Improving the Lifecycle Performance of Engineering Projects with Flexible Strategies: A Study About On-Shore LNG Production Design

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Abstract

This paper presents a flexibility analysis as a practical procedure to evaluate large-scale capital-intensive projects considering market uncertainty. It considers the combined effects of the time value of money, economies of scale, and learning, and demonstrates the additional benefits stemming from considerations of uncertainty and flexibility in the early stages of design and project evaluation. This study focuses on the long-term deployment of liquefied natural gas (LNG) technology in the Australian market to supply the transportation sectors. Two design alternatives are considered: 1) fixed design, a big centralized production facility; 2) flexible modular designs, either using phasing approach at the big plant site or the same flexible approach with an option to move modular plants at distance. To compare the design alternatives, a structured flexibility methodology is applied based on several economic lifecycle performance indicators (e.g. Net Present Value, Initial CAPEX, etc.). Results indicate that a flexible modular deployment strategy improves the economic performance as compared to optimum fixed designs. They also indicate that factoring flexibility to locate modules at a distance further improves system performance. Considering $\alpha = 0.95$ as the magnitude of the economies of scale, the flexible modular design and the flexible modular design with move strategy improve the expected net present value by 33% and 36% respectively as compared to the optimum fixed design. Moreover, this improvement enhances as learning rate increases. Overall, the study shows that flexibility in engineering design of LNG plants has multiple, supporting advantages due to uncertainty, location and learning.

Keywords: engineering economic analysis, project valuation, flexibility in engineering design, LNG production, real options analysis, systems engineering

1 Introduction

The advantage of using natural gas products has increased over the last three decades, resulting in a considerable demand growth for LNG. Research has shown that by 2030 there is a possibility that the overall LNG demand will be more than three times higher than from where it was in 2011 and the regional distribution will significantly change accordingly [Kumar et al., 2011]. More specifically, gas product demand and supply forecasts in Australia indicate a potential shortfall of 300 to 600 TJ/day by 2015, and between zero and 600 TJ/day by 2020 [ECS, 2011]. A combination of growth and replacement production indicates there is a need to source at least 1,100 TJ/day of new production by 2020.

Over the past 20 years price differentials between fuel oil, gasoil/diesel and LNG have changed significantly. In 1997 oil prices hovered around $20 per barrel (West Texas Intermediate - WTI) and around $2.50 per Million British Thermal Unit (MMBtu) for Henry Hub natural gas in the United States. Today, these are around $100 per barrel for oil and $5 per MMBtu for natural gas [GLE, 2011]. Natural gas prices have only doubled in 20 years while WTI prices gone up 5 times in 20 years, making the price difference even more attractive.

In liquefied form, the volume of LNG is 600 times less than the same amount of natural gas at room temperatures while the volume of compressed natural gas (CNG) is 1% less of its original volume [GLE, 2013]. Hence, the energy density of LNG over CNG increases the driving range significantly. With one fuel tank, a road truck can go around 800-1,200 km distance [GLE, 2011]. New emissions control regulations are making LNG an increasingly attractive alternative for the shipping sector as well as for heavy road transport. Furthermore lower LNG tax compared to diesel tax is attractive for investors in this market. These advantages make LNG an excellent option for the heavy transportation sector.

Since LNG can be used reliably as on-road transport fuel, there are growing business opportunities for LNG production. Development of this business can be risky, however, as it requires substantial amount of initial investment. The project will be subject to different uncertainties such as LNG demand uncertainty, gas price, and facility availability. Hence the design stage of such projects is very important, as critical decisions need to be made as changing the configuration of the system later on might be too costly.

This study presents flexibility analysis as a practical procedure to maximize the expected value of a system over its useful time. It enables developers to adapt the system for better performance as its requirements and opportunities evolve over its useful life by exploiting the notion of modularity in design [Cardin, 2014, de Neufville and Scholtes, 2011]. The study contrasts and compares to others as it considers explicitly the combined effects of uncertainty, the time value of money, economies of scale, and learning to highlight the economic benefits stemming from flexibility. It is first to do this in the context of LNG production systems.

The rest of this paper is organized as follows. The next section discusses the motivations to apply the practical flexibility procedure, which considers explicitly uncertainty and flexibility, to designing and evaluating LNG production systems. It reviews relevant literature, and identifies the research gap for further contribution. The section identifies the scope of the problem under consideration. Following the introduction of the details of the proposed methodology, a case study on a LNG production system demonstrates the implementation of the approach. The final section summarizes major findings, providing conclusions and insights for further research.

2 Background and motivation

Flexibility in engineering design

Since last decades, real options and flexibility in engineering design, as a real options analysis evaluation techniques, has been introduced by adapting the concept from financial options analysis (e.g. Black and Scholes [1973]; Cox et al. [1979]) and real options analysis (e.g. [Trigeorgis, 1996] [Dixit and Pindyck, 1994]) in a way to suit the needs of engineering design in such highly uncertain world.

Flexibility in engineering design is an interdisciplinary field for research and practice [Cardin, 2014, de Neufville and Scholtes, 2011]. It adapts the concept of financial options to real engineering systems, with the goal of increasing the expected economic value by providing the "right, but not the obligation to change a system" to respond to uncertainties most profitably [Trigeorgis, 1996]. Flexibility exists "on" and "in" engineering systems. Flexibility "on" systems is associated with managerial flexibility like abandoning, deferring until favorable market conditions, expanding/contracting/reducing capacity, deploying capacity over time, switching inputs/outputs, and/or mixing the above [Trigeorgis, 1996]. Flexibility "in" systems refers to technical engineering and design components enabling real options – another word for flexibility – in deployment and operations [Wang, 2005]. Cardin [2014] provides a taxonomy and design framework to organize design and evaluation activities to enable flexibility in engineering systems.

According to Savage's [2009] "Flaw of Averages", relying on the most likely or average scenario may lead to incorrect design selection and investment decisions. This is because the output from an upside scenario (e.g. high demand growth) does not necessarily balance the output from a downside scenario (e.g. low demand growth). Equation 1 captures this formally:

$$f(E[x]) \neq E[f(x)] \quad (1)$$

Here, *E[x]* represents for instance expected LNG demand, and *f(E[x])* the Net Present Value (NPV) associated to such demand scenario (i.e. the time discounted value of the cash flows generated by the project). What Equation 1 means is that a design evaluation based on the average or expected demand scenario – as captured by *f(E[x])* – does not lead to the same value as an evaluation relying on individual system responses from different demand scenarios, and then taking the average of the responses – as captured by *E[f(x)]*. If one chooses a systems design based on the left hand side – as often done in standard design and evaluation – a better design that can adapt to each scenario and provide better average NPV may be ignored altogether. Also, the right hand side of the scenario requires calculating the NPV over several scenarios, thus being a more realistic assessment that accounts for uncertainty.

