Berthing Pain Prevention:
Flexibility in the Design of a Marine Dock for Bulk Liquid Chemicals Loading

Abstract: In this paper, we analyze the value of flexibility in the design of a marine dock for the loading of bulk chemicals from a riverside petrochemical manufacturing facility in the Gulf Coast region of the United States. After describing the general operating context and constraints, we investigate the output of a stochastic simulation model, comparing the expected financial impact of design approaches with and without built-in expansion flexibility. Additionally, we provide accompanying sensitivity analysis for the various uncertainties. The outcomes revealed through Monte Carlo simulation show that flexibility in the original design, combined with an option for later expansion, delivers the optimal expected net present value.

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INTRODUCTION

Background

Though petrochemical manufacturing operations utilize various outbound transport modes—pipelines, tanker trucks, tanker rail cars, etc.—the primary transportation "workhorse of chemical logistics" is bulk marine shipping via ocean-going vessels and river barges (2118 Li et al 2010, 1365 Arons et al. 2006). Because of this reliance on water transport, bulk marine loading facilities can become a very expensive bottle-neck for a chemical manufacturer: vessel holdovers fees (demurrage) are in the tens of thousands of dollars per day while the opportunity costs of lost production capacity run even higher (1268 Jetlund 2004). Unfortunately, the high capital and operating costs imposed by these structures prohibits the profitable maintenance of considerable excess capacity.

Typical marine loading facilities for petrochemicals consist of four primary components: berths/moorings, loading arms, pipelines, and a platform (e.g. piles and decking). As seen in Figures 1 and 2, a single platform typically hosts multiple pipelines, berths/moorings and loading arms, though the number varies by deployment. In our analysis, we attempt to exploit this componentization in order to gain the flexibility to incrementally expand marine loading capacity.

Figure 1

Figure 2

Methodology

The deterministic engineering design approach to such a capital construction project will seek the optimal fixed capacity which maximizes the value of the loading facility within the chosen timeframe. We use a stochastic simulation model to compare this deterministic approach to two designs which incorporate flexible expansion options. Our model incorporates several constant variables in addition to the stochastic variables (see Table 1). These variables are described in further detail in the following section.

Table 1

Stochastic Variables	Deterministic Variables
Demand Growth	Discount Rate
Panama Canal Expansion Project Completion Year	Starting Demand
Panama Canal Expansion Project Completion Factor	Starting Capacity
Asset Utilization	Expansion Capacity
Average Chemical Price per Ton Growth	Expansion Cost
	Starting Average Chemical Price per Ton

We demonstrate two approaches to implementing expansion flexibility with our model. Both approaches rely on additional initial capital investment in Period 0. This additional investment represents the cost of installing two components with excess capacity—the platform and pipeline. This staging in Period 0 allows for the addition of incremental loading arms and berth/mooring systems at a later date, based on increases in product demand. The first flexibility scenario demonstrates the option of making a single additional investment (i.e. adding two additional loading arms and equivalent berthing/mooring capacity at one time) in the loading system. The second flexibility scenario allows for multiple, smaller investments (i.e. adding the two additional loading arms and equivalent berthing/mooring capacity one at a time). The decision to execute the expansion options, or not, is made programmatically during each period based on the level of demand compared to the level of capacity.

Our comparative analysis includes the expected NPV and discounted capital expenditure of each scenario. As an appendix (B) we provide a sensitivity analysis of the variables and the distributions of select stochastic variables. Microsoft Excel and Palisade @Risk provide the environment for our modeling and analysis.

Data Sources, Uncertainties and Parameters

Most of the research and data for this project was gathered as part of a separate Master's thesis currently underway in cooperation with a large, multinational petrochemical manufacturer. Wherever possibly, we use data and forecasts provided directly by this corporate research partner. In some cases, the corporate data is sanitized for confidentiality.

Our stochastic variables, or uncertainties, are defined as follows. First, the uncertainty in future demand for petrochemicals is simulated using a random multiplier. For the expected annual growth in demand we use 5%, the most recent estimate from Business Monitor International (BMI United States Petrochemicals Report 2010). However, given the high level of volatility in this measure we use @Risk to simulate variability in the growth rate assuming an approximately normal distribution with a mean of 5% and a standard deviation of 4%. The corresponding growth in demand value is simulated for each period in the model.

