}^M C_{vd} V_m^{-M} \tag{7}$$

where f_w is the Moody friction factor for water flow, g is gravitational acceleration in m/sec^2 (ft/sec^2), D is the inner diameter of the pipe in meters (ft), V_m is the mean velocity of the mixture (m/s), S_s is relative density of the solid in the mixture, $V_{50}$is mean velocity of the fluid at which 50% of the solid particles are suspended by the flow (m/s), M is a parameter of the particle size (generally 1.7), C_{vd} is the delivered concentration of solids. The Moody friction factor is often found from a chart lookup, but Herbich (2000) and Randall (2000) recommend a formula developed by Swamee and Jain (1976) as follows:

$$f_w = 0.25/\left[log\left(\frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2 \tag{8}$$

Where ϵ is the surface roughness in millimeters, D is the pipe diameter in meters, and Re is the Reynolds number, recalling that the Reynolds number is:

$$Re = \frac{\rho VD}{\mu} = \frac{VD}{\nu} \tag{9}$$

where ρ is the fluid density in kg/m^3, V is the fluid velocity in m/s, D is the pipe diameter in meters, μ is the dynamic viscosity in kg/(m×s), or ν is the kinematic viscosity in m^2/sec

Wilson et al. provide solutions for the variables that affect Equation 7 and also offer modifications based on non-horizontal orientations of the pipe in question. Wilson explains that V_{50} is mean velocity of the fluid at which 50% of the solid particles are suspended by the flow m/sec, defined in Equation 10

$$V_{50} = w\left(\frac{8}{f_f}\right) cosh[60d/D] \tag{10}$$

where w is the particle associated velocity shown in Equation 11, f_f is the Moody friction factor for the fluid flow, d is the particle diameter, taken to be d_{50} in meters, and D is the internal diameter of the pipe in meters. The particle associated velocity is described by Equation 11:

$$w = 0.9v_t + 2.7\left[\frac{S_S - S_f}{S_f} gv\right]^{1/3} \tag{11}$$

where w is the particle associated velocity in m/sec, v_t is terminal settling velocity of a single particle in m/sec, S_S is the specific gravity of the solids which is generally 2.65

for hopper dredge applications (Randall, 2009), S_f is the specific gravity of the fluid (water), g is gravitational acceleration m/sec^2 , and μ is dynamic (or shear) viscosity kg/(m×s) of water. The terminal settling velocity is given in Equation 12 as:

$$v_t = 134.14(d_{50} - 0.039)^{0.972} \tag{12}$$

where v_t is the terminal settling velocity of a single particle in mm/sec, d_{50} is the median grain diameter in millimeters. C_{vd} is the volume concentration of delivered solids (a ratio), given as:

$$C_{vd} = \frac{S_m - S_f}{S_s - S_f} \tag{13}$$

where S_m is the mean specific gravity of the mixture (slurry), S_f is the specific gravity of the fluid (water), and S_s is specific gravity of the solids.

A slightly different approach is required for the inclined slurry flow found in a deployed dragarm. Wilson et al. (2006) present the use of Equation 14 when an inclined, heterogeneous slurry flow is encountered.

$$\Delta i(\theta) = \Delta i(0) cos\theta^{(1+M\gamma)} + (S_s - 1) C_{vd} sin\theta \quad (14)$$

Where $\Delta i(\theta)$ is an additional pressure gradient in meter/meter (ft/ft) in addition to the horizontal clear water pressure gradient that results from the heterogeneous slurry moving up an inclined pipe. The incremental pressure gradient $\Delta i(0)$ is equal to $i_m - i_w$, the difference between i_m from Equation 7 and the clear water pressure gradient i_w which is given in Equation 15. The angle of inclination between the dragarm and horizontal is given as θ, while S_s is the specific gravity of the slurry and C_{vd} is the concentration by volume of solids in the delivered slurry. Two factors are used in Equation 14: M is generally 1.7 as in Equation 7, and γ is generally 0.5 for dredged sands.

Equation 15 illustrates the i_w required for Equation 14.

$$i_w = f\frac{V^2}{2\mathrm{gD}} \qquad (15)$$

Equation 15 is a fundamental pressure gradient definition where f is the Moody friction factor, g is gravitational acceleration in m/sec^2 (ft/sec^2), V is the mean velocity of the mixture m/sec (ft/sec)), and D is the inner diameter of the pipe in meters (ft).

With accurate descriptions of the pressure gradient through both the inclined and horizontal sections to the trailing suction hopper dredge piping system, it is possible to calculate the pressure loss throughout the flowrate operating range. This profile of system head loss through the flowrate domain is compared against the pump head created throughout the same domain as shown in Figure 5. The system is operating at the maximum flowrate when pressure supplied and pressure loss is equal.

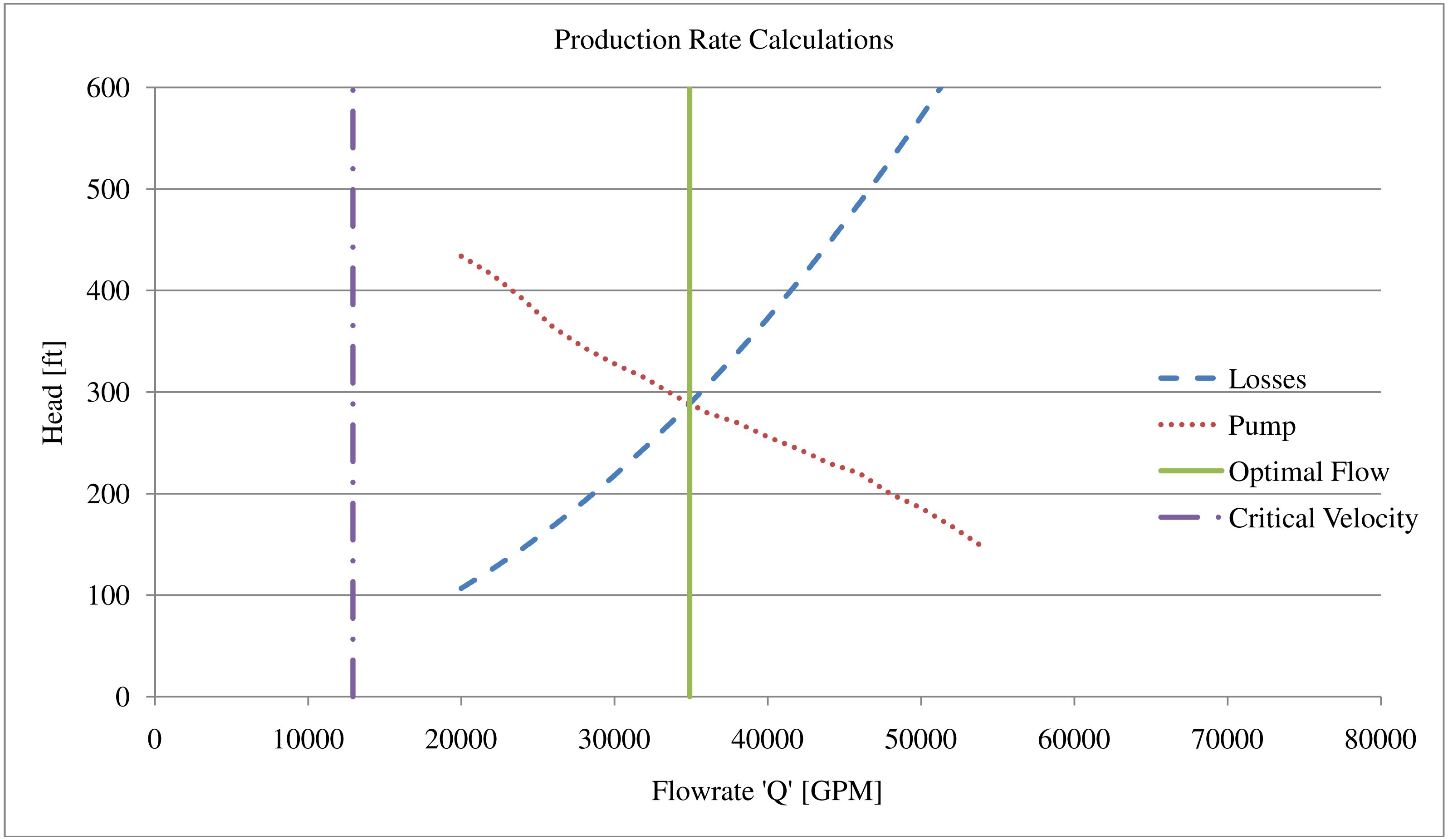

Figure 5. System Head Plot.

Note in Figure 5 how the head generated by the pump decreases, while head losses in the system increase as the flow rate increases. As long as the critical velocity has been exceeded, the most efficient place to operate the system is where head losses match the pump head.