For example, suppose a hypothetical LNG production facility at 1.0 ton per day (tpd) based on the expected or average demand forecast (referred as "Medium" demand) has $f_M(x) = NPV_M(1.0) = \$1.0$ million, where NPV stands for Net Present Value, or the sum of discounted cash flows (DCF). Suppose also using the same economic model a low demand forecast at 0.5 tpd leads to $f_L(x) = NPV_L(0.5) = \$0.5$ million with equal 1/3 probability. Now consider with equal probability a forecast where demand is higher at 1.5 tpd than installed capacity. The latter would lead to $f_H(x) = NPV_H(1.5) = \$1.0$ million as well, because the maximum production capacity of 1.0 tpd is already reached. Considering that $E[x] = 1/3(0.5 + 1.0 + 1.5) = 1.0$ tpd, $f(E[x]) = NPV(1.0) = NPV_M(1.0) = \$1.0$ million based on the average forecast, but in reality the average

NPV outcome should be $E[f(x)] = 1/3(NPV_L) + 1/3(NPV_M) + 1/3(NPV_H) = 1/3(0.5 + 1.0 + 1.0) =$ \$0.83 million. This is lower than the anticipated \$1.0 million by 17%. Therefore, a design decision based on standard analysis may lead to incorrect production capacity and project selection, given that the real expected return of a system cannot be measured via standard evaluation methods (i.e. like NPV based on DCF analysis). A different approach is needed to capture the full value of oil and gas systems, and different approach to systems design recognizing both uncertainty and flexibility is needed.

Because the economic response from complex systems is highly nonlinear, long-term decisions should not be made considering only the average or most likely scenario. The NPV of projects based on optimization for the most likely demand scenario is not the same as the expected NPV resulted based upon different demand scenarios, as captured by equation (1). A system may appear more or less valuable than it is, as compared to other mutually exclusive design alternatives.

Flexibility enables a system to capture the potential value associated with different scenarios. I might enable, for instance, capturing more demand in the high demand cases, thus increasing the expected economic value (i.e. like a call option). It might reduce the financial losses in a downside demand scenario (i.e. like insurance). Figure 1 conceptually illustrates the effect of embedding flexibility into an engineering system: it shifts the cumulative density function of the system design to the right. This leads to improvements in expected NPV, the value at risk, and the value at gain simultaneously.

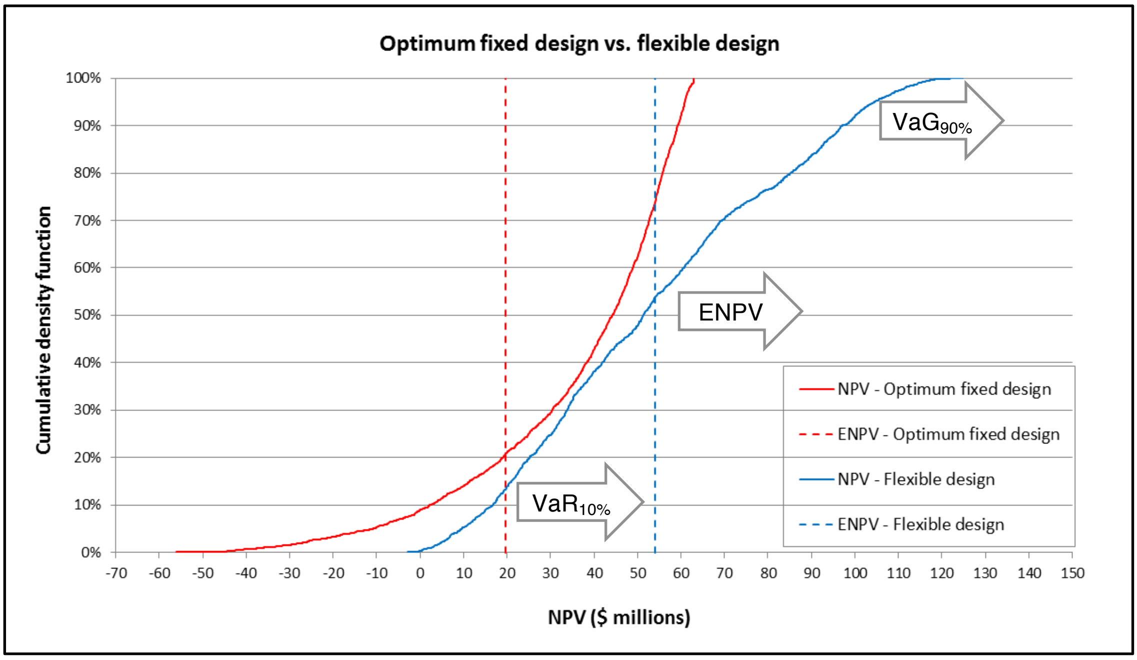

Figure 1: Optimum fixed design versus flexible design

Because of these combined effects, many studies indicate that flexibility can improve expected lifecycle performance between 10% and 30% as compared to standard design and evaluation approaches [Cardin, 2014, de Neufville and Scholtes, 2011]. This study provides guidance into applying this thinking for LNG projects, an example of distributed engineering systems, with the prospect of being applicable to a wider range of systems, and delivering better value to clients and owners.

Simulation based analysis to evaluate flexibility in engineering design

Monte Carlo simulation is used to simulate the behavior of systems in different contexts and applications. This method is now widely accepted for evaluation of flexibility in engineering design [Cardin, 2014, de Neufville and Scholtes, 2011]. The rationale for using this method emerges from the fact that using theoretical methods from finance have serious shortcomings, especially for solving complex real-world problems. On the other hand, Monte Carlo simulation provides a platform so that even a complex system can be modeled easily. Theoretical evaluation methods relying on standard real options analysis (e.g. binomial lattice) used for complex projects over simplify the original problem so that it can be solved. These simplifications can lead to inaccurate results. By using Monte Carlo simulation, one has the freedom to incorporate precisely the detailed attributes of the real-world problem using design variables, parameters and decision rules. Cardin [2014] provides a more detailed discussion of the pros and cons of other approaches to value flexibility in an engineering setting.

LNG production system design

LNG production system design has become more critical due to the growth of natural gas supply and demand and the great risks in this industry. The design of the LNG production system seeks a solution that offers better expected economic value over system lifetime, and an efficient LNG supply chain, from LNG upstream to the end user. The LNG supply chain can be defined as all processes from extraction of the natural gas until used by end users, which consists of exploration, extraction, liquefaction, transportation, storage and regasification. There are different types of LNG supply chain as there are different types of upstream resources (e.g. gas well at onshore or offshore sites), liquefaction process types (e.g. onshore or offshore liquefaction plants), and end users (e.g. power plant, home use and transportation sector).

Literature has shown a growing research towards designing value LNG production systems focusing on different segments of the LNG supply chain, depending on the problem under consideration and geographical situation. Özelkan et al. [2008] studied the coupled segments of large scale shipping and receiving terminal of an LNG supply chain to minimize cost and storage inventory, while maximizing the output of natural gas to be sold to the market. Grønhaug and Christiansen [2009] presented both an arc-flow and a path-flow model for tactical planning to optimize the LNG inventory routing problem. Andersson et al. [2010] worked on transportation planning and inventory management of a LNG supply chain used in tactical planning during negotiations about deliveries to different regasification terminals and annual delivery plan used in operational level decision making.

As the overview suggests, more work is needed to evaluate LNG production systems in the early stages of design. In particular, more efforts are needed considering strategic level decisions involving flexibility and uncertainty in the analysis of site production capacity and deployment over time. In addition, to these authors' knowledge there has been no other study considering the combined effects of economies of scale, time value of money, and learning in this context. The main contribution of the paper is thus to investigate these effects on key strategic factors affecting the design of LNG production systems, a downstream portion of LNG supply chain, from onshore natural gas transmission pipeline to end users at candidate geographical demand sites. The goal is to identify designs that provide better expected economic value over the entire lifetime of a project, as compared from the typical outputs from standard design and project evaluation.