Second, we simulate a random binary variable representing the completion of the Panama Canal Expansion. The stated expected completion date for this project is currently 2014. However, the actual durations of large-scale projects are typically considerably longer than initial estimates, overall fitting to a lognormal distribution (see Appendix 1; 50 Little 2006). We assume a similar distribution to simulate the project completion: $2{,}013 + \sim LN(3{,}2)$.

This second point of uncertainty controls a binary variable that, when true for a given time period, applies a second multiplier to the demand estimate. This multiplier accounts for the additional demand likely to be generated when post-Panamax tankers are able to ship from the Gulf Coast (the location of our chemical manufacturing plant) to customers in the Asia-Pacific region and takes the form of $\sim N(3\%, 2\%)$ in our model. It should be noted that a single simulated value is used for these variables for an entire iteration of the model, rather than a different simulated value for each period.

A fourth uncertainty is the percent asset utilization of the dock. A brief aside here—the other uncertainties we have described are largely exogenous and independent of manager actions. As an exception, the efficiency of marine dock utilization is open to management impact, but in consideration of demurrage penalties should this lever be pulled too hard.

The final uncertainty taken into consideration is the average price of petrochemicals, which is simulated as increasing annually based on a distribution of $\sim N(3\%, 2\%)$.

Our discount rate is set at 20%, starting demand at 624,000 tons, and starting chemical price per ton at $1,159. The remaining non-stochastic parameters vary by scenario (see Table 2 below).

None of the uncertainties are constrained to positive or integer values.

Each scenario undergoes 10,000 iterations of Monte Carlo simulation to produce our result set.

Table 2

Parameter Name	**Inflexible, Low Capacity**	**Inflexible, High Capacity**	**Flexible, Single Stage**	**Flexible, Multi Stage**
Starting Capacity	936,000	1,040,000	936,000	936,000
Expansion Capacity	-	-	104,000	52,000*
Expansion Cost	-	-	$90,000,000	$50,000,000*
Initial Capital Investment	$180,000,000	$250,000,000	$200,000,000	$200,000,000