Critical Velocity

Critical velocity is the limit below which suspended particles will fall out suspension in slurry transport. This is an important factor to consider, whatever value is identified as the optimal flowrate by balancing the system power and losses must be greater than this critical velocity. Equation 16 is given by Herbich and is used to calculate the critical velocity.

$$V_c = \frac{8.8\left[\frac{\mu_s\left(S_s - S_f\right)}{0.66}\right]^{0.55} D^{0.7} d_{50}^{1.75}}{d_{50}^2 + 0.11D^{0.7}} \tag{16}$$

Equation 16 describes the critical velocity V_c in meters/second where μ_s, is the coefficient of mechanical friction between particles, (0.44 or 0.55), S_s is the specific gravity of solids, S_f is the specific gravity of fluid, D is the diameter of pipe in meters, and $d_{50}$is the particle grain diameter in millimeters. Hopper dredges generally operate at high flowrates and the critical velocity limitation is less of a concern than in cutter suction dredges for example.

Production Estimate

The production estimate for a hopper dredge is carried out in the spreadsheet by first obtaining important project information from the user, then calculating the rate at which material can be dredged from the sea floor. Using the provided project information and Equations 5 through 12, a flowrate through the dragarms can be determined. With the dragarm intake established, it is possible to calculate the time required to fill the hopper for each individual load. The operating flowrate is determined by finding the level of flow (gpm) at which the energy (head, feet) supplied by the pump is balanced by the losses in the piping system. In a generic hopper dredge, the balance of pump energy and losses will look similar to Figure 5 where the pump head decreases as flow increases. At the same time, head losses increase as the flowrate increases. At some point, the losses due to friction and system design will overcome the head generated by the pump, and the flow will reach a balanced steady-state rate. Pump information has been generously provided by the GIW Industries Inc. for a number of representative dredge pumps. Pump characteristics have been transcribed from pump curves similar to Figure 4 into a tabulated form in the spreadsheet, allowing the user to select from a range of pumps, or to import characteristics from a new pump. Studies indicate that it is common for hopper dredge projects to have a no-overflow requirement due to environmental concerns (Palermo and Randall, 1990). Thus, the time to fill a hopper dictates the duration of that collection cycle with no additional overflow period, and the volume collected will be the hopper volume multiplied by the expected concentration specified in the spreadsheet. Expected concentration is defined in Equation 11 and can be defined by the user with local knowledge of the project at hand and the specific gravity of the material present. Default information for the spreadsheet includes a solids specific gravity of 2.65 and a slurry specific gravity of 1.35, yielding an expected concentration by volume in the hopper of 21.2%. The program uses the slurry flow rate to determine the time required to fill the hopper, the expected concentration to determine how much material is in each of those hopper loads, and the amount of material in each load to determine how many loadings and trips are required for the entire project.

Using further project parameters such as the average distance between the dredging site and the placement site as well as average dredge transit speed and daily hours of operation allow the user to tailor the operational details to match their plans. Along with operational details, changeable default values are provided to describe time required for repairs and fueling, anticipated breakdowns and maintenance and delays in accordance with Bray et al. to give a realistic expectation of the project duration. The duration of delays during a project is estimated by Turner (1996) as 50% of time that would otherwise be spent on the project.

To summarize the fluid mechanics fundamentals involved in the production estimate, Table B-2 lists the important equations used in determining the production flow rate and critical velocity. The assumption has been made that an operator will wish to operate at or near the optimal flowrate. If a situation arises where the operator wishes to operate at a lower rate, the user can manually enter the lower flowrate into the spreadsheet cell on the production estimate page, causing duration and cost calculations to be recalculated based upon that new flowrate.

COST ESTIMATE

Once the production rate has been estimated for the job at hand, it becomes possible to create a cost estimate for the projects. The production rate previously determined depended on many physical factors of the material being dredged and the hopper dredge being used to collect that material, and ultimately gave us a production rate defined by cubic yards per day. The cost estimate begins with the projects scope and uses the production rate to determine the duration of the project, and then the costs associated with operations during that timeframe. Bray et al. provide guidance on factors to consider during the development of a cost estimate, and these include: crew and labor, fuel and lubricants, repairs and maintenance, depreciation, insurance, bonding, and profit.

Crew and Labor

Hopper dredges, like all commercial ships, require an adequate and competent crew to deal with their operations. For a hopper dredge, this includes the usual deck and engineering personnel, as well as specialist dredge operators. Belesimo gives an indication of required dredge crews, as does the Army Corps of Engineers in their various dredge profiles. This crew complexion will vary from to ship to ship depending upon sized based manning requirements, the complexity or automation of equipment and operations, or the duration of an expected voyage. The input spreadsheet for labor has been made adjustable for this providing a number of personnel types to choose from in order to fill out the crew for any particular dredge. The dredges Essayons, Wheeler, McFarland, and Yaquina of the Corps of Engineers give an indication of the scope of a dredge crew. These 4 ships range in capacity from 1050 to 8256 cubic yards and are manned by between 20-23 personnel with a breakdown similar to that indicated by Belesimo and provided on the spreadsheet. Wage rates included on the spreadsheet are obtained from the US Bureau of Labor Statistics for 2008 and are adjustable if any special requirements are identified.

Fuel and Lubricants

Fuel costs are another significant portion of the operating budget. Fuel consumption for a hopper dredge is determined by the amount of installed power and the utilization of that power. A method presented by Bray et al. is based on the installed horsepower and varying rates of usage.

Repairs and Maintenance

Bray et al. define maintenance needs in two categories: routine maintenance and running repairs, as well as major repairs and overhaul. Minor repairs entail work that can be done during operations with minimal interruption and are recommended as a daily cost of 0.000140 times the capital cost of the hopper dredge. Major repairs involve those that require removing the dredge from operation and are given at a daily cost of 0.000300 times the capital value of the dredge. This arrangement is used in the spreadsheet, but also with the opportunity to adjust the separate cost levels as individual experience dictates. Along with the monetary cost of repairs and maintenance, a significant amount of delay can be experienced due to these problems and other inefficiencies. Turner (1996) provides guidance that delay times on the order of 50% again on top of the fully efficient calculated duration of the project. To account for these delays, a 50% delay factor is included in the calculation for project duration. This is adjustable by the user, though Turner cautions against over-estimation of productive time as "a major cause of project failure".

Depreciation

Depreciation accounts for the operator's cost of purchasing the dredging plant. In this case the capital cost of a hopper dredge must be paid off over the service life of the dredge. The daily cost of this depreciation depends on the initial price and the useful life of the dredge. If the capital cost of a dredge is not known, Figure 6 is provided which uses information from Bray et al. (1997) and RS Means Heavy Construction Indices to provide a reasonable capital cost estimate. Bray et al. recommend a 30 year period for large trailing suction hopper dredges which is the default in the spreadsheet.

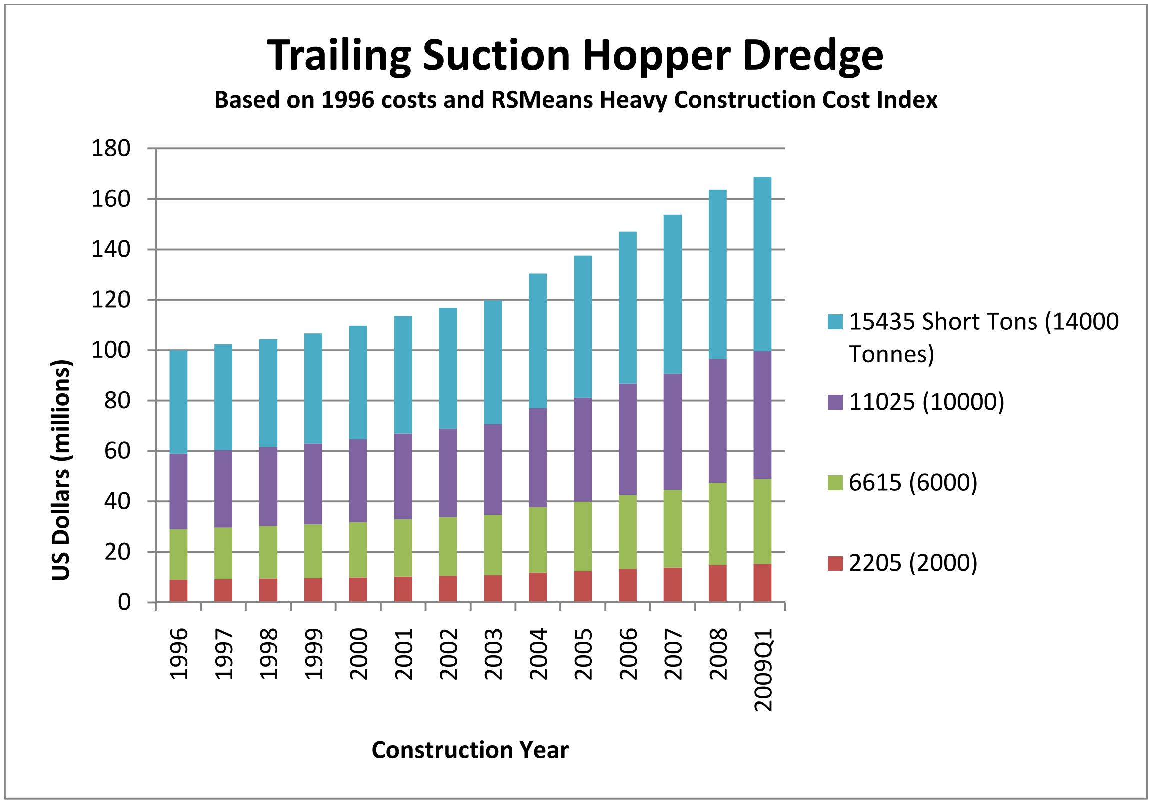

Figure 6. Hopper Dredge Capital Cost Projections.