3 Scope and problem definition

This study focuses on the design and development of the LNG production system to provide fuel for trucks used in on-road product transportation in southeast Australia. The scope of the problem lies in the LNG supply chain where natural gas from on-shore pipeline is converted into LNG through liquefaction, and then delivered to the transportation sector for the end users. The goal is to meet the LNG demand at different geographical sites, knowing that these sites have direct access to an existing natural gas pipeline. Figure 2 schematically represents the LNG production system, from a fixed towards a more flexible design. This example has five candidate demand points equipped with filling station facilities and a main production site dedicated to a centralized LNG plant. All sites have access to the on-shore pipeline distributing the natural gas. In the main production site, LNG produced through the liquefaction process is transferred to the candidate demand sites. In this study, two main LNG system designs are investigated, 1) fixed centralized design, Figure 2(a); and 2) flexible modular designs, Figure 2(b and c). In the fixed centralized design, the optimal capacity significantly depends on the strength of the economies of scale. A big LNG plant is built in the main production site and LNG produced is carried to the market sites using fuel trucks. The flexible modular designs includes: 1) flexible modular design – no move, see Figure 2(b), which considers a phasing approach using a modular LNG plant with the flexibility to expand capacity at all at the main production sites, and transport LNG to demand sites; 2) flexible modular design with move, see Figure 2(c), which is the same design as the flexible modular design but with the ability to move the modular LNG plants to other demand sites.

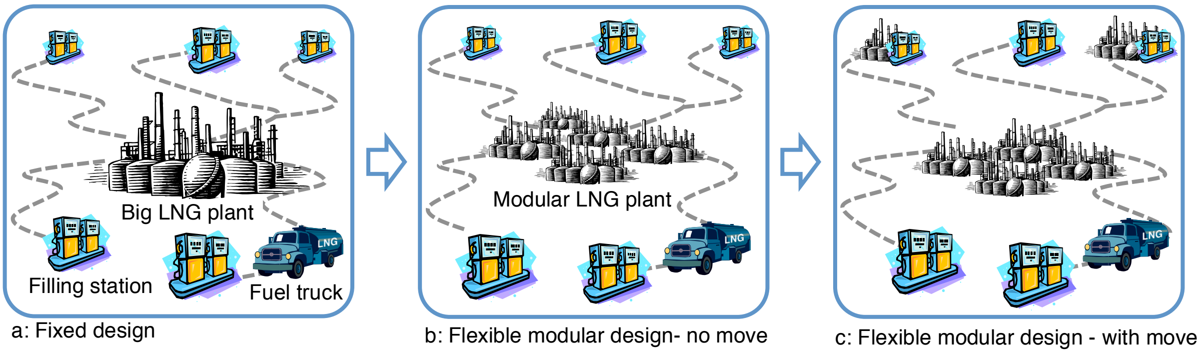

Figure 2: Shift from a fixed LNG system design towards a more flexible LNG system design

4 Methodology

This paper proposes a practical approach to quantify flexibility under uncertainty. This approach improves the lifecycle performance of a project dependent on a range of potential uncertainties. To compare the design alternatives under uncertainty, the paper provides and applies a structured four-step methodology based on several economic lifecycle performance indicators (e.g. Net Present Value, Initial CAPEX, etc.) in order to illustrate the "Value of Flexibility". The steps below describe the generic process followed to analyze the system for flexibility, under market uncertainty related to LNG demand growth. Figure 3 illustrates the process.

Step 1: Deterministic DCF Model

The proposed methodology starts with the deterministic analysis. The aim is to understand the key components of the system that influence its lifecycle performance. The performance metric used in this problem is NPV, calculated as the sum of discounted cash flows throughout the project lifecycle T = 20 years – see Equation 2. Variables TR_t and TC_t are the total revenues and costs incurred in years t = 1, 2, ... T, and r is the discount rate.

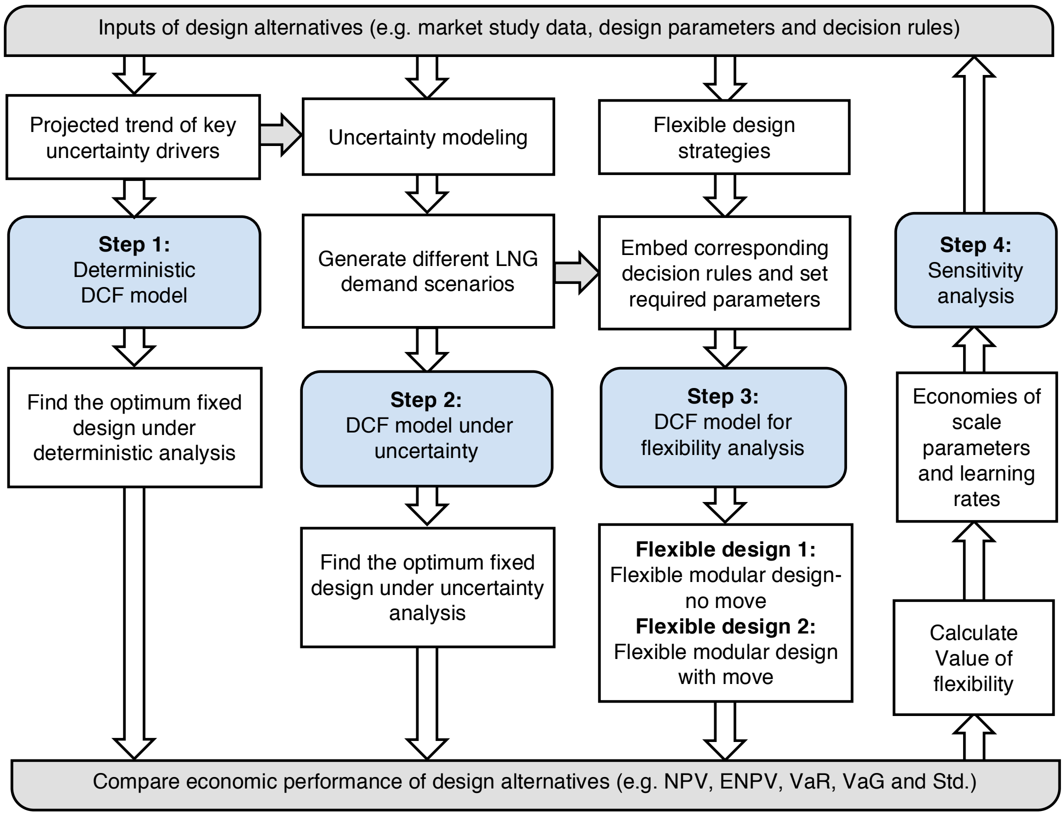

Figure 3: A methodology to evaluate and compare candidate flexible LNG system designs

$$NPV = \sum_{t=1}^{T} \frac{TR_t - TC_t}{(1+r)^t} \tag{2}$$

LNG demand is a key driver of system performance. A deterministic S-curve function is assumed to simulate LNG demand over the study period, as shown in equation (3). The rationale is that LNG demand initially grows slowly; it then increases exponentially, and finally tapers as it approaches a saturation limit. Variable M_T is the maximum expected demand for LNG, b is the sharpness parameter that determines how fast demand grows over time to reach the upper bound for demand. The parameter a translates the curve horizontally.

$$D_t = \frac{M_T}{1 + ae^{-bt}} \tag{3}$$

where a is calculated using Equation 4.

$$a = \frac{M_T}{D_0} - 1 \tag{4}$$

In general, the conventional DCF model is built to assess the performance of the system under deterministic conditions. This step captures standard industry practice in terms of design and project evaluation [Cardin et al., 2013b].