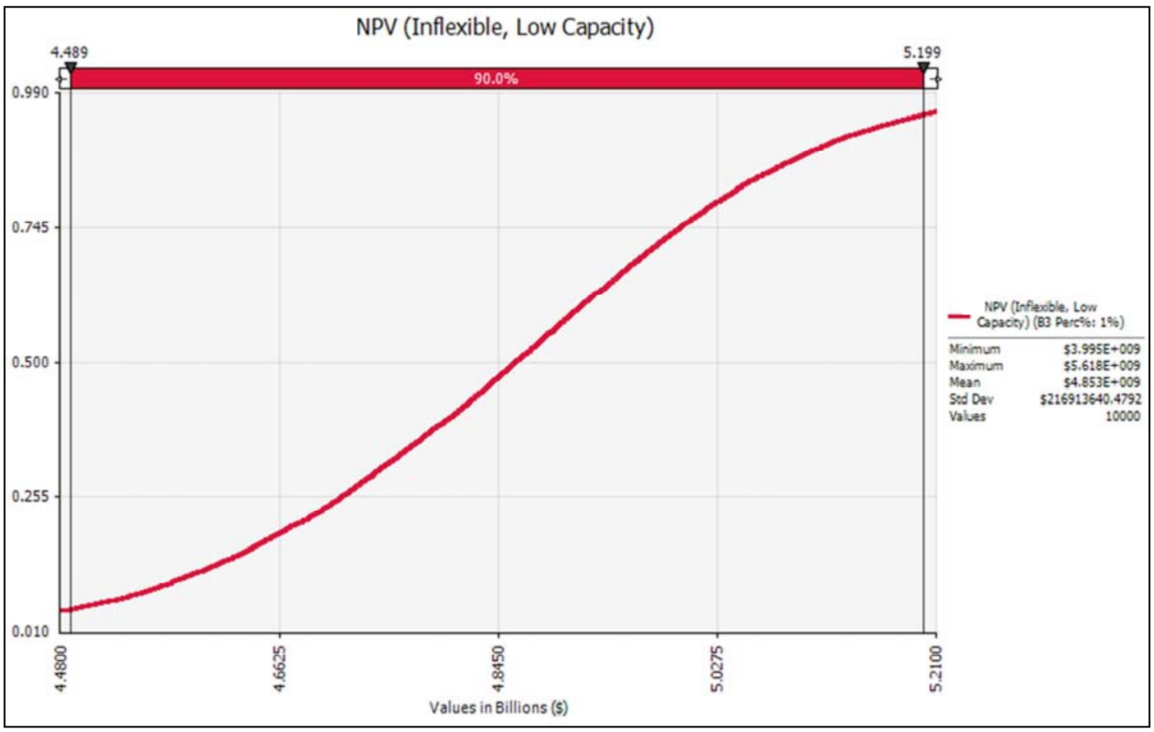
* Per stage

ANALYSIS

Inflexible, Low Capacity

The first scenario we simulate begins in Period 0 with an $180,000,000 capital investment, which represents the cost of the smaller, fully-equipped marine dock system. This dock system offers an annual maximum throughput of 936,000t. As there is no room for expansion, the simulation does not include any decision rules. Hence, without any future capital expenditure, the total present value capital expenditure is the same as the initial investment amount. As seen in the cumulative distribution (Figure 3), the expected net present value in this scenario is ~$4.853b. The distribution is approximately normally distributed with a 90% confidence interval of [$4.489b, $5.199b].

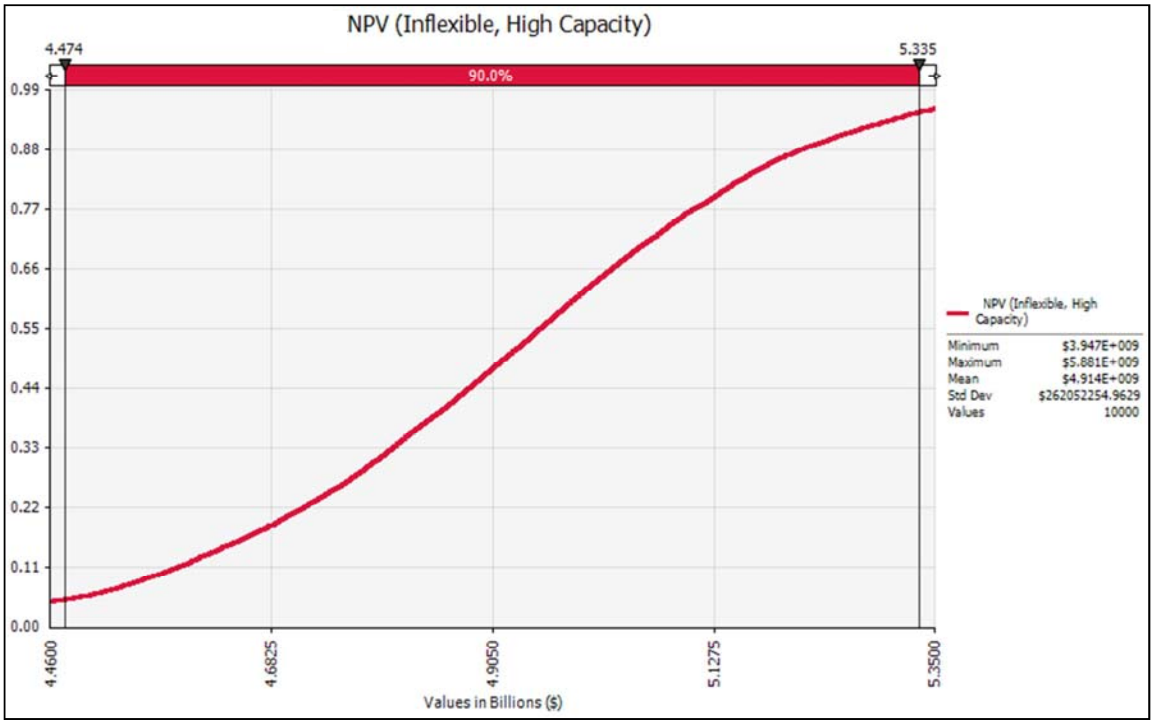
Figure 3



Inflexible, High Capacity

Our second scenario only differs from the first in the Period 0 investment amount. In this formulation we represent the construction of the larger, fully-equipped marine dock. The starting (and final) capacity in this scenario is set to 1,040,000t. Due to the project size increase, the Period 0 capital expenditure rises to $250,000,000. As seen in the first scenario, future capital investment remains out of scope so there are no additional components of present value capital expenditure. The VARG curve below shows a simulated mean of $4.914b and a 90% confidence interval of [$4.474b, $5.335b] under this parameter set.