Insurance, Overhead, Bonding and Profit

Insurance on the hopper dredge is given by Randall (2004) as the capital cost multiplied by 0.025 and divided by the number of working days per year. Bray et al. present overhead as nine percent of the working costs already established to this point. Belesimo advises that project bonding may cost between 1.0 and 1.5 percent of the working costs. With these descriptions, overhead and bonding can be combined to an additional ten percent on top of the determined operating costs. Finally, Profit is determined by the individual contractor and may differ between jobs. In order to account for this variability, the spreadsheet contains an adjustable input for the user.

USING THE SPREADSHEET

The spreadsheet is structured with four input areas that require use by the operator to define the project. The four sections accept values for: hopper data, pump data, project data, and costs data categories. These sections are displayed in the tables to follow and highlighted cells indicate values which require user input. Table 3 displays the input section for hopper data, this section includes data describing the capabilities and configuration of the hopper dredge. The first input is the hopper capacity, entered in cubic yards which are the standard U.S. method of classifying dredge capacity. The next inputs are for the number of dragarms on the hopper, the average sailing speed in knots, distance from dredging site to placement area, and time required to unload the hopper dredge. The last group in the hopper data input section is used to describe the piping system in the dredge and accepts values for the length of pipe section in feet, the diameter of each section in inches, the surface roughness or ε factor, and losses values (k value) from Munson et al., 2002, and based on a general geometric layout required for pump operation and shipboard pumping arrangements.

Table 3. Data Entry Section for Hopper Dredge Properties.

DREDGE INFORMATION					
Hopper Capacity		4000	cy	3058	m^3
Number of Dragarms		2	number		
Length of Dragarms		100	feet	30.5	m
Sailing Speed (avg)		6	NM/hr	11.1	km/hr
Time to Unload		0.1	hours		
Capital value of dredge		10,000,000	dollars		
Horsepower Total		5400	Hp	4027	kw
Equipment Lifespan		30	years		
Draghead to first pump					
	Length	30	ft	9.15	m
	Dia. (inner)	26	in	0.2201	m
	ε roughness	0.00015	ft	0.00004575	m
	Losses(k)	1.6			
First to second pump (ZERO if only one pump)					
	Length	70	ft	21.35	m
	Dia. (inner)	26	in	0.2201	m
	ε roughness	0.00015	ft	0.00004575	m
	Losses(k)	0.6			
Final pump to hopper					
	Length	80	ft	24.4	m
	Dia. (inner)	24	in	0.2032	m
	ε roughness	0.00015	ft	0.00004575	m
	Losses(k)	0.6			

The pump data input section allows the user to designate one the provided pump profiles, or to input their own flowrate-head profile. Each profile represents a pump or the described size and horsepower, and provides the amount of head generated at each flowrate increment. If multiple pumps are in series, the user simply selects multiple pumps to describe those, according to the effects of pumps in series described by Wilson et al. (2006). Table 4 displays the pump data for one selected pump from the spreadsheet.

Table 4. Data Selection from Pump Characteristic Spreadsheet.

	Georgia Iron Works				
	Model LHD 20x20-42				
Selection:	0	1	0	0	0
RPM:	500	550	600	650	700
Flow Rate (Q)	Head (H)	Head (H)	Head (H)	Head (H)	Head (H)
GPM					
8000	148	180	215	254	295
10000	146	178	213	251	292
12000	143	175	210	248	289
14000	140	172	207	245	286
16000	138	169	204	242	283
18000	132	165	200	238	279
20000	130	162	196	234	275
22000	127	157	192	230	271
24000	122	153	188	225	266
26000	118	148	182	220	260
28000	113	143	177	214	255
30000	109	138	172	209	250
32000	105	134	167	203	243
34000		130	162	198	237
36000		125	157	193	232
38000		120	152	187	225
40000		117	147	181	220
42000					
44000					

The project information input section takes information related to the scope of work to be conducted. Table 5 illustrates the contents of section, and its focus on material properties and quantity

Table 5. Data Entry Section for Project Information.

PROJECT INFORMATION				
Average depth	47	ft	14.3	m
Volume	1,310,000	cy	1001567	m^3
Hours Worked per Day	24	hrs		
Distance to Placement Site	5	NM	9.26	km
Median Particle Diameter (d50)	0.00591	in	0.15	mm
Specific Gravity of Mixture (Sm)	1.35			
Specific Gravity of Fluid (water)	1			
Specific Gravity of Solids (Ss)	2.65			
Concentration (ratio)	0.212			

The cost data section provides values for crew labor costs, fuel costs. Default values are provided based on the national average for labor rates given in the United States Department of Labor's Bureau of Labor Statistics (BLS, 2009). These labor costs provide a good starting point for a project estimate, and can be updated by a user with knowledge of current local labor markets, or varying company policies. Also input through the costs data section are some operating characteristics: Working days per year, hours spent at full power daily, fuel costs, and the cost index. Fuel costs for various regions of the U.S. for 2008 and 2009 are provided in the spreadsheet, as well as 2009 total project cost indices from the U.S. Department of Energy and RS Means respectively. Finally, mobilization and demobilization costs are included. The default mobilization/demobilization costs are based on Belesimo (2000) and can be tailored to suit the individual project. Table 6 illustrates the cost data inputs.

Table 6. Data Entry Section for Cost Information.

COST INFORMATION		
Working days per year	300	days
Effective hours at 100% power	12	hrs
Fuel Cost, see cost sheet	2.63	$/gal
Cost Index (see costs sheet)	1	ratio
Mobilization/demobilization	100,000	dollars

RESULTS

To confirm the accuracy and utility of the estimating spreadsheet, the outcome was compared with actual projects that have been bid upon, and carried out. The United States Army Corps of Engineers publishes all projects which have been carried out in past years on their website http://www.iwr.usace.army.mil/NDC/dredge/dredge.htm (NDC, 2009). The published record of these historical projects includes information on the date and location of the project, volume of material involved, the type of dredge used for the project, and importantly, the government cost estimate as well as the winning bid amount. A second resource available for comparison is the hopper dredge section of the dredge project estimating program by Belesimo (2000). Belesimo (2000) conducted two hopper dredge project estimates that provide inputs which can be used in the program developed in this thesis to validate results.

Comparison with Historical Projects

When examining estimates, it is critical to understand the projects and parameters being compared. Table 7 shows the government cost estimates, winning bid prices, and the spreadsheet estimate developed in this thesis for the same projects. The government estimate is prepared by the Corps of Engineers to provide a benchmark for budget planning purposes and to check the reasonability of any contractor's bids. The winning bid is the lowest submitted by any contractor that can reasonably carry out the job being bid upon. Contractors will use their own knowledge from historical projects as well as proprietary estimating systems to get what they believe to be the most accurate estimate. Having the most accurate estimate for their dredging operation allows them to reduce uncertainty in the planning and bidding phase, and thus to make better, more informed decisions. Looking at Table 7, it is apparent the government estimate can be higher or lower than the winning bid, and that with the exception of one outlier (Palm Beach Harbor) most per-volume costs are in the $4-$7 per cubic yard range.

Some details from the projects used in the comparison are displayed below in Table 8. Along with being in different geographic locations, there is wide variation in project depth and distance between the dredge site and placement site. Based on local nautical charts, the Palm Beach Project appears to involve beach nourishment placement and is far more expensive per cubic yard than all other projects. The existence of this type of special project illustrates the limitations of generic cost estimating programs and serves as a reminder that experience in specialized projects is often the best resource for project planning.

Table 7. Historical Project Comparison Information. (2007-2009)

PROJECT NAME	VOLUME (CY)	GOVERNMENT ESTIMATE ($)	WINNING BID ($)	THESIS ESTIMATE ($)	GOV $/CY ($)	WINNING $/CY ($)	CALCULATED $/CY ($)
Charleston Entrance 2007	951,000	$3,528,970	$2,524,800	$3,837,690	$3.71	$2.65	$4.04
Charleston Entrance 2009	1,310,000	$4,612,400	$3,751,000	$4,737,316	$3.52	$2.86	$3.62
Brazos Island Harbor, Inside Jetty Channel	450,000	$2,221,660	$2,525,250	$2,416,209	$4.94	$5.61	$5.37
Houston Ship Channel - Redfish North	1,300,000	$9,304,664	$6,961,820	$7,298,446	$7.16	$5.36	$5.61
Fernandina Harbor	715,000	$3,787,760	$3,787,760	$3,830,031	$5.30	$5.30	$5.36
Palm Beach Harbor	150,000	$1,773,220	$1,949,100	$484,262	$11.82	$12.99	$3.23
Brunswick and Savannah Entrance	2,000,000	$3,326,140	$3,333,025	$3,794,636	$1.66	$1.67	$1.90

Multiply $/CY by 1.3 to yield $\$/m^3$

Table 8. Historical Project Details.