Step 2: Uncertainty Analysis

The analysis under uncertainty considers a distribution of outcomes instead of a single performance output. Hence, in this step NPV_S, which refers to NPV under demand scenario *s*, is calculated in terms of different realized demand scenarios. A stochastic S-curve function simulated LNG demand over the system's lifecycle using additional uncertainty factors, as shown in Equation 5.

$$R_t = \frac{M_T \pm \Delta_{M_T}}{1 + a_u e^{-(b \pm \Delta_b)t}} \tag{5}$$

where

$$a_u = \frac{M_T \pm \Delta_{MT}}{D_0 \pm \Delta_{D_0}} - 1 \tag{6}$$

In equation 5, Δ_{M_T} shows the demand limit volatility where the realized demand in year 0 can differ from its projected one, Δ_b determines sharpness parameter volatility, meaning that the value of sharpness parameter b may differ from its forecasted value, a_u is the stochastic translation factor that varies because of volatilities in initial demand and demand limit (i.e. $\Delta_{M_T}$and Δ_{D_0}). Realized demand at time t + 1 equals realized demand at time t plus annual volatility multiplied by growth rate at time t, as Equation 7 shows.

$$R_{t+1} = R_t + (\Delta_{av} \times G_t) \tag{7}$$

where G_t is the annual growth rate assuming that it follows standard normal distribution and Δ_{av} is assumed as a fixed parameter throughout the project lifetime calibrated using historical data. Monte Carlo simulation is used to simulate a wide range of LNG demand scenarios. This analysis recognizing uncertainty provides designers a more realistic overview of system performance as compared to the deterministic analysis in Step 1.

Step 3: Flexibility Analysis

To account for system flexibility, decision rules are embedded into the DCF model under uncertainty. For example, to embed the capacity expansion policy in flexible modular designs, a simple decision rule is programmed in the Excel® spreadsheet DCF model under uncertainty. For instance a capacity expansion policy can be: IF "*observed aggregate demand in the current year is higher than a certain threshold value at the main production site*" THEN "*build extra modular plant as capacity expansion policy"* ELSE *"do nothing*". The threshold value determines when extra capacity should be built, either at the main production site or other demand sites. For example, decision-makers may decide to add another modular plant as soon as the difference between the realized and current capacity (i.e. unmet demand) reaches 60% of the capacity of a modular plant for the site. The value of flexibility is calculated as shown in Equation 8.

$$\text{Flexibility Value} = \max\left(0, \text{ENPV}_{\text{Flexible design}} - \text{ENPV}_{\text{Optimum fixed design}}\right) \tag{8}$$

Multi-criteria decision making table

In evaluating flexible designs, the analyst needs to factor in a distribution of outcomes instead of one single point to support design decision-making. These distributions can be interpreted using the shape of different criteria. For instance, one may seek to maximize ENPV or to minimize downside risk or to choose some balance between these criteria. Given the several possible criteria that are not directly compatible, it is useful to create a multi-criteria table, providing decision makers with the information needed to trade-off criteria among flexible design alternatives. In the field of decision-making under uncertainty, the expected value is widely used as an objective function, for instance using expected NPV.

$$\mathrm{ENPV} = \frac{1}{N} \times \sum_{s=1}^{N} NPV_s \tag{9}$$

This value, however, is based on risk neutral preference, which may not match with different risk preferences in reality. In practice indeed, downside risk is an important factor that decision makers often need to take into account. For instance, typical decision makers prefer lower risks given the same value of expected value. So other criteria for selection of projects include the Value at Risk (VAR) for a given level of probability and, equally, the potential for upside gain, the Value of Gain (VAD).

Step 4: Sensitivity Analysis

A sensitivity analysis is performed to observe how the system responds to different parameter and input data. This study investigated the effects of varying discount rate, economies of scale, and learning on the results. These parameters capture key tradeoffs in engineering design and economic analysis.

Time value of money

The discount rate is a key factor in the valuation process. It captures the time value of money and provides incentives to delay initial capital expenditures to later in the future, especially when the opportunity cost of capital is high. A high discount rate favors a more modular approach to design, where capacity is deployed over time. Sensitivity analysis is conducted in terms of different discount rates to observe its effect on the performance metric, more specifically the value of flexibility.

Economies of scale

Economies of scale mean that the average cost per unit of production capacity decreases as one builds larger plants. Economies of scale are crucial factors because they drive designers to create the largest economically reasonable facilities, thereby counteracting a modular approach to capacity deployment [de Neufville and Scholtes, 2011]. This phenomenon is typically represented by the so-called cost function in Equation 10. The parameter α is the economies of scale factor: the lower α is, the greater the economies of scale. Here it is assumed that the Operating Costs (Opex) of an LNG plant is proportional to its Capex as in Equation 11.

$$\text{Capex of a fixed LNG plant} = \text{capacity}^{\alpha} \tag{10}$$

$$\text{Opex of a fixed LNG plant} = \text{k} \times \text{Capex} \tag{11}$$

The case study analyzed designs with different capacities for the fixed LNG plant ranging from 25 to 300 tpd, with 25 tpd capacity increments. The sensitivity analysis investigated different economies of scale parameters to see their influence on optimum capacity for fixed LNG designs, and thus on the value of flexibility.

Learning rate

The case study considered modular designs for LNG plants in the proven size of 25 tpd. Because of the learning phenomenon, the unit cost of these modules can decrease as more are installed. The more one builds, the more efficient one becomes. The learning curve in Equation 12 represents this situation [de Neufville and Scholtes, 2011]:

$$\mathrm{U_i} = U_1 \times i^B \qquad (12)$$

where U_i is the Capex of the ith modular LNG plant, U_1 the Capex of the first modular LNG plant, and B is the slope of the learning curve. The slope is calculated with different empirical values for L, from 0%, 10% and 20%, using Equation 13.

$$\mathrm{B} \; = \; \log\left(100 \text{ percent} - \text{ L percent}\right) / \log\left(2\right) \qquad (13)$$

Thus if the cost of the first modular LNG plant is \$25 million, the cost of the 5th module (given a 10% learning rate) is: B = log (100 percent – 10 percent) / log (2) = –0.1520 so that U5 = \$25M (5)–0.1520= \$19.57M. The learning phenomenon provides great incentives to install capacity consisting of many smaller units instead of a few large units. Together with high discount rates, learning counteracts the effects of economies of scale.

5 Application and Discussion

Modeling Assumptions

The following assumptions are made for model development. Demand is assumed to be evenly distributed in the region over five distinct demand sites. There is no market at the main production site. All sites have access to on-shore natural gas pipeline in the region. Time to build is 2 years for the big plant, but only 1 year for small plants. Also, if one decides to expand capacity in year t, extra capacity will be available for production in year t+1. Regarding financial parameters, the project lifetime is assumed to be 20 years. A 10-year straight-line depreciation method is used for all LNG production facilities with zero salvage value. The discount rate is assumed to be 10% and the corporate tax rate is 15%. Parameters associated with deterministic and stochastic LNG demand modeling are summarized in Table I.

With regards to design parameters, the fixed design analysis examined economies of scale: α=1, 0.95, 0.9 and 0.85. The modular design analysis investigated different learning rates: LR = 0, 10 and 20%. The capacity of modular LNG plant was set to 25 tpd with initial Capex \$25 million. The Opex of the plant is assumed 5% of the plant's Capex. Flexibility cost is 10% of the CAPEX of the first capacity deployment at each site because of gas tie-in to the existing natural gas pipeline and extra land cost. Transportation cost is set to \$0.4 per ton-kilometer, while travel distance from the main production site to each site are 118, 121, 281, 318, and 446 Km.