Figure 4

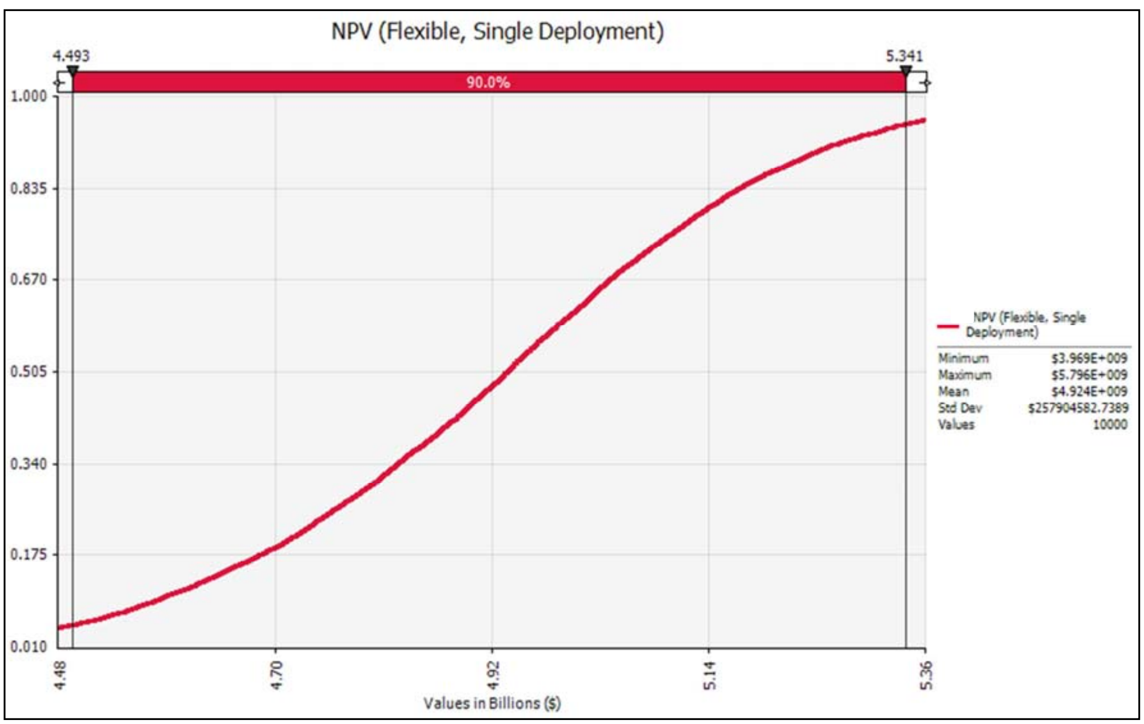


Flexible, Single Stage

The third scenario that we model is the first to include flexibility. This flexibility is achieved by constructing a large, partially-equipped marine dock in Period 0, thus allowing capacity expansion in later periods. Although the dock is of the same size as in the second scenario, a portion will not be usable until it is equipped with loading arms and berth/mooring systems. The initial capacity is the identical to the first scenario at 936,000t but because of the added cost of the larger supporting structure(s), the initial capital expenditure is higher. However, by not fully equipping the dock at first, we require a $50m lower initial capital expenditure compared to the large, fixed scenario—$200,000,000 vs. $250,000,000. This initial savings compared to scenario two is offset, in future value terms and *if* the expansion option is utilized, by an expansion cost of $90m.