Project Name	NOAA Chart Number	Project Depth (ft)	(m)	Distance to Placement Site (NM)	(km)
Charleston Entrance Channel	11523	47	14.3	6	5.1
Brazos Island Harbor, Inside Jetty Channel	11322	47	14.3	5	4.3
Houston Ship Channel - Redfish North	11327	45	13.7	3	2.6
Fernandina Harbor	11503	37	11.3	4	3.4
Palm Beach Harbor	11472	32	9.8	1	0.9
Savannah and Brunswick	11506/11512	42	12.81	6	5.112

Comparison to Other Estimate Programs

In addition to comparing with the government produced estimates for recent hopper dredge projects, a comparison can be made with previous hopper dredge estimating systems. Belesimo (2000) produced an estimating system suitable for cutter-suction and hopper dredges. Belesimo conducted two estimtes of hopper dredge projects in Mobile Harbor, and Savannah and Brunswick from the 1998-2000 timeframe. Belesimo's resulting estimates were found to be 2.5% and 37.2% respectively different from the winning bid price. Applying identical parameters including dredge properties, project scope, and labor and fuel prices to the estimating program developed in this thesis, the author produced estimates which were 9.3% and 15.5% different respectively from the winning bids demonstrating the validity of estimates produced by this spreadsheet. The inputs to both the Mobile and Savannah/Brunswick estimates are shown highlighted in Tables 9 and 10 respectively. Additionally, the Brazos Island Harbor project from 2008 was estimated using the spreadsheet developed in this thesis, and also by this author using the program from Belesimo (2000). Identical inputs were used in both programs as listed and highlighted in Table 11. The spreadsheet developed in this thesis was found to be 4.3% different from the winning bid while the spreadsheet from Belesimo (2000) was found to be 30.9% different. Results from all three test cases involving the Belesimo (2000) estimates are included in Table 12. By comparing the mean absolute difference, which captures how far “off-target” the estimating program is, one can observe that the spreadsheet developed in this thesis is highly competitive with both the government generated estimates, and past estimating programs.

Table 9. Mobile Harbor Project Comparison Inputs (1998-2000).

Dredge Properties				
Hopper Capacity	6000	CY	4587.3	m^3
Number of Dragarms	2			
Sailing Speed	6.5	Kts	12.04	km/hr
Capital Cost	$ 10,000,000	Dollars		
Suction Diameeter	30	Inch	0.762	m
Discharge Diameter	30	Inch	0.762	m
Pipe Length	110	Feet	33.5	m
Pipe Rougness	0.00015	Feet	0.00004572	m
Total Losses in Pipe	28			
Project Properties				
Project Volume	1000000	CY	764555	m^3
Dredging Depth	42	Feet	12.8016	m
Distance to Placement	15	NM	27.78	km
d50	0.002559	Inch	0.065	mm
Specific Gravity of Solids	2.65			
Average Specific Gravity of Slurry	1.6			
Fuel Price	$ 0.62	Dollars		
Daily Crew Expenses	$ 4,335	Dollars		
Mobilization Costs	$ 300,000	Dollars		

Table 10. Savannah and Brunswick Project Comparison Inputs (1998-2000).

Dredge Properties				
Hopper Capacity	6000	CY	4587.3	m^3
Number of Dragarms	2			
Sailing Speed	6.5	Kts	12.04	km/hr
Capital Cost	$ 10,000,000	Dollars		
Suction Diameeter	30	Inch	0.762	m
Discharge Diameter	30	Inch	0.762	m
Pipe Length	110	Feet	33.5	m
Pipe Rougness	0.00015	Feet	0.0000457	m
Total Losses in Pipe	28			
Project Properties				
Project Volume	2,000,000	CY	1,529,110	m^3
Dredging Depth	42	Feet	12.8	m
Distance to Placement	6	NM	11.1	km
d50	0.002559	Inch	0.065	mm
Specific Gravity of Solids	2.65			
Average Specific Gravity of Slurry	1.6			
Fuel Price	$ 0.62	Dollars		
Daily Crew Expenses	$ 6,503	Dollars		
Mobilization Costs	$ 1,600,000	Dollars		

Table 11. Brazos Island Harbor Project Comparison Inputs (2008).

Dredge Properties				
Hopper Capacity	4000	CY	3058.2	m^3
Number of Dragarms	2			
Sailing Speed	4	Kts	7.4	km/hr
Capital Cost	$ 10,000,000	Dollars		
Suction Diameeter	26	Inch	0.6604	m
Discharge Diameter	24	Inch	0.6096	m
Pipe Length	180	Feet	54.86	m
Pipe Rougness	0.00015	Feet	0.00004572	m
Total Losses in Pipe	2.8			
Project Properties				
Project Volume	450000	CY	344049.8	m^3
Dredging Depth	47	Feet	14.3256	m
Distance to Placement	4	NM	7.408	km
d50	0.0059	Inch	0.15	mm
Specific Gravity of Solids	2.65			
Average Specific Gravity of Slurry	1.35			
Fuel Price	$ 4.08	Dollars		
Daily Crew Expenses	$ 6,552	Dollars		
Mobilization Costs	$ 100,000	Dollars		

Table 12. Estimate Accuracy Comparison.

Percent Difference between Estimates and Winning Bid			
Project	Hollinberger	Belesimo*	Government
Mobile (1998-2000)	-9.3%	2.5%	-5.4%
Savannah (1998-2000)	-15.5%	-37.2%	-11.3%
Brazos Island Harbor (2008)	-4.3%	30.9%	-12.0%
Charleston Entrance (2007)	52.0%		39.8%
Charleston Entrance (2009)	26.3%		23.0%
Houston Ship Channel - Redfish North (2007)	4.8%		33.7%
Fernandina Harbor (2007)	1.1%		0.0%
Brunswick and Savannah Entrance (2008)	13.8%		-0.2%
Mean Absolute Difference	15.9%	19.8%	15.7%

* Mobile and Savannah from Belesimo (2000), Brazos estimate done by Hollinberger using Belesimo's program with common inputs to Hollinberger estimate.

A comparison of the project volumes and cost estimates from 2008 and 2009 is presented in Figure 7. This figure shows only those projects conducted in the 2008-2009 range due to the long term trend of rising average unit costs (dollars per cubic yard dredged) seen in the United States (Randall, 2009). In Figure 7, Project volumes are indicated by the shaded area, and project estimate costs are shown as the various markers. The estimate generated in this thesis is generally close to the government estimate, though the Palm Beach Harbor project yields considerable error. Further investigation into the Palm Beach Harbor area indicated that this project involved placement of dredged material near the shore, which would require longer placement times, thus extending the duration of the project and increasing costs as seen. This example illustrates the limitations of a generalized project estimating program, further consideration would be necessary to account for specialized placement projects. Lists of all inputs used for these sample projects are provided in the Appendix. When comparing the accuracy of estimates to the accepted bid price, the Palm Beach Harbor project was not factored in due to special circumstances in the project which resulted in cost per cubic yard to be over double the next highest project and nearly triple the average of the remaining projects. Observing the remaining projects, it can be seen that the government estimate was, on average, 15.7% different than the winning bid, and that the developed spreadsheet was an average of 15.9% different than the winning bid. This level of agreement indicates that the spreadsheet estimate is a reasonable predictor of costs associated with a hopped dredging project.

