Design and Management of Flexible On-Shore LNG Production Engineering Systems

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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 a target 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. Such improvement enhances as learning rate increases. Overall, the study shows that flexibility in engineering design has multiple, supporting advantages due to uncertainty, location and learning.

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 [1]. More specifically, gas product demand and supply forecasts in a target market indicate a potential shortfall of 300 to 600 TJ/day by 2015, and between zero and 600 TJ/day by 2020 [2]. 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.

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 uncertainty in LNG demand, gas price, and facility availability. The design stage of such projects is significantly large as critical decisions need to be made, and as changing the system configuration 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 [3,4]. The study contrasts and compares to others as it considers explicitly the combined effects of uncertainty, the time value of money, economies of scale (EoS), 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. Section 2 discusses the motivations to apply the practical flexibility procedure, which considers explicitly uncertainty and flexibility, to designing and evaluating LNG production systems. It also reviews relevant literature. Section 3 identifies the research gap, and defines the scope of the problem under consideration. Section 4 describes the methodology in generic terms. Section 5 presents a case study on a LNG production system that demonstrates the implementation of the analytical approach. Section 6 summarizes major findings, providing conclusions and insights for further research.

2 Background and motivation

2.1 Flexibility in engineering design

Flexibility in engineering design is an interdisciplinary field for research and practice [3,4]. 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 [5]. 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 [5]. Flexibility "in" systems refers to technical engineering and design components enabling real options – another word for flexibility – in deployment and operations [6]. Cardin [4] provides a taxonomy and design framework to organize design and evaluation activities to enable flexibility in engineering systems.

Flexibility enables a system to capture the potential value associated with different scenarios. It enables, for instance, capturing more demand in high demand cases, thus increasing the expected economic value (i.e. like a call option). It might reduce financial losses in a downside demand scenario (i.e. like insurance).

2.2 Simulation based flexibility analysis

Monte Carlo simulation combined with an approach base on managerial decision rules is used to simulate the behavior of systems in different applications. A decision rule is a triggering mechanism based on a criterion – typically related to an observed state of uncertainty – determining the appropriate moment to exercise the flexibility in operations. This method is now widely accepted for evaluation of flexibility in engineering design [3,4]. 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 and decision rules, one has the freedom to incorporate precisely the detailed attributes of the real-world problem by parameterizing the physical design variables, analytical parameters and decision rules. Fitzgerald et al. [7] presented an extended version of a simulation based analysis called Epoch Era Analysis (EEA) [8,9] to investigate the value of changeability in complex engineering systems at early stage of the design process. They used transition rule matrix in EEA whereas in this study different decision rules and their corresponding parameters were used in the Monte Carlo Simulation framework.

2.3 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. 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. [10] 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, Christiansen [11] presented both an arc-flow and a path-flow model for tactical planning to optimize the LNG inventory routing problem. Andersson et al. [12] 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 to investigate these effects on key strategic factors affecting the design of LNG production systems, from onshore natural gas transmission pipeline to end users at candidate geographical demand sites. The goal is to identify designs and decision rules 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 a target market. 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 1 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.

Two main LNG system designs are investigated: 1) fixed centralized design (a), and 2) flexible modular designs, (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, (b), which considers a phasing approach using a modular LNG plant with the flexibility to expand capacity at the main production site, and transport LNG to demand sites; 2) flexible modular design with move, (c), which is the same design as the flexible modular design, (b),but with the ability to move the modular LNG plants to other demand sites.

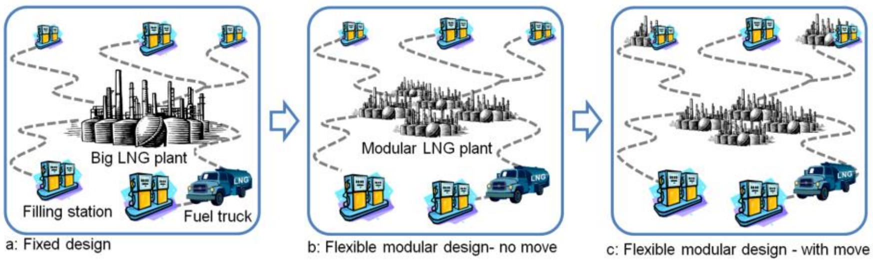

Figure 1: Shift from a fixed LNG system (a) design towards more flexible systems (b, c)

4 Methodology

This paper uses a practical four-step process to quantify flexibility under uncertainty [3]. This approach improves the lifecycle performance of a project dependent on a range of potential uncertainties. Several economic lifecycle performance indicators are used (e.g. Net Present Value, Initial CAPEX, etc.) to quantify the "Value of Flexibility". The steps below describe the generic process followed as it relates to LNG demand growth.

4.1 Step 1: Deterministic Analysis

The proposed methodology starts with a 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 (1). 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.