As discussed in the *Data Sources, Uncertainties & Parameters* section above, the flexible, single stage model configuration incorporates the option to expand capacity based on a two-part decision rule. If either of the two triggers is activated in a given year, the decision is made to expand capacity. This decision is based on the percentage of excess demand and the Panama Canal expansion status: if the Panama Canal expansion is completed, or the excess demand is outside of the tolerance range then the dock capacity expansion will be activated. The $90m expansion fully equips the larger dock, bringing the maximum throughput up to 1,040,000t per annum. Using optimal decision rules, this implementation yields a simulated NPV mean of $4.924b and a corresponding 90% confidence interval of [$4.493b, $5.341b] (see Figure 5 below).

Figure 5



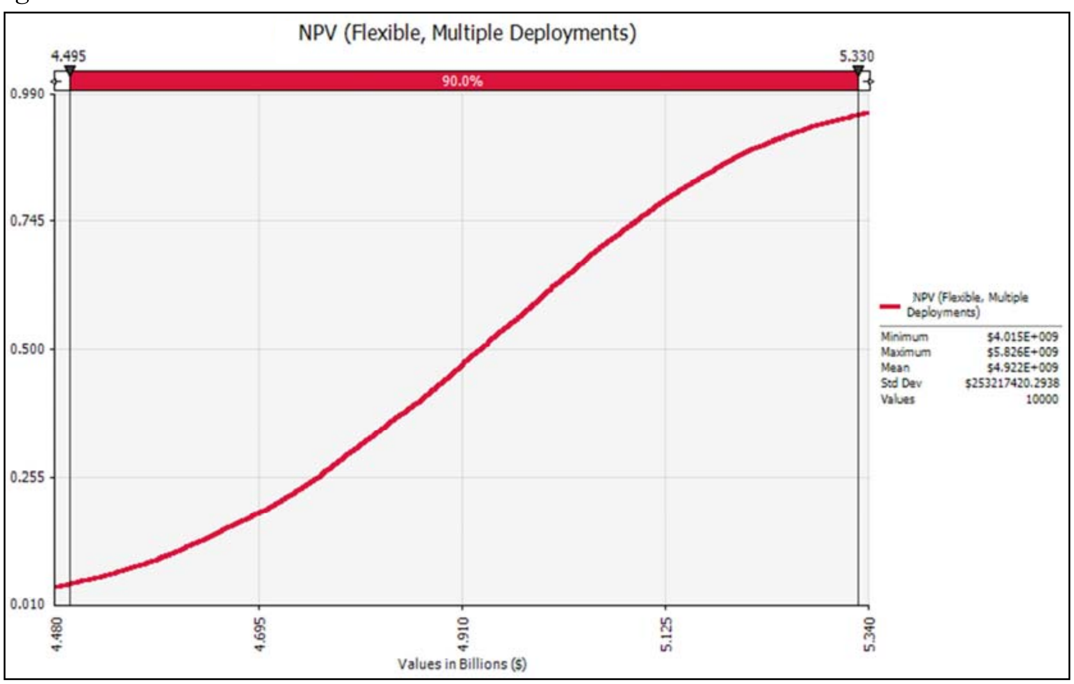
Flexible, Multi Stage

The final implementation of our model includes assumes the same initial construction scheme and costs—larger, partially-equipped dock with 936,000t throughput at a cost of $200m. However, it differs in the expansion parameters. Rather than a single expansion of 104,000t at a cost of $90m, this scenario allows for the expansion to occur in two separate additions of 52,000t throughput each at a cost of $50m per expansion. The higher overall cost of expansion in this scenario is due to lost economies of scale in construction.

The decision rules in this scenario are based only on excess demand levels: if the excess demand is outside of the tolerance range then the dock capacity expansion will be activated.

As shown in Figure 6, this flexibility yields a simulated NPV distribution with a mean of $4.922b and a 90% confidence interval of [$4.495b, $5.330b].

Figure 6



Comparison

By overlaying the cumulative distribution functions of the four designs, we immediately note the inferiority of the Inflexible, Low Capacity design from a NPV perspective (Figure 7). However, comparison of the remaining three designs is more difficult. Upon closer inspection, we find that while the two flexible designs consistently perform better than the Inflexible, High Capacity approach, neither demonstrates clear stochastic dominance over the other (Figure 8). The Flexible, Single Stage approach displays more appealing central tendency statistics for NPV, but consistently produces a worse 90% confidence interval lower bound. Depending on the priorities of the decision maker, this could influence the final design choice. That being said, it is highly likely that the Flexible, Single Stage will be chosen as the optimal design amongst the four.