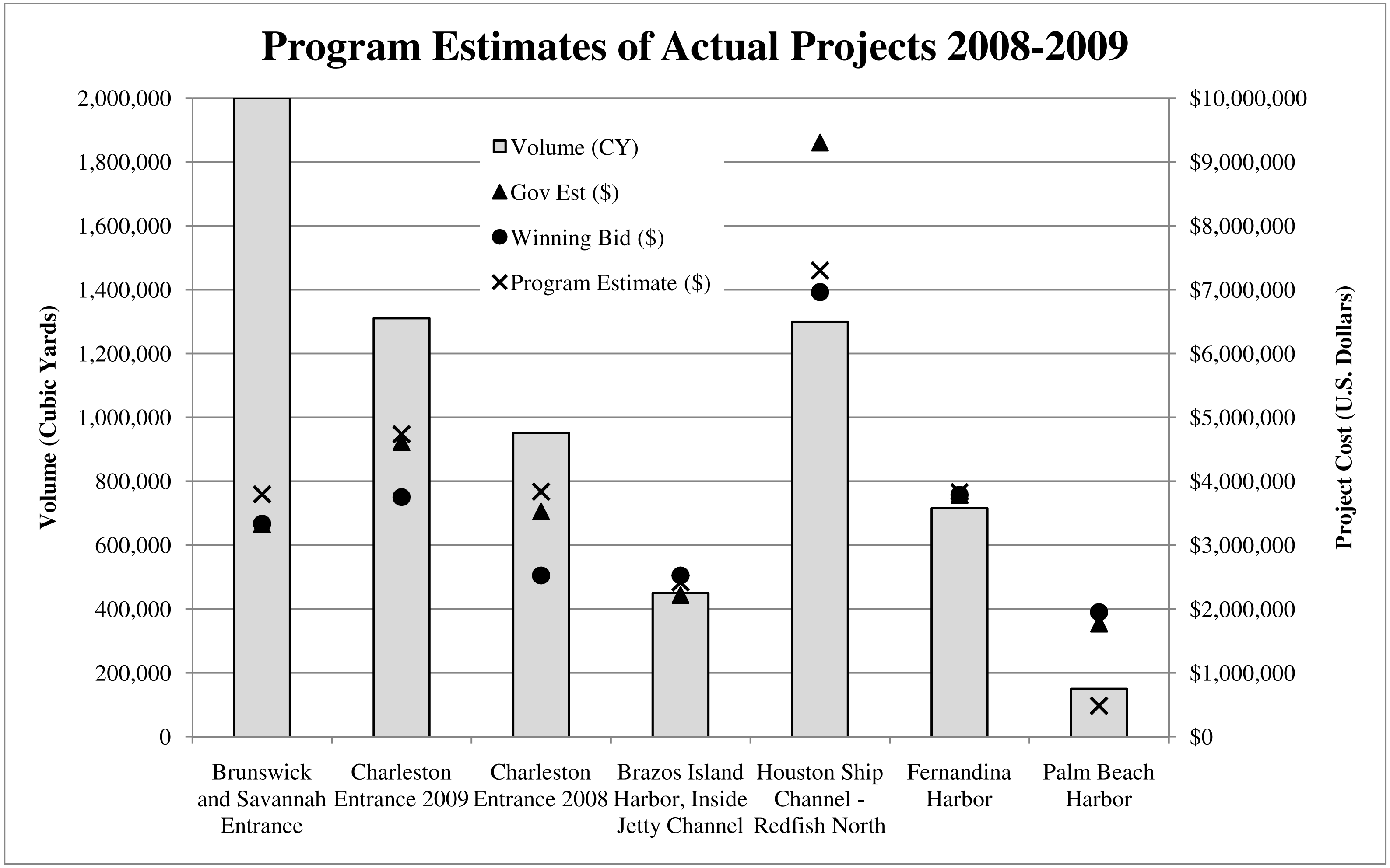

Figure 7. Comparison of Sample Project Estimates.

Sensitivity Analysis

To better understand how various independent factors affect the costs of a dredging project, a sensitivity analysis was conducted. In this analysis, all but one factor feeding into the project cost were kept constant and the individual factor was manipulated to determine what the result of the total project cost would be. The 'standard project' which the analysis was based upon involved 764,550 cubic meters (1,000,000 cubic yards) of material with a d_{50} grain size of 0.4 millimeters, a slurry specific gravity of 1.4, average depth of 14 meters (45 feet), and 9.26 kilometers (5 nautical miles) from dredge site to placement area. The hopper dredge used is based on a 3,800 cubic meter (5,000 cubic yard) capacity hopper with total installed pumping horsepower of 3,500 horsepower. The hopper dredge's average sailing speed is based at 7.4 kilometers per hour (4 nautical miles per hour), mobilization/demobilization costs at $100,000, and fuel costs at $3.50 per gallon. To carry out the sensitivity analysis, sailing speed, sailing distance, fuel costs, and mobilization costs are varied in 10% increments to determine the effect on the total project cost.

The results of the sensitivity analysis are shown in Figure 8. The chart demonstrates the percent change of the total project cost as a function of the percent change of the individual elements. For example, if the hopper dredge sailing speed is decreased by 30%, the total project cost will increase by approximately 38%. Based on Figure 8, the sailing speed has a dramatic effect on the total cost for the project at hand. It is worth noting that a user trying to optimize an upcoming project will be limited in the extent to which they can control factors such as sailing distance or the price of fuel. However, this sensitivity analysis provides a firm reality check, showing the relation between component costs and showing expected result trends that are in agreement Belesimo and Miertschin.

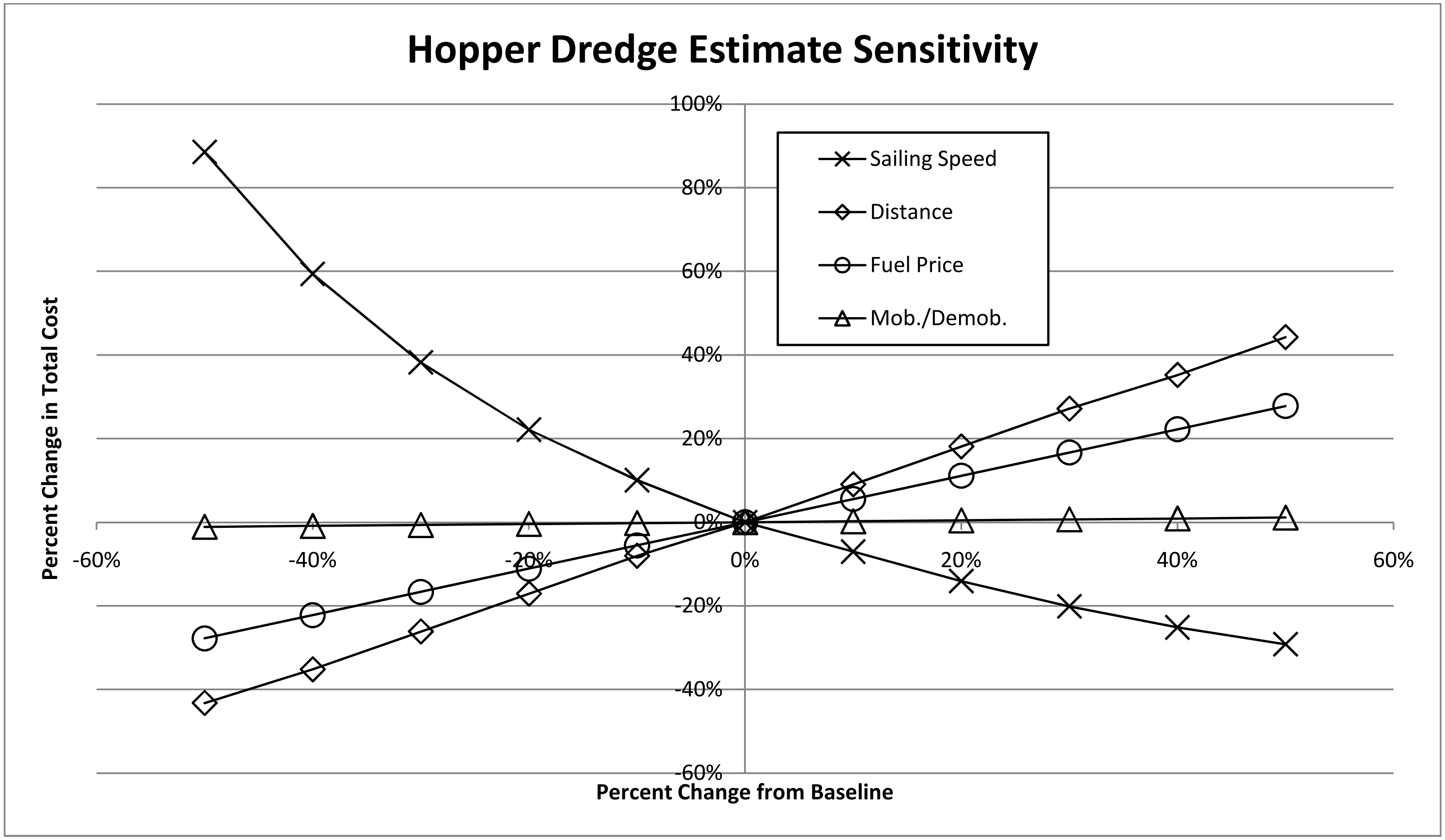

Figure 8. Hopper Dredge Estimate Sensitivity.

CONCLUSIONS AND RECOMMENDATIONS

A trailing suction hopper dredge production and cost estimating system was developed in Microsoft Excel. The heart of the estimate is based on the rate at which material is collected, calculated from the balance of pump generated head, and head losses in the piping system aboard the hopper dredge. Head losses occurring in pipeline slurry transport are derived from work by Wilson et al. (2006) and Herbich (2000). Additional cost data related to the project is based on guidelines from Bray as well as RS Means, and some generalized cost information from the U.S. Department of Labor and U.S. Department of Energy.

The output of the spreadsheet varied 15.9% from the accepted contract price. This compares favorably to a 15.7% variation between the government generated estimate and indicates that the spreadsheet is an effective tool in generating hopper dredge project cost estimates. A sensitivity analysis conducted on the spreadsheet estimating program demonstrated the expected behavior of an estimate when individual components were varied and was in agreement with past work by Belesimo (2000). The developed spreadsheet included, for the first time in production estimating systems, the effect of inclined slurry transport, and regional cost factors.

It is important to remember that this spreadsheet estimating program was developed with general knowledge of the dredging fleet and publicly available information on a number of contracted projects. The USACE Manual Engineer Instruction 01D010 accords higher priority to local historical knowledge than to an estimating program when developing a project estimate. This is important to keep in mind when developing an estimate as details such as local weather, traffic patterns, navigational peculiarities, dredge capabilities, and dredge performance all influence the pace, duration, and cost of a dredging project. It is recommended that detailed operational information of a vessel or project be sought when estimating the project in order to refine the accuracy of this program. The sample case from Palm Beach Harbor, which involved beach placement of dredged material, illustrates this fact well. The open structure of the spreadsheet provides an opportunity for users with specialized projects in mind to accomplish this action in the future.