Table I: parameters used in uncertainty modeling for each demand site

Parameter	Deterministic demand	Parameter	Stochastic demand
D_0	5 tpd	Δ_{D_0}	50%
M_T	50 tpd	Δ_{M_T}	50%
a	9	G_t	~ Normal(0,1)
b	0.35	Δ_b	70%
T	20 years	Δ_{av}	5%

Four step analysis

The four-step analysis described above is applied to the analysis of the example LNG system. First, the deterministic DCF model is presented and second by taking uncertainty into account the DCF model under uncertainty is evaluated. Third, by incorporating decision rules into the DCF model under uncertainty the flexible DCF model is analyzed. Finally sensitivity analysis is presented and main findings are discussed.

Step 1: Deterministic analysis

Figure 4 shows the results of the fixed design analysis assuming a deterministic LNG demand forecast. It shows the NPV for different sizes of plants that have various economies of scale factors. It shows, as might be anticipated intuitively, that: a) for any set of plant size and economies of scale, there is a "sweet spot": build too small, and there is no profit from higher demands; build too large, and there is risk of overcapacity and attendant losses (stars on the curves indicate the best design for each set of parameters), and b) the greater the economies of scale, the larger the fixed design should be.

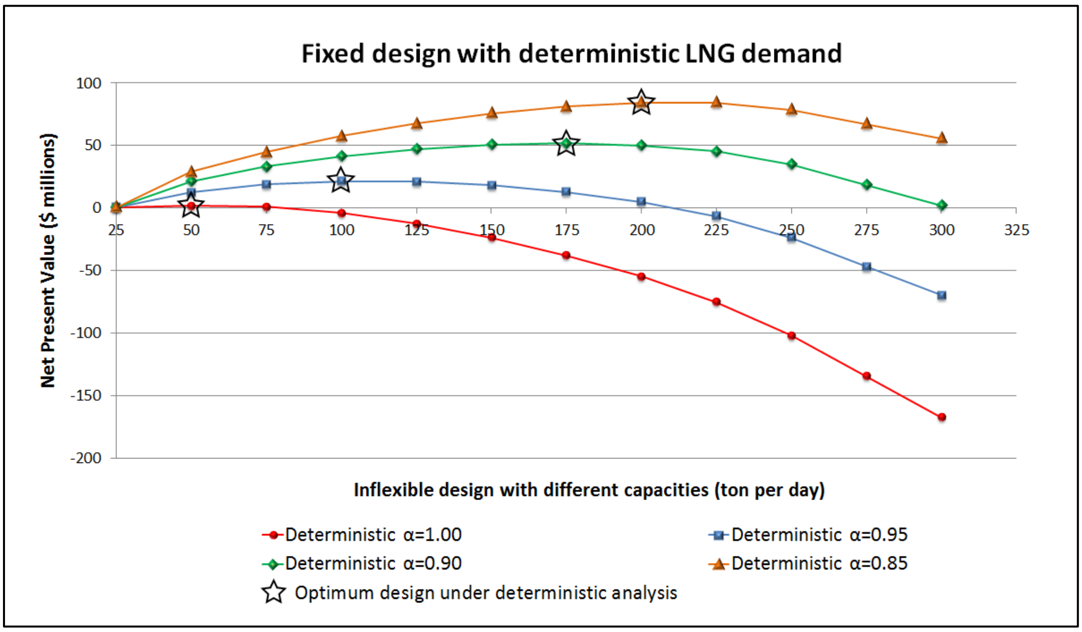

Figure 4: NPV of fixed designs under deterministic LNG demand. A star shows the optimum design for a given economies of scale factor

The advantages of these economies compensate for the overcapacity of the greater size over initial demand, and counterbalance the economic advantages of deferring costs (due to the discount rate). Note however, that deterministic analysis based on expected LNG demand gives wrong results, compared to realistic analysis that recognizes uncertainty, as shown next.

Step 2: Uncertainty analysis

The deterministic analysis gives a false impression of lower value due to the Flaw of Averages [Savage, 2009]. Engineering systems typically respond non-linearly to inputs, and any decision based on average value of these factors is almost certain to provide a false reading on the actual average value of an alternative. To get the right answer, one needs to analyze the system under uncertainty.

The case study recognized LNG demand as a key source of uncertainty. Using Monte Carlo simulation it explored how design alternatives behave under different LNG demand scenarios. These simulations used different LNG plant capacities and economies of scale parameters. The aim was to find the stochastically optimum design for plant capacity. The results show when using 2000 demand scenarios the system performance converged to a steady state value with a negligible variation. Figure 5 compares the projected LNG demand (i.e. doted line) with 25 representative LNG demand scenarios (i.e. grey lines).

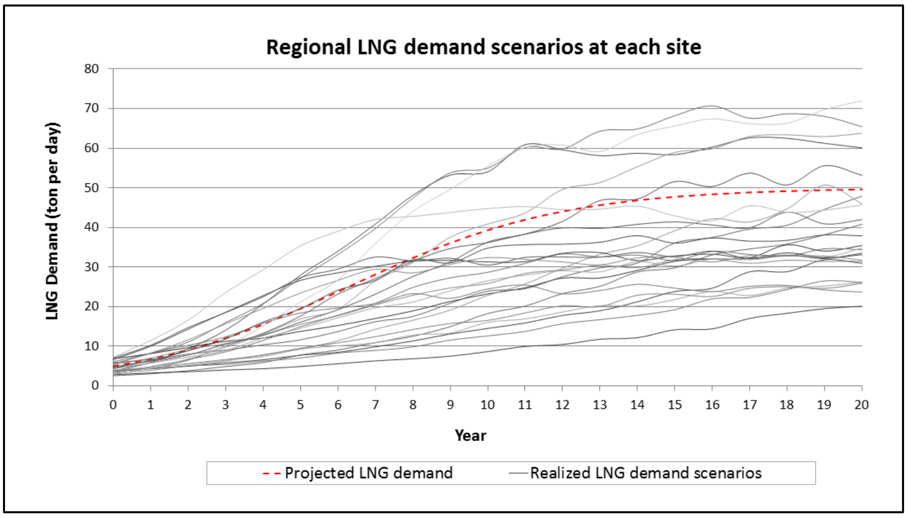

Figure 5: projected and realized regional LNG demand at each geographical site

Table II compares the results of the deterministic and uncertainty analyses. The result is that optimum capacities and values generated by the uncertainty analysis are systematically different (in this case, smaller) than those obtained from the deterministic analysis.

Table II: optimum fixed designs under deterministic and uncertain LNG demand with different α

Economies of scale parameter, α	Optimum capacity (ton per day)		Optimum value ($ millions)	
	Deterministic	Uncertainty	Deterministic(NPV)	Uncertainty(ENPV)
1	C_d=50	C_u=25	V_d=1.75	V_u=0.87
0.95	C_d=100	C_u=75	V_d=21.51	V_u=14.27
0.90	C_d=175	C_u=125	V_d=51.75	V_u=37.18
0.85	C_d=200	C_u=175	V_d=84.56	V_u=61.18

The intuition is that an asymmetric response of the system occurs because of variations in demand: lower demands lead to losses, which higher demands can only partially compensate, because of limitations in installed capacity. This reality favors smaller capacity designs that cost less and minimizes unused capacity when uncertainty is considered, as compared to a deterministic analysis.