From a capital expenditure perspective, it is interesting to note the effect of discounting on the cash flows of the flexible scenarios. Since the inflexible scenarios account for all capital expenditure in Period 0, the total investment costs and present value investment costs are the same. Contrastingly, the flexible scenarios tend to expend portions of their total investment in later years, lowering the impact to NPV. Though in both of the future value scenarios we almost always observe a higher future value capital expenditure compared to the Inflexible, High Capacity case, discounting the cash flows results in a ~90% probability that the flexible scenarios will yield a lower present value capital expenditure (Figure 9).

Figure 7

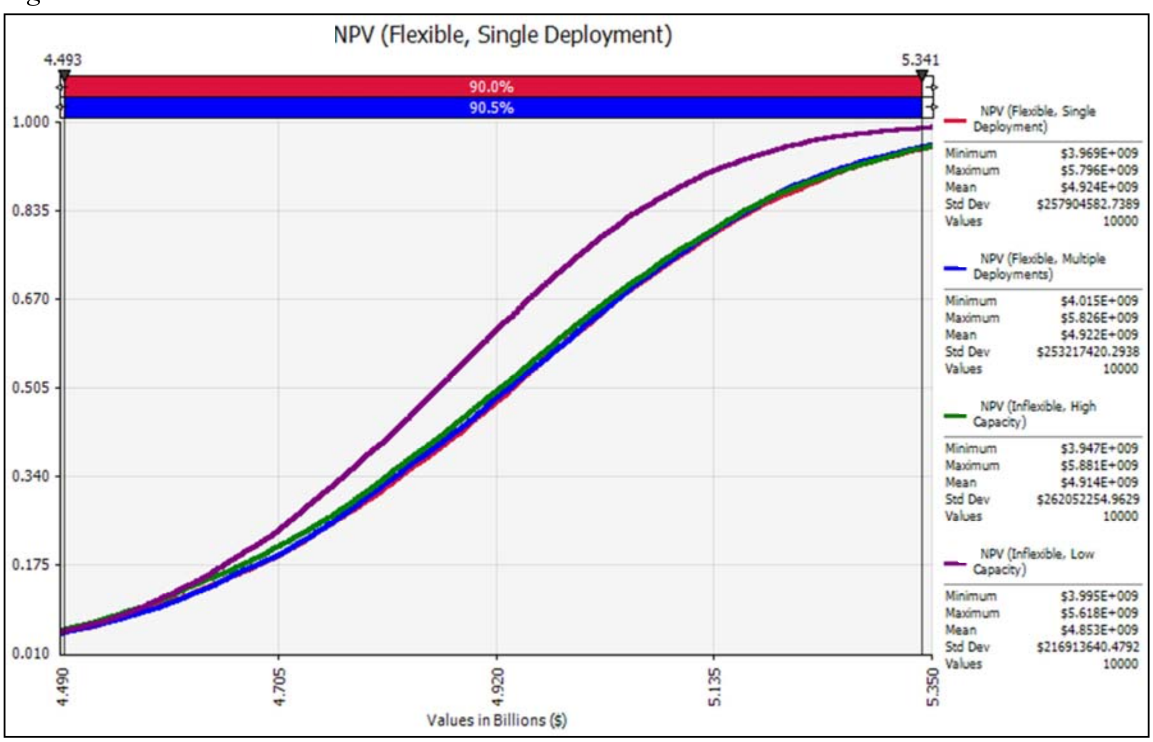


Figure 8 (detail of Figure 7)