REFERENCES

Belesimo, F.J. (2000). "*Cost Estimating Projects for Large Cutter and Hopper Dredges*". M.S. Thesis, Texas A&M University, College Station.

Bray, R.N., Bates, A.D., and Land J.M. (1997). "*Dredging a Handbook for Engineers*". 2nd Edition. John Wiley & Sons, Inc., New York, NY.

GIW (1998). "*LHD 24 x 26-49 Clear Water Performance*". Pump Test Results Document, GIW Industries Inc., Grovetown, GA.

Herbich, J.B. (2000). "*Handbook of Dredging Engineering*". 2nd Edition, McGraw-Hill Professional, New York, NY.

Manson Construction Company (Manson) (2008). "*Trailing Suction Hopper Dredge "Glenn Edwards*"". [http://www.mansonconstruction.com/images/Glenn_ Edwards_ Hopper.pdf], Manson Construction Co., Seattle, WA.

Miertschin, M.W. (1997). "*Cost And Production Estimation for a Cutter Suction Dredge*". M.S. Thesis, Texas A&M University, College Station, TX.

Miertschin, M.W., and Randall, R.E. (1998). "*A General Cost Estimating Program for Cutter Suction Dredges*", Proceedings of the 15th World Dredging Conference. Las Vegas, NV. pp. 1099-1115.

Munson, B.R., Young, D.F., and Okiishi, T.H. (2002). "*Fundaments of Fluid Mechanics*". John Wiley and Sons, Hoboken, NJ.

Navigation Data Center (NDC) (2009). "*Dredging Program*". [http://www.iwr.usace.army.mil/NDC/dredge/dredge.htm]. United States Army Corps of Engineers, Alexandria, VA.

Office of Coast Survey (OCS) (2010). "*NOAA's On-Line Chart Viewer*". [http://www.nauticalcharts.noaa.gov/mcd/OnLineViewer.html]. National Oceanographic and Atmospheric Administration, Washington DC.

Palermo, M. R. and Randall, R. E. (1990). "*Practices and Problems Associated with Economic Loading and Overflow of Dredge Hoppers and Scows*". Technical Report, United States Army Corps of Engineers, Washington DC.

Randall, R. E. (2000). "Pipeline Transport of Dredged Material". Chapter 7, Section 2, "*Handbook of Dredging Engineering"*. 2nd Edition. Editor: J. B. Herbich, McGraw-Hill Book Co., New York, NY.

Randall, R.E. (2004). "Dredging". Chapter 11, "*Port Engineering"*. Editor: G. P. Tsinker, John Wiley & Sons, Inc., Hoboken, NJ.

Randall, R.E. (2009). Notes, Twenty Ninth Dredging Engineering Short Course. Texas A&M University, College Station, TX

Randall, R. E., Edge, B. L., Basilotto, S. J. Graalum, S. J., Miertschin, M. and He, Q. (1998). "*Alternative Dredging and Disposal Methods for the Texas Gulf Intracoastal Waterway (GIWW)*". Final Report Submitted to Texas Department of Transportation, Austin, TX.

Randall, R.E. and Koo, B.J. (2003). *"Dredging Alternatives for Delivering Sand for Beach Nourishment"*, Proceedings of the Western Dredging Association 23rd

Technical Conference and 35th Annual Texas A&M Dredging Seminar. Chicago, IL, No. 376, pp. 73-88.

RS Means Company Inc. (2009). "*Facilities Construction Cost Data*". 24th Annual Edition. RS Means Company Inc., Kingston, MA.

Turner, T. M. (1996). "*Fundamentals of Hydraulic Dredging*" 2nd Edition. ASCE Press, Reston, Virginia.

USACE (1997). "*Engineering Instructions Construction Cost Estimates*". Engineer Instruction EI 01D010. United States Army Corps of Engineers, Washington DC.

Wilson, K. C., Addie, G. R., Sellgren, A., and Clift, R. (2006). "*Slurry Transport Using Centrifugal Pumps"*. 3rd Edition, Springer, New York, NY.

APPENDIX A

TEST CASES

TEST CASE, TRAILING SUCTION HOPPER DREDGE – BRAZOS ISLAND HARBOR, INSIDE JETTY CHANNEL, 2008

Table A-1. Dredge Data Used to Estimate Brazos Island Harbor, 2008.

DREDGE INFORMATION		
Hopper Capacity	4000	Cubic Yard
Number of Dragarms	2	Number
Length of Dragarms	100	Feet
Sailing Speed (avg)	4	Nautical Miles per Hour
Time to Unload	0.1	Hours
Capital value of dredge	10,000,000	Dollars
Horsepower Total	5400	Horsepower
Equipment Lifespan	30	Years
Draghead to first pump		
Length	30	Ft
Dia. (inner)	26	Inches
ε roughness	0.00015	Ft
Losses(k)	1.6	
First to second pump (ZERO if only one pump)		
Length	70	Ft
Dia. (inner)	26	Inches
ε roughness	0.00015	Ft
Losses(k)	0.6	
Final pump to hopper		
Length	80	Ft
Dia. (inner)	24	Inches
ε roughness	0.00015	Ft
Losses(k)	0.6	

Table A-2. Project Data Used to Estimate Brazos Island Harbor, 2008

PROJECT INFORMATION		
Average depth	47	Ft
Volume	450,000	CY
Hours Worked per Day	24	Hours
Distance to Placement Site	4	NM
Median Particle Diameter (d50)	0.15	mm
Specific Gravity of Mixture (Sm)	1.35	
Specific Gravity of Fluid (water)	1	
Specific Gravity of Solids (Ss)	2.65	
Concentration (ratio)	0.212	

Table A-3. Cost Data Used to Estimate Brazos Island Harbor, 2008.

COST INFORMATION		
Working days per year	300	Day
Effective hours at 100% power	12	Hours
Fuel Cost, see cost sheet	4.08	$/Gal
Cost Index (see costs sheet)	1	
Mobilization/demobilization	100,000	Dollars

Table A-4. Pump Data Used to Estimate Brazos Island Harbor, 2008.

Georgia Iron Works	
Model LHD 24"x26"-49	
Selection:	2 ea
Horsepower:	1500
Flow Rate (Q)	Head (H)
GPM	Ft.
20000	217
22000	208
24000	196
26000	182
28000	172
30000	164
32000	157
34000	148
36000	140
38000	135
40000	128
42000	122
44000	115
46000	110
48000	100
50000	93
52000	84
54000	74
56000	-
58000	-
60000	-

Table A-5. Project Estimate Summary for Brazos Island Harbor, 2008.

PROJECT ESTIMATE RESULTS		
Optimal Flow Rate	53,000	GPM
Project Duration	78	Days
Total Project Cost	2,416,209	Dollars

Table A-6. Job Summary for Brunswick and Savannah Harbor Entrance

Brunswick and Savannah Harbor Entrance			
Average Depth		35	Feet
Volume Dredged		2,000,000	Cubic Yards
Distance to Placement Site		3	Nautical Miles
Hopper Capacity		4000	Cubic Yards
Government Estimate	$ 3,326,140		
Winning Bid	$ 3,333,025		
Program Estimate	$ 3,794,636		
% Differences (% of Winning Bid)			
Winning Bid vs. Gov. Estimate		0%	
Winning Bid vs. Program Estimate		-14%	
Program Estimate vs. Gov Estimate		14%	

Table A-7. Job Summary for Charleston Harbor Entrance 2008

Charleston Harbor Entrance 2008			
Average Depth		47	Feet
Volume Dredged		951,000	Cubic Yards
Distance to Placement Site		5	Nautical Miles
Hopper Capacity		4000	Cubic Yards
Government Estimate	$	3,528,970	
Winning Bid	$	2,524,800	
Program Estimate	$	3,837,689	
% Differences (% of Winning Bid)			
Winning Bid vs. Gov. Estimate		-40%	
Winning Bid vs. Program Estimate		-52%	
Program Estimate vs. Gov Estimate		12%	

Table A-8. Job Summary for Charleston Harbor Entrance 2009

Charleston Harbor Entrance 2009			
Average Depth		47	Feet
Volume Dredged		1,310,000	Cubic Yards
Distance to Placement Site		5	Nautical Miles
Hopper Capacity		4000	Cubic Yards
Government Estimate	$ 4,612,400		
Winning Bid	$ 3,751,000		
Program Estimate	$ 4,737,316		
% Differences (% of Winning Bid)			
Winning Bid vs. Gov. Estimate		-23%	
Winning Bid vs. Program Estimate		-26%	
Program Estimate vs. Gov Estimate		3%	

Table A-9. Job Summary for Fernandina Harbor

Fernandina Harbor			
Average Depth		37	Feet
Volume Dredged		715,000	Cubic Yards
Distance to Placement Site		4.5	Nautical Miles
Hopper Capacity		3000	Cubic Yards
Government Estimate	$ 3,787,760		
Winning Bid	$ 3,787,760		
Program Estimate	$ 3,830,031		
% Differences (% of Winning Bid)			
Winning Bid vs. Gov. Estimate		0%	
Winning Bid vs. Program Estimate		-1%	
Program Estimate vs. Gov Estimate		1%	