Step 3: Flexibility Analysis

Using concept generation techniques inspired from Cardin et al. [2013a], flexibility to expand capacity is recognized as a strategy to deal with uncertain demand growth. The idea is to build less capacity at the start – to avoid over commitment and over capacity, and to add capacity based upon demonstrated demand. Key to this strategy, of course, is that the original design should be designed to facilitate capacity expansion easily. The analysis considered two kinds of capacity expansion. First, it looked at the benefits of building up capacity incrementally at the main site. Second, it considered the further advantage of moving additional modules in the field, close to the demand sites, as way of lowering transportation costs, and further exploiting the benefits from a modular approach to design and management.

5.1.1 Flexible modular design – no move

Instead of building a fixed plant of optimal size as previously considered, this flexible strategy starts with a small initial module and expands as desired. The question when it would be good to expand is answered by a decision rule. As an example, the case study embedded the following decision rule in the simulation spreadsheet mode: IF "*the difference between the observed aggregate demand and current capacity at this site is higher than a threshold value*" THEN "*the capacity using the modular design capacity is expanded*" ELSE "*do nothing*". Using an exhaustive enumeration technique, the threshold value 80% offered a better system performance among other threshold values. Figure 6 illustrates the results.

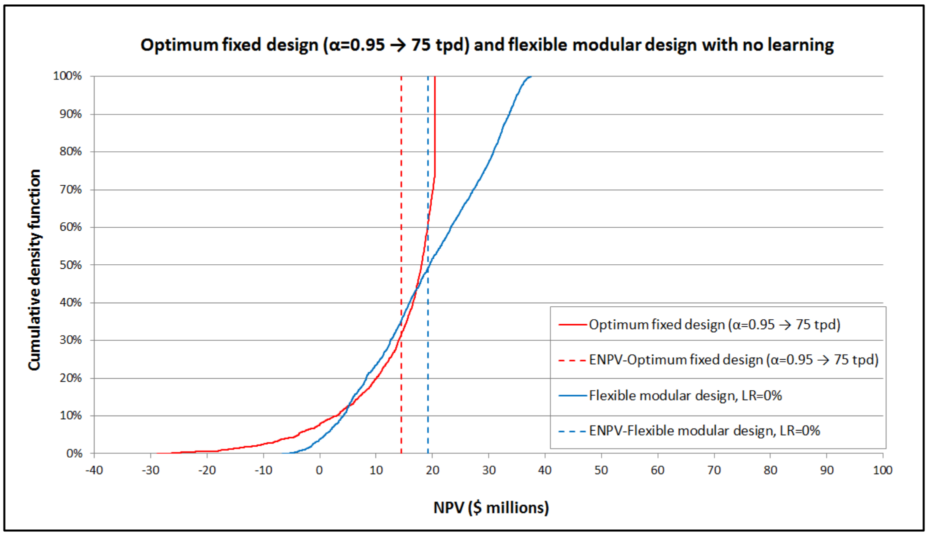

Figure 6: optimum fixed design (α=0.95 →75 tpd) and flexible modular design

The main observations are that flexible modular design has the following advantages:

1) It reduces exposure to downside risks. The intuition is that when one invests less, one has less to lose. In the example, flexibility improved the VaR_{10} (i.e. 10^{th} percentile or P10) by \$4.23M – \$2.96M = \$1.27M
2) It improved the overall expected NPV (ENPV) by \$19.27M – \$14.53M = \$4.47M or nearly 30%
3) It captured more upside potential, increasing VaG_{90} (i.e. 90^{th} percentile of P90) by \$33.63M –\$20.46M = \$13.17M or about 50%;

Hence, this flexible design alternative provides better-expected performance overall.

5.1.2 Flexible modular design - with move

This flexible design strategy allowed the designers to add capacity away from the main site, and to place it in the field nearer the demand sites. The analysis has to implement two additional decision rules to explore this flexibility, to address two important questions: when should the modular plant be built for the first time at distance, and where should it be built?

The decision rule used regarding the capacity expansion was**:** IF "*demand at each demand site reaches a certain threshold value as a parameter of the decision rule*" THEN "*a modular production plant can be built in the demand site*" ELSE "*do nothing*". This threshold value was tuned by conducting another comprehensive enumeration. The results show that the threshold value of 200% offers more economic value as compared to others. The decision rule used regarding the geographical location for capacity expansion was**:** IF "*distance* *between the main production site and each demand site exceeds the maximum preferred coverage range*" THEN "*a modular production facility can be moved into the demand site*" ELSE "*do nothing*". To build extra modular plants at demand sites, a capacity expansion is triggered based on the decision rule embedded at each geographical site: IF "*the difference between the observed demand and the current capacity (i.e. unmet demand) at the demand site reaches certain threshold value*" THEN "*extra modular capacity is deployed*" ELSE "*do nothing*". This decision rule was tuned using the same exhaustive enumeration method, and the threshold value was set to 80%.

Figure 7 shows the additional advantages of the flexibility to locate capacity away from the main site. In this case, the benefits arise when the demand is sufficiently great to justify the distant facility. This flexibility thus improves the upside potential ($VaG_{90\%}$) thus the ENPV compared the case of flexibility only at the main site. Table III shows the improvement of multi-criteria performance metrics because of flexibility as compared to the optimum fixed design for both kinds of flexibility examined here.

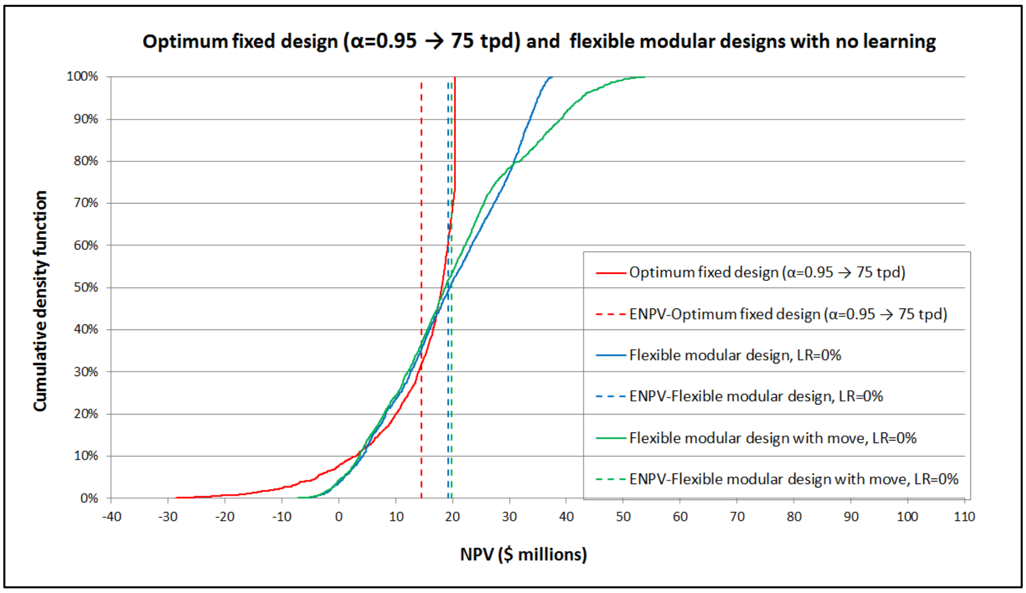

Figure 7: optimum fixed design (α=0.95 →75 tpd) and flexible modular designs

Table III: Improvement of multi-criteria performance metrics due to flexibility with no learning

Criteria	Value ($ millions)			Improvement (%)	
	Optimum fixed design	Modular	Modular with move	Modular	Modular with move
ENPV	14.53	19.27	19.81	32.65%	36.40%
$VaR_{10\%}$	2.96	4.23	3.59	42.92%	21.28%
$VaG_{90\%}$	20.46	33.63	38.88	64.36%	90.04%

5.1.3 Exploring the design space using enumeration method

To find promising flexible strategies, a comprehensive enumeration technique was used to explore the design space. The first column of Table IV describes the elements of a flexible design vector comprised of both design variables describing the system architecture, and decision rules to manage the flexibility strategies describes the design space corresponding to each design component with possible configurations. The second and columns show the values investigated for each vector element and the incremental step size used in the enumeration. Looking at the number of possible values in column four, the total number of possible flexible design configuration is thus 3×2×6×3×5×11= 5,490. Table V summarizes the best flexible design vectors. The best no-move design consisted of initial and modular capacity deployment of 25 tpd, augmented by a decision rule expanding capacity when the difference between the observed aggregate demand and current capacity was higher than 80%.