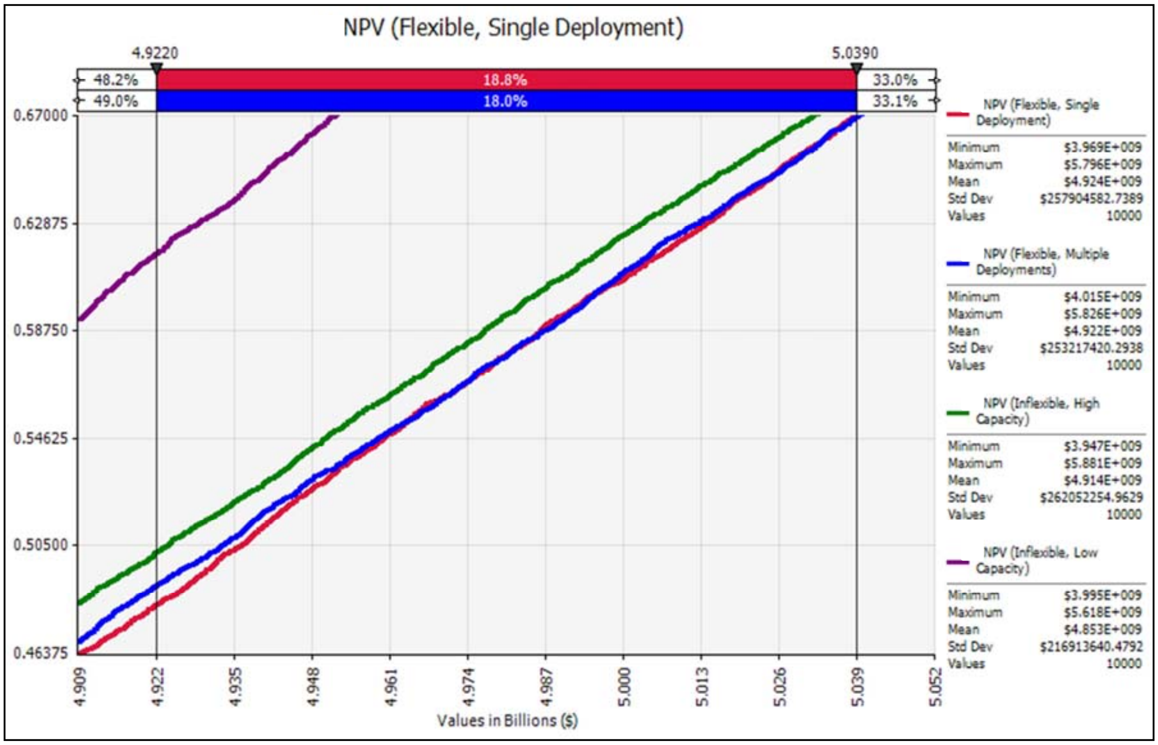
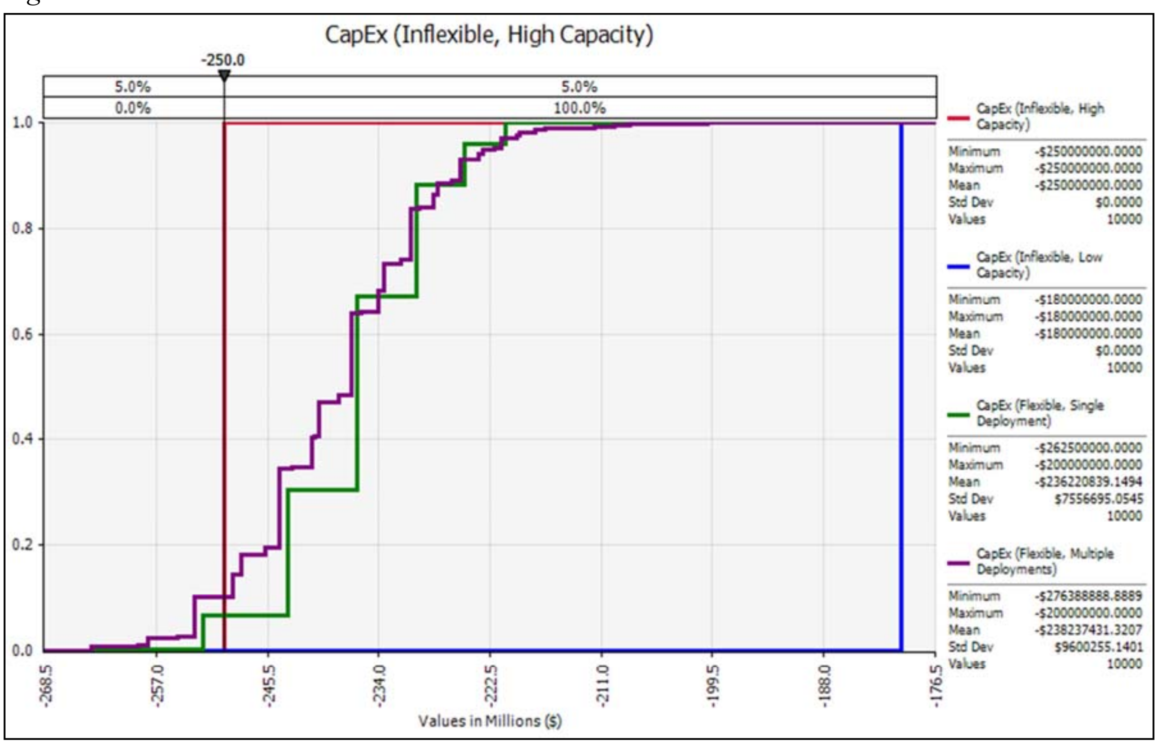