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

LNG demand is a key driver of system performance. A deterministic S-curve functionis assumed to simulate LNG demand at time t (D_t) over the study period, as shown in Equation (2). 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.

$$D_t = \frac{M_T}{1 + ae^{-bt}} \tag{2}$$

where a is calculated using Equation (3).

$$a = \frac{M_T}{D_0} - 1 \tag{3}$$

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 [13].

4.2 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 (4).

$$R_t = \frac{M_T \pm \Delta_{M_T}}{1 + a_u e^{-(b \pm \Delta_b)t}} \quad (4)$$

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.

4.3 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 (5).

$$\text{Flexibility Value} = \max(0, \text{ENPV}_{\text{Flexible design}} - \text{ENPV}_{\text{Optimum fixed design}}) \quad (5)$$

1.1.1 Multi-criteria decision making table

To evaluate 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 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.

4.4 Step 4: Sensitivity Analysis

A sensitivity analysis is performed to observe how the system responds to different parameters 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.

5 Application and Discussion

5.1 Modeling Assumptions

The following assumptions are made. 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 target 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. The project lifetime is 20 years. Ten-year straight-line depreciation is used for all LNG production facilities with zero salvage value. The discount rate is 10%, and the corporate tax rate is 15%. Parameters associated with deterministic and stochastic LNG demand modeling are summarized in Table 1.

Regarding design parameters, the capacity of modular LNG plant is set to 25 tpd with initial capital expenditure (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 distances from the main production site to sites 1 to 5 are 118, 121, 281, 318, and 446 Km respectively.

Table 1: parameters used in uncertainty modeling for each demand site

Parameter	Deterministic demand	Parameter	Stochastic demand
D_0	5 tpd	Δp_0	50%
M_T	50 tpd	Δp_T	50%
a	9	Gt	~ Normal(0,1)
b	0.35	Δ_b	70%
T	20 years	Δ_{av}	5%

5.2 Step 1: Deterministic analysis

Results show 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, and b) the greater the economies of scale, the larger the fixed design should be. 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 may give incorrect results, compared to realistic analysis that recognizes uncertainty, as shown next.

5.3 Step 2: Uncertainty analysis

The deterministic analysis gives a misleading impression of lower value due to the Flaw of Averages [14]. 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 recognizes LNG demand as a key source of uncertainty. Using Monte Carlo simulation, it explores how design alternatives behave under different LNG demand scenarios. Simulations use different LNG plant capacities and economies of scale parameters. The aim is to find the stochastic optimum design for plant capacity. The results show that when using 2,000 demand scenarios, the system performance converges to a steady state value with negligible variations.

Table 2 compares the results of the deterministic and uncertainty analyses. It shows that optimum capacities and values generated by the uncertainty analysis are systematically different (in this case, smaller) than those obtained from the deterministic analysis.

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, which typically favors more capacity to be deployed upfront.

Table 2: optimum fixed designs under deterministic and uncertain LNG demand with different Economies of Scale parameters 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

5.4 Step 3: Flexibility Analysis

Using concept generation techniques inspired from Cardin et al. [15], 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 enable capacity expansion easily. The analysis considers two kinds of capacity expansion. First, it looks at the benefits of building up capacity incrementally at the main site. Second, it considers 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.

1.1.2 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 the decision rule. The following decision rule was embedded in the simulation spreadsheet: 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, it is found that the threshold value 80% offers a better system performance among other threshold values.

1.1.3 Flexible modular design – with move

This flexible design strategy allows 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 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 at 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*". Using exhaustive enumeration, the decision rule is tuned and the best threshold value is set to 80%.

Table 3 shows the improvement in multi-criteria performance metrics because of flexibility, as compared to the optimum fixed design for both kinds of flexibility examined here.

Table 3: 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%

1.1.4 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 4. 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.

Table 4: Multi-criteria decision making table considering α=0.95, figures are in million dollars

α=0.95	Optimum	Flex 1: Flexible-no move			Flex 2: Flexible-with move			Best design			Value of flexibility		
	On-shore LNG production system design												
	Fixed	Learning rate			Learning rate			Learning rate			Learning rate		
Criteria	(75 tpd)	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	Flex	Flex	Flex	N/A	N/A	N/A

5.5 Step 4: Sensitivity Analysis

This section investigates the sensitivity of the flexibility analysis to different economies of scale and learning rates. Table 5 shows 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.

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.

Table 5: Sensitivity of value of flexibility to different α and LR

Economies of scale (α)	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

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. The study represents an argument for a shift in the design paradigm away from the frequent focus on economies of scale focusing on the development and deployment of unitary large facilities that embody this advantage.

The paper relies on a structured four-step methodology inspired from existing literature [3]. It demonstrates the economic value of flexibility in the long-term design and deployment of production facilities subject to demand growth uncertainty. It considers 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 a target transportation market. 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 is feasible here, considerations of more uncertainty sources, flexibility strategies (e.g. site abandonment, investment deferral), and more sophisticated 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.

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