Table IV: characterization of the design space for flexibility analysis

Design variables and decision rules (dimension)	Value	Increment step size	Possibility
Initial capacity (tpd)	[0, 25 & 50]	25	3
Modular capacity (tpd)	[25 & 50]	25	2
Main production site capacity expansion threshold value (percent of modular design)	[0% to 100%]	20%	6
Coverage distance (km)	[200, 300 & 400]	100	3
Moving threshold value (percent of modular design)	[100% to 300%]	50%	5
Demand site capacity expansion threshold value (percent of modular design)	[0% to 100%]	10%	11

Table V: best flexible design vectors

Flexible modular design	ENPV	Design code
No move	19.27	25 - 25 - 80% - N/A - N/A - N/A
With move	19.81	25 - 25 - 80% - 400 - 200% - 80%

The best with-move design corresponded to a similar architecture, although augmented by a decision rule suggesting expansion to different sites when demand reached 200% of installed capacity at the main site, with geographical location exceeding 400 km, and on-site capacity expansion occurring when demand reached 80% of installed capacity in each site.

5.1.4 Effect of Learning

Learning affects the value of flexibility. Because learning reduces the cost of modules as they get implemented, it favors their use and thus the usefulness and value of flexibility. Figure 8 shows how this occurs. It compares the target curves for the flexible design with move with no learning to those that have various levels of learning. The message is clear: the greater the potential for learning, the better the flexibility through the use of modules.

5.1.5 Multi Attribute Decision-Making

The best design alternative can be chosen based on many criteria. Some common economic metrics in project evaluation under uncertainty are shown in Table VI. The results correspond to the optimum fixed design with the economies of scale 0.95 and the flexible designs (with and without move) in terms of different learning rates. The aim is to choose a design based on the highest value for ENPV (or mean NPV), P10 VaR and P90 VaG, and smaller values for semi-standard deviation of NPV distribution and initial CAPEX.

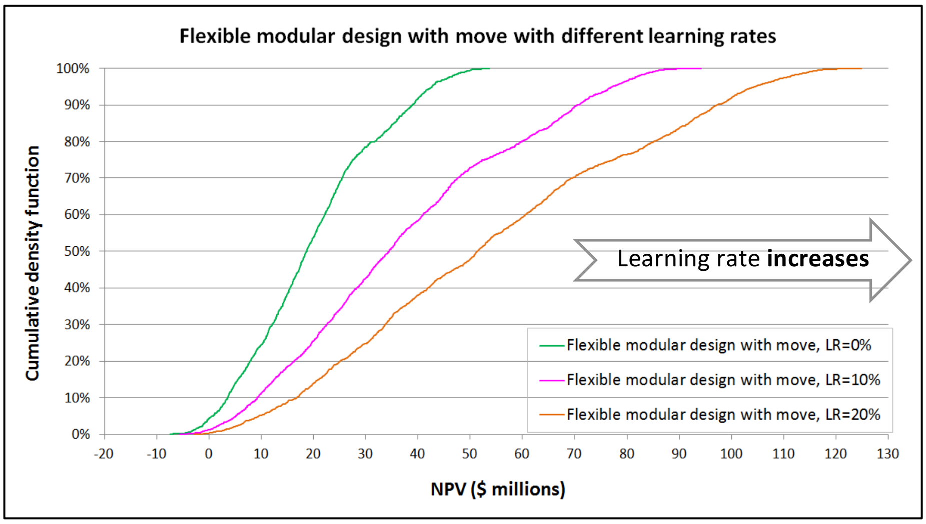

Figure 8: flexible modular design with move in terms of different learning rates

Table VI: Multi-criteria decision making table considering α=1, figures are in million dollars

α=0.95	On-shore LNG production system design							Best design			Value of flexibility		
	Optimum Fixed (75 tpd)	Flex 1: Flexible-no move			Flex 2: Flexible-with move								
		Learning rate			Learning rate			Learning rate			Learning rate		
Criteria		0%	10%	20%	0%	10%	20%	0%	10%	20%	0%	10%	20%
ENPV	14.53	19.27	36.77	49.92	**19.81**	**37.23**	**53.97**	Flex 2	Flex 2	Flex 2	5.29	22.70	39.44
VaR	2.96	**4.23**	**10.26**	15.01	3.59	9.29	**16.79**	Flex 1	Flex 1	Flex 2	1.27	7.29	13.83
VaG	20.46	33.63	62.57	85.30	**38.88**	**70.44**	**97.12**	Flex 2	Flex 2	Flex 2	18.42	49.98	76.66
SSTD	10.85	**2.54**	**1.91**	**1.61**	2.76	2.54	1.63	Flex 1	Flex 1	Flex 1	8.31	8.94	9.24
Capex	60.44	**27.50**	**27.50**	**27.50**	**27.50**	**27.50**	**27.50**	Flexible	Flexible	Flexible	N/A	N/A	N/A

Step 4: Sensitivity Analysis

This section investigates the sensitivity of the flexibility analysis to different economies of scale and learning rates. Table VII and Figure 9 show the results: a) when economies of scale are stronger (α is smaller), the value of flexibility decreases. The reason is that strong economies of scale negate the value of deferring investments in capacity; b) when learning is greater, modules are cheaper, and flexibility is more valuable.

Table VII: Sensitivity of value of flexibility to different α and LR

Value of flexibility	Flexible 1: modular design - no move			Flexible 2: modular design – with move		
	Learning rate			Learning rate		
	0%	10%	20%	0%	10%	20%
α=1	18.40	35.90	49.06	18.94	36.36	53.10
α=0.95	4.74	22.24	35.40	5.29	22.70	39.44
α=0.90	0.00	0.01	13.17	0.00	0.47	17.22
α=0.85	0.00	0.00	0.00	0.00	0.00	0.00

Overall, the value of flexibility depends mostly on four factors: a) uncertainty – the greater the uncertainty, the greater the value of flexibility, b) discount rate – which motivates the deferral of investment so as to minimize the present value of costs, c) economies of scale – which provide the incentive to build single big facilities at once, rather than smaller facilities developed in phases, leading to decreased value of flexibility, and d) learning effects – that counterbalance economies of scale, in that they reduce the cost of implementing second and later addition of modules, and thus lead to improve the value of flexibility.