Figure 9



CONCLUSION

In conclusion, our analysis shows clear stochastic dominance of the flexible design over the inflexible design. Additionally, due to the delay in expenditure for the expansion(s) we find that the flexible options have a present value capital expenditure advantage over the inflexible design which achieves the equivalent total capacity, but in Period 0. Contrary to initial expectations, under the parameters used in our model, the multi-stage flexibility design did not prove a clear advantage over the single stage design. Further analysis is required to determine the point at which the additional capital expenditure required by the multi stage design would be low enough, or demand growth uncertain enough, to provide advantage to this design.

This exercise has proven beneficial on three points. First and foremost, it has honed my ability to model and quantify various design scenarios using decision rules and stochastic parameters. This aptitude will help me to evaluate and provide decision support for critical supply chain design problems as I continue my career after graduation. The guided use of several programming and problem solving techniques and the accompanying software packages has been an invaluable experience.

Second, this exercise has helped me to think in terms of flexibility—to see a problem and quickly recognize opportunities to incorporate flexibility into the solution. This evolution took the most time, but here, near the end of the course, I find myself applying the framework of design options to projects that I encounter in other courses and even outside of my academic pursuits. To this point, a helpful reference I have been attempting to compile—and one that would be a wonderful handout for this course—is a one-page bulleted listing of the most common design flexibility archetypes. I imagine that as I progress through my career in industry, I will likely encounter most of them at least once.

Third, the unexpected inferiority of the multi stage design using this model served me as a stern reprimand. Going into the analysis, I firmly believed that this approach would display unequivocal advantage over the others; I spent hours trying to find decision rules that would support this hypothesis. However, as the results show, it is important to model and compare various approaches before determining the optimal level of flexibility to incorporate in a particular project.

Overall, this project was challenging, engaging and very enjoyable. It has already provided value to my thesis and I look forward to extending this benefit to my professional endeavors.

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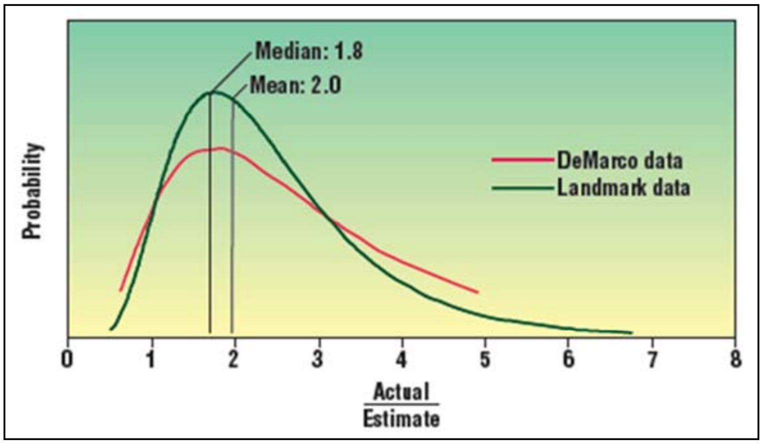
Appendix A



Appendix B