Table A-10. Job Summary for Houston Shipping Channel

Houston Ship Channel, Redfish North			
Average Depth		45	Feet
Volume Dredged		1,300,000	Cubic Yards
Distance to Placement Site		4	Nautical Miles
Hopper Capacity		4000	Cubic Yards
Government Estimate	$9,304,664		
Winning Bid	$6,961,820		
Program Estimate	$7,298,446		
% Differences (% of Winning Bid)			
Winning Bid vs. Gov. Estimate		-34%	
Winning Bid vs. Program Estimate		-5%	
Program Estimate vs. Gov Estimate		-29%	

Table A-11. Job Summary for Palm Beach Harbor

Palm Beach Harbor			
Average Depth		32	Feet
Volume Dredged		150,000	Cubic Yards
Distance to Placement Site		1	Nautical Miles
Hopper Capacity		3000	Cubic Yards
Government Estimate	$ 1,773,220		
Winning Bid	$ 1,949,100		
Program Estimate	$ 484,262		
% Differences (% of Winning Bid)			
Winning Bid vs. Gov. Estimate		9%	
Winning Bid vs. Program Estimate		75%	
Program Estimate vs. Gov Estimate		-66%	

APPENDIX B

EQUATIONS

Table B-1. List of important equations and units involved in determining the optimal flowrate of a hopper dredge.

Inputs, (units):	Equation:	Output, (units):	Reference:
ρ/μ = ν, Kinematic viscosity of water, (0.0000126 ft2/sec). V, Velocity of flow, (ft/sec). D, Diameter of pipe, (feet).	$Re = \frac{\rho V D}{\mu} = \frac{VD}{\nu}$	Re, Reynolds Number, (number).	Wilson et al. (2006). Eq. 2.31.
ϵ, Pipe surface roughness, (feet). D, Diameter of pipe, (feet). Re, Reynolds number.	$f_w = 0.25/\left[log\left(\frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2$	f_w, Friction Factor (number).	Herbich (2000). Eq. 7.93.
S_m, Specific gravity of mixture, (spec. grav.) S_f, Specific gravity of fluid, (s.g.). S_s, Specific gravity of solids, (s.g.).	$C_{vd} = \frac{S_m - S_f}{S_s - S_f}$	C_{vd}, Concentration delivered, by volume, (ratio).	Herbich (2000). Eq. 7.75.
d_{50}, Median grain diameter, (millimeters).	$v_t = 134.14(d_{50} - 0.039)^{0.972}$	v_t, Settling velocity, (mm/sec)	Herbich (2000). Eq. 7.58.
v_t, Settling velocity, (m/sec) S_s, Specific gravity of solids. S_f, Specific gravity of fluids. g, Acceleration due to gravity, (9.81 m^2/sec). μ, Dynamic viscosity of water, (0.0012 N*sec/m^2).	$w = 0.9v_t + 2.7\left[\frac{S_S - S_f}{S_f} g\nu\right]^{1/3}$	w, Particle associated velocity, (m/sec)	Wilson et al. (1996). Eq. 6.12., Randall (2009).

Table B-1 Continued.

Inputs, (units):	Equation:	Output, (units):	Reference:
w, Particle associated velocity, (m/sec). f_f, Friction factor (number) d, particle diameter, (meters or feet). D, Pipe diameter, (meters or feet).	$V_{50} = w\left(\sqrt{\frac{8}{f_f}}\right)cosh[60d/D]$	V_{50}, Velocity of flow where 50% of solids are suspended, (m/sec).	Wilson et al. (2006). Eq. 6.2.
f_w, Friction factor (number) g, Acceleration due to gravity, (9.81 m^2/sec). D, Pipe diameter, (meters). V_m, Flow velocity (m/sec). S_s, Specific gravity of solids, (s.g.). V_{50}, Velocity of 50% suspension, (m/sec). M, Particle grading factor, (generally 1.7). C_{vd}, Concentration of delivered solids, (ratio).	$i_m = \frac{f_w}{2gD}V_m^2 + 0.22(S_s - 1)V_{50}^M C_{vd} V_m^{-M}$	i_m, Loss of head per unit length of pipe, (ft/ft or m/m).	Wilson et al. (2006). Eq. 6.5.

Table B-1 Continued.

Inputs, (units):	Equation:	Output, (units):	Reference:
μ_s, Coefficient of mechanical friction between particles, (0.44 or 0.55). S_s, Specific gravity of solids, (s.g.). S_f, Specific gravity of fluid, (s.g.). D, diameter of pipe, (meters). d_{50}, Grain diameter, (mm)	$V_c = \dfrac{8.8\left[\dfrac{\mu_s(S_s - S_f)}{0.66}\right]^{0.55} D^{0.7} d_{50}^{1.75}}{d_{50}^2 + 0.11D^{0.7}}$	V_c, Critical velocity (m/s)	Herbich (2000). Eq. 7.80, from Matousek (1997).
$\Delta i(0)$, Incremental pressure gradient $i_m - i_w$ (m/m) θ, Dragarm inclination (radian or degrees). M, Factor, 1.7. γ, Factor, 0.5. C_{vd}, Concentration of delivered solids, (ratio).	$\Delta i(\theta) = \Delta i(0)cos\theta^{(1+M\gamma)} + (S_s - 1)C_{vd}sin\theta$	$\Delta i(\theta)$, Additional pressure gradient (m/m)	Wilson et al. (1996). Eq. 6.13., Randall (2009).
f_w, Friction factor (number) g, Acceleration due to gravity, (9.81 m^2/sec). D, Pipe diameter, (meters). V_m, Flow velocity (m/sec).	$i_w = f\,\dfrac{V^2}{2gD}$	i_w, Clear water pressure gradient (m/m)	

APPENDIX C

USER'S GUIDE

This Guide is designed to walk the user through an estimating project for a medium sized hopper dredge project. The guide begins in the research phase and leads through the data entry, and results output.

Step 1: Research.

Information on the area to be dredged can be acquired by the user from acutual site measurements, or for initial estimates, from standard navigational charts. United States charts are viewable at the National Oceanographic and Atmospheric Administration's Office of Coast Survey online chart viewer: [http://www.nauticalcharts.noaa.gov/mcd/OnLineViewer.html]. A screen capture of the website in use, viewing the part of the Houston Shipping Channel is included in Figure C-1. The charts may be used to capture information including project depth or volume, sailing distances, expected traffic, of other regional peculiarities. A second aspect to research is the dredge to be used. Many dredging companies publish details of their fleets online like Manson Construction Co. at [http://www.mansonconstruction.com/hopper_dredges_fleet.html], and even detailed ship-specific information pamphlets from [http://www.mansonconstruction.com/images/Glenn_Edwards_Hopper.pdf] shown in Figure C-2. Datasheets such as this include dredge capacity and capability, pipe diameter, speed, power, and applications.

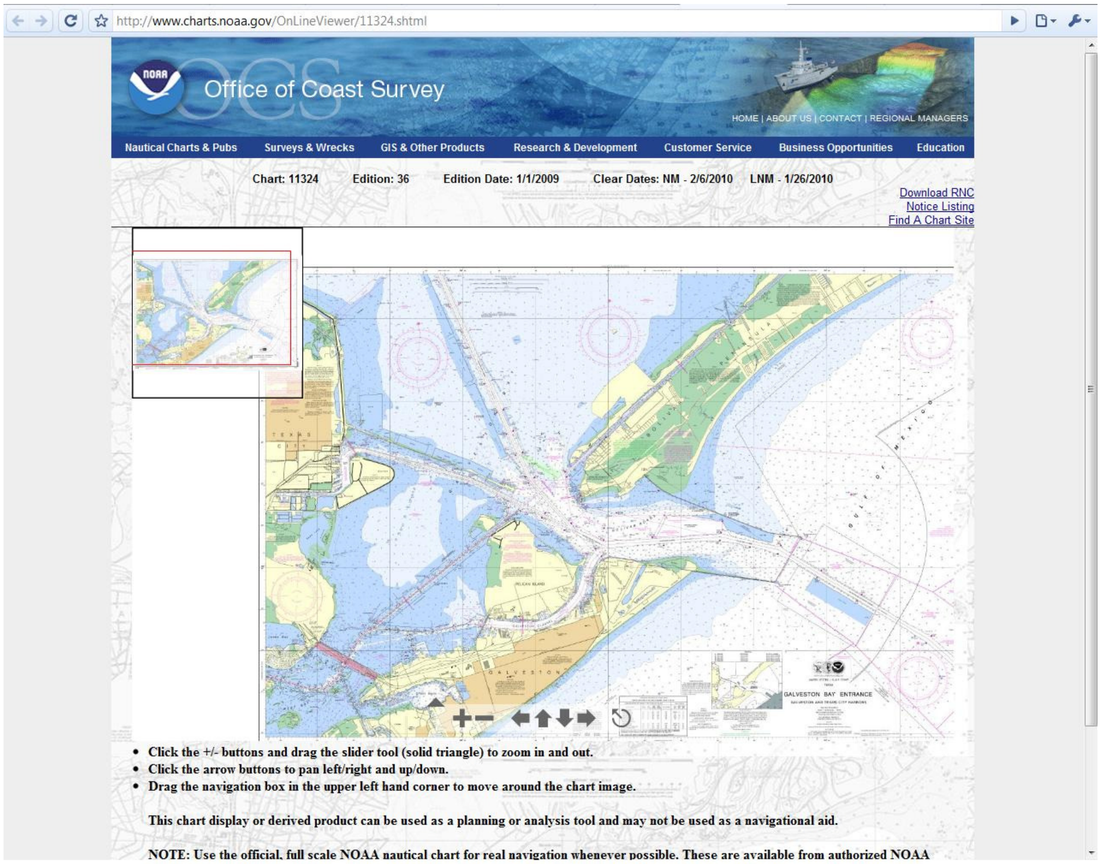

Figure C-1. NOAA Chart Viewer. (OCS, 2010)