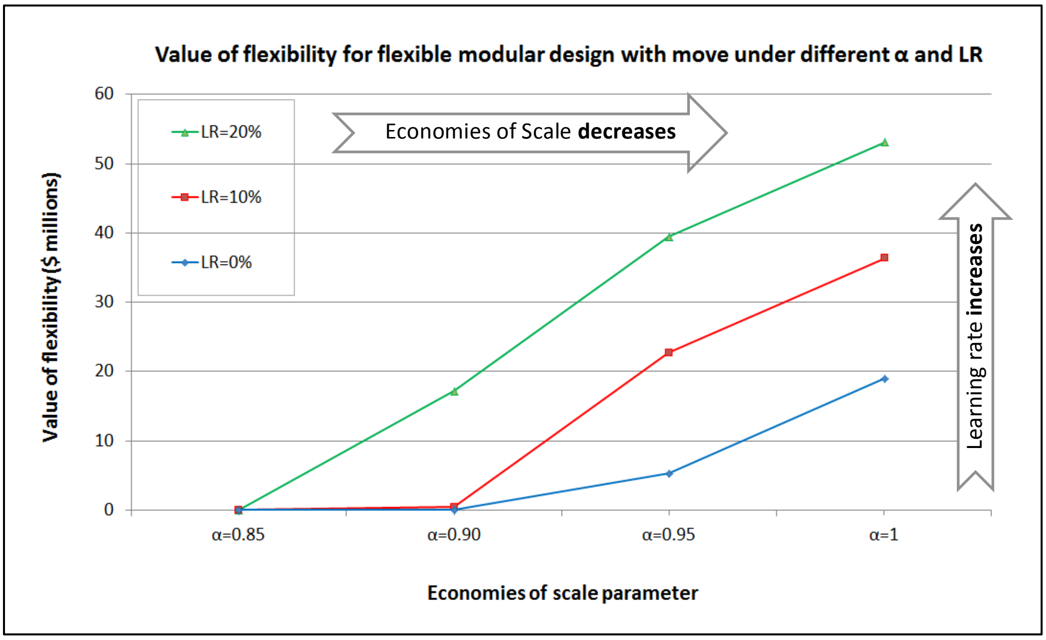

Figure 9: Value of flexibility with different α and learning rates

6 Conclusion

This study illustrates the value of flexibility in the design of production facilities under explicit considerations of uncertainty. It motivates the use of flexibility in engineering design as a paradigm to deal with uncertainty affecting lifecycle performance of engineering systems. In this respect, the study represents an argument for a shift in the design paradigm away from the frequent focus on economies of scale and the development and deployment of unitary large facilities that embody this advantage.

The paper introduced a structured four-step methodology and applied it to demonstrate the economic value of flexibility in the long-term design and deployment of production facilities subject to demand growth uncertainty. It considered the combined effects of economies of scale, learning, and the time value of money to highlight the economic benefits stemming from explicit considerations of uncertainty and flexibility. The case study concerns the prospects for LNG facilities in the Australian transportation sector. The concepts are general, however, and can be applied to other distributed engineering systems sharing similar characteristics.

The results support the view that a flexible modular design can enhance economic performance compared to an optimum fixed design strategy. Furthermore, the flexibility to locate additional capacity beyond the main facility can further enhance the value of the system. Consideration of flexibility, however, adds another layer of complexity to the analytical problem. While an exhaustive search for the optimal design variables and decision rules was feasible, considerations of more uncertainty sources, flexibility strategies (e.g. site abandonment, investment deferral), and decision rules can turn a tractable problem into a highly complex computational one. More work is under way to address these issues by combining meta-modeling and simulation-based optimization budgeting with stochastic programming techniques.

Nomenclature

T = project lifetime/study period, year

a = translation parameter

b = sharpness parameter

D_0 = demand in year 0, ton per day

M_T = limit of forecast demand in year T, ton per day

D_t, R_t = deterministic and realized LNG demand in year t

Δ_{D_0}, Δ_{M_T}= volatility of realized demand in year 0, and of limit of demand at year T, percent

Δ_b = volatility of sharpness parameter, percent

Δ_{av} = annual demand volatility, percent

G_t = annual LNG demand growth rate

α = economies of scale parameter

LR = learning rate, percent

B = slope of learning effect

U_1 , U_i = Capex required for building the first and the i-th plant, \$M

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Appendix

α=1	On-shore LNG production system design												
	Fixed design (25 tpd)	Flex 1: no move			Flex 2: with move			Best design			Value of flexibility		
		Learning rate			Learning rate			Learning rate			Learning rate		
Criteria		0%	10%	20%	0%	10%	20%	0%	10%	20%	0%	10%	20%
ENPV	0.87	19.27	36.77	49.92	**19.81**	**37.23**	**53.97**	Flex 2	Flex 2	Flex 2	18.94	36.36	53.10
VaR	0.89	**4.23**	**10.26**	15.01	3.59	9.29	**16.79**	Flex 1	Flex1	Flex 2	3.35	9.37	15.90
VaG	0.89	33.63	62.57	85.30	**38.88**	**70.44**	**97.12**	Flex 2	Flex 2	Flex 2	37.99	69.55	96.23
SSTD	**0.83**	2.54	1.91	1.61	2.76	2.54	1.63	Fixed	Fixed	Fixed	0.00	0.00	0.00
Capex	**25.00**	27.50	27.50	27.50	27.5	27.5	27.5	Fixed	Fixed	Fixed	N/A	N/A	N/A

α=0.90	On-shore LNG production system design												
	Fixed design (125 tpd)	Flex 1: no move			Flex 2: with move			Best design			Value of flexibility		
		Learning rate			Learning rate			Learning rate			Learning rate		
Criteria		0%	10%	20%	0%	10%	20%	0%	10%	20%	0%	10%	20%
ENPV	36.75	19.27	36.77	49.92	**19.81**	**37.23**	**53.97**	Fixed	Flex 2	Flex 2	0.00	0.47	17.22
VaR	2.34	**4.23**	**10.26**	15.01	3.59	9.29	**16.79**	Flex 1	Flex1	Flex 2	1.89	7.91	14.45
VaG	59.23	**33.63**	62.57	85.30	38.88	**70.44**	**97.12**	Fixed	Flex 2	Flex 2	0.00	11.21	37.89
SSTD	21.53	**2.54**	**1.91**	**1.61**	2.76	2.54	1.63	Flex 1	Flex1	Flex 1	18.99	19.62	19.92
Capex	77.13	**27.50**	**27.50**	**27.50**	**27.5**	**27.5**	**27.5**	Flexible	Flexible	Flexible	N/A	N/A	N/A

α=0.85	On-shore LNG production system design												
	Fixed design (175 tpd)	Flex 1: no move			Flex 2: with move			Best design			Value of flexibility		
		Learning rate			Learning rate			Learning rate			Learning rate		
Criteria		0%	10%	20%	0%	10%	20%	0%	10%	20%	0%	10%	20%
ENPV	**61.67**	19.27	36.77	49.92	19.81	37.23	53.97	Fixed	Fixed	Fixed	0.00	0.00	0.00
VaR	2.43	**4.23**	**10.26**	15.01	3.59	9.29	**16.79**	Flex 1	Flex 1	Flex 2	1.80	7.82	14.36
VaG	**106.62**	33.63	62.57	85.30	38.88	70.44	97.12	Fixed	Fixed	Fixed	0.00	0.00	0.00
SSTD	24.72	**2.54**	**1.91**	**1.61**	2.76	2.54	1.63	Flex 1	Flex 1	Flex 1	22.18	22.80	23.10
Capex	80.65	**27.50**	**27.50**	**27.50**	**27.5**	**27.5**	**27.5**	Flexible	Flexible	Flexible	N/A	N/A	N/A