Serving the Nation's Waterways Since 1905

Fleet

Trailing Suction Hopper Dredge "Glenn Edwards"

The newest dredge to the Manson Construction fleet is the *"Glenn Edwards"*, having been christened in 2006. The *"Glenn Edwards"* is the largest trailing suction hopper dredge in the United States. Dredged material can be disposed of by either bottom-dumping through her bottom doors or by slurifying the load with her fluidization piping and pumping out over the bow.

Along with her enormous size and exceptionally large hopper capacity, this vessel features three azimuth drives which, along with her bow thruster, gives her 360° maneuverability. This makes her well suited to make quick work of harbors and channels.

The *"Glenn Edwards"* is equipped with state-of-the-art instrumentation for both positioning and production monitoring purposes.

Applications of the *"Glenn Edwards"* include, but are not limited to:

- Channel & Harbor Maintenance
- Upland Disposal
- Beach Nourishment

Glenn Edwards Specifications

Dimensions
Length:
390 ft / 118.9 m
Beam:
76 ft / 23.16 m
Light Draft:
15 ft / 4.57 m
Loaded Draft:
28 ft / 8.53 m
Suction Diameter:
38 in / 965 mm
Discharge Diameter:
38 in / 965 mm

Performance
Hopper Capacity:
13,500 yd³ / 10,321 m³
Maximum Digging Depth:
90 ft / 27.4 m
Sailing Speed Light:
13 KT
Sailing Speed Loaded:
11 KT

Power Data
Total Installed Power:
12,000 hp / 8,951 kW
Fuel Capacity:
200,000 gal / 787,000 l

 Seattle Office (Headquarters): 5209 East Marginal Way S., Seattle, WA 98134
Phone: (206) 762-0850 • Fax: (206) 764-8590 • email@mansonconstruction.com • www.mansoncontruction.com

Figure C-2. Manson Construction Co. Fleet Info Pamphlet. (Manson, 2008)

Step 2: Data Input

Once the user has conducted their initial research, they can begin to enter data into the estimating spreadsheet. All required inputs are highlighted for ease of use. First to be entered will be dredge information shown in Table C-1.

Table C-1. Dredge information input.

Hopper Capacity	4000	cy	3058	m^3
Number of Dragarms	2	number		
Length of Dragarms	100	feet	30.5	m
Sailing Speed (avg)	6	NM/hr	11.1	km/hr
Time to Unload	0.1	hours		
Capital value of dredge	10,000,000	dollars		
Horsepower Total	5400	Hp	4027	kw
Equipment Lifespan	30	years		
Draghead to first pump				
Length	30	ft	9.15	m
Dia. (inner)	26	in	0.2201	m
ε roughness	0.00015	ft	4.58E-05	m
Losses(k)	1.6			
First to second pump (ZERO if only one pump)				
Length	70	ft	21.35	m
Dia. (inner)	26	in	0.2201	m
ε roughness	0.00015	ft	4.58E-05	m
Losses(k)	0.6			
Final pump to hopper				
Length	80	ft	24.4	m
Dia. (inner)	24	in	0.2032	m
ε roughness	0.00015	ft	4.58E-05	m
Losses(k)	0.6			

The second area for input is used to describe the project at hand and is shown in Table C-2. These are basic project parameters that describe the amount and quality of material involved. The specific gravities shown in Table C-2 are standard for maintenance hopper dredging according to Randall (2009)

Table C-2. Project information input.

Average depth	47	ft	14.3	m
Volume	1,310,000	cy	1001567	m^3
Hours Worked per Day	24	hrs		
Distance to Placement Site	5	NM	9.26	km
Median Particle Diameter (d50)	0.00591	in	0.15	mm
Specific Gravity of Mixture (Sm)	1.35			
Specific Gravity of Fluid (water)	1			
Specific Gravity of Solids (Ss)	2.65			
Concentration (ratio)	0.212			

After the project information is supplied, the user may input values that influence project pricing, an example is shown in Table C-3. The cost index value is set as 1 (national average) as a default and can be modified by the user according to local knowledge, of by looking up value for major areas provided in another sheet in the workbook from RS Means (2009).

Table C-3. Cost information input.

Working days per year	300	days
Effective hours at 100% power	12	hrs
Fuel Cost, see cost sheet	2.63	$/gal
Cost Index (see costs sheet)	1	ratio
Mobilization/demobilization	100,000	dollars

Labor rates may be changed as required by the user and are provided in the form shown in Table C-4, note that not all positions may be required in all dredges of projects, and an allowance is made to remove or include individual positions from the total.

Table C-4. Labor input

	Hourly Rate	Cost of hopper dredge($) Daily Rate	Number	Daily Total
	$	$/day	#	$
Master	30	720	1	720
Dredger	30	720	2	1440
Chief mate	20	480	1	480
Mate	18	432	1	432
AB	16	384	2	768
Seaman	16	384	2	768
Chief Eng.	30	720	1	720
Asst Eng.	25	600	1	600
Oiler	18	432	2	864
Elect.	30	720	1	720
Cook	20	480	1	480
Mess.	15	360	1	360
			Daily Total ($)	8352

The last important detail requiring input for the estimation is the dredge pump selection. Several pump characteristic curves have been provided and the user selects how many of which pumps are operating in series on the dredge flow route. Wilson et al. (2006) illustrate how properly designed pumping systems with multiple pumps in series can be considered additive in terms of head generated, which is how the pumps are modeled in this spreadsheet. As shown in Table C-5, the user enters the number of pumps in the selection fields above the head data in order to include those pumps in the calculations.

Table C-5. Pump selection input.

	Georgia Iron Works Model LHD 24x26-49		
Selection:	2	0	0
Horespower:	1500	3000	4500
Flow Rate (Q) GPM	Head (H) Ft.	Head (H) Ft.	Head (H) Ft.
20000	217		
22000	208		
24000	196		
26000	182		
28000	172		
30000	164	310	
32000	157	296	
34000	148	283	
36000	140	275	
38000	135	260	
40000	128	250	
42000	122	240	350
44000	115	230	340
46000	110	223	330
48000	100	215	320
50000	93	208	310
52000	84	200	300
54000	74	190	290
56000		183	280
58000		174	270
60000		163	260
62000		155	250
64000		140	240
66000		132	230
68000		120	220
70000		110	210

Output

With the appropriate data entered into the spreadsheet as illustrated in Tables C-1 through C-5, the spreadsheet will create a plot similar to Figure 5 and calculate the production rate, project duration, and associated costs. Cost output are provided in the form shown in Table C-6

Table C-6. Cost estimate ouput.

Project Name

Average Depth	47	Feet	
	14.3	Meters	
Volume Dredged	1,310,000	Cubic Yards	
	1,001,567	Cubic Meters	
Distance to Placement Site	5	Nautical Miles	
	9.26	Kilometers	
Hopper Capacity	4000	Cubic Yards	
	3058	Cubic Meters	
Project duration (days)	192	days	
Production rate (cy/hr)	6679	cy/hr	
	Daily Rate:		Project Total:
Minor repairs ($)	$1,400		$268,800
Major reapirs($)	$3,000		$576,000
Insurance ($)	$833		$160,000
Fuel cost ($)	$8,194		$1,573,213
Cost of lubricants ($)	$819		$157,321
Depreciation cost ($)	$1,111		$213,333
Total project costs	$ 4,652,251		
Plus 10% bond and profit ($)	$ 5,117,476		
After location indexing	$ 5,117,476		

VITA

Thomas Elliot Hollinberger

Thomas 'Elliot' Hollinberger graduated from the United States Coast Guard Academy in 2006 with a Bachelor of Science degree in mechanical engineering.

After graduation, Elliot was stationed on the U.S. Coast Guard Cutter ACUSHNET, homeported in Ketchikan Alaska, the oldest commissioned cutter in the U.S. Coast Guard. His duties included Deck Watch Officer and Engineering Watch Officer, as well as Assistant Engineering Department Head, Damage Control Assistant, Gas Free Engineer, and Law Enforcement Boarding Officer.

In 2008, Elliot transferred to Texas A&M University as part of the U.S. Coast Guard Advanced Education program in ocean engineering. Elliot graduated with a Master of Science degree in ocean engineering from Texas A&M University in May 2010.

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