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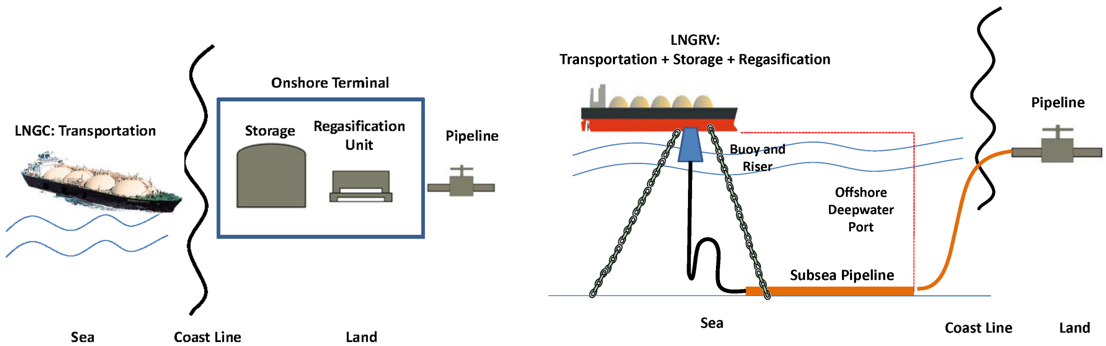
Abstract

Energy plays a fundamental role in both manufacturing and services, and natural gas is quickly becoming a key energy source worldwide. Facilitating this emergence is the expanding network of ocean-going vessels that enable the matching of natural gas supply and demand on a global scale by transporting it in the form of liquefied natural gas (LNG) for eventual regasification at its destination. Until very recently only one type of technology has been available for transporting and regasifying LNG: Conventional LNG vessels and land based LNG regasification. It is now possible to transport *and* regasify LNG onboard special LNG vessels. Companies such as Excelerate Energy and Höegh LNG are currently developing LNG supply chains based on this new technology. Motivated by this recent development we engaged executives at Excelerate Energy to develop and apply to data an integrated analytic framework to compare these incumbent and emerging technologies. Our analysis brings to light basic principles delineating when to deploy each technology and how to configure the emerging technology. Some of our findings challenge conventional wisdom on the role to be played by the emerging technology; others provide answers to open questions faced by companies currently engaged in the commercial deployment of this technology. In addition, our integrated analytic framework has potential relevance for the evaluation of new technologies beyond this specific application.

1. Introduction

Energy is fundamental to any manufacturing and service activity, and natural gas is rapidly acquiring a prominent role as a source of energy worldwide (Geman 2005, Chapter 10). But, due to local imbalances, matching the supply of and the demand for natural gas requires its transportation from locations with excess supply to locations with excess demand. Over short distances, natural gas transportation is done by pipelines; over longer distances, natural gas is transported in the form of liquefied natural gas (LNG) by ocean-going vessels (Tusiani and Shearer 2007). This LNG industry is currently developing on a global scale (EIA 2003, Jensen 2003).

LNG must be regasified before it can be consumed as natural gas. Until very recently, there existed only one type of LNG regasification technology. In this incumbent technology (onshore terminal-based regasification, see Figure 1(a)), LNG is regasified into natural gas at a land based



(a) Incumbent technology: Onshore terminal based regasification.

(b) Emerging technology: Onboard regasification.

Figure 1: LNG regasification technologies.

terminal, which receives it from vessels (LNG carrier-LNGC) that transport LNG produced at liquefaction plants (Tusiani and Shearer 2007, Flower 1998). In contrast, new regasification technology (onboard regasification) has recently been developed that allows special LNG vessels (LNG regasification vessel-LNGRV) to regasify LNG onboard such a ship at an offshore location, see Figure 1(b). In this system, when an LNGRV arrives at an offshore deepwater port, it connects to a submerged unloading buoy. The LNG is then vaporized onboard the LNGRV and delivered to shore through a subsea pipeline[1]. In other words, LNGRV (the new technology) integrates the transportation, storage and regasifation tasks, as opposed to the incumbent process architecture in Figure 1(a), which decomposes these tasks. The primary advantage of the new technology is that it does not require the construction of a costly land based terminal. Its main disadvantage is its reduced task modularity relative to the incumbent technology. Hence, an onboard regasification facility is relatively cheap and fast to build, but features slower unloading of vessels compared to a land based terminal[2].

The new technology is currently being commercially deployed by companies such as Excelerate Energy and Höegh LNG. Companies investing in the development of new LNG supply chains (Jensen 2003) face the challenge of selecting between the incumbent and emerging LNG regasification technologies. This is complex, because these technologies can be deployed using different configurations of the underlying LNG transportation and regasification processes. These process configurations are characterized by different operational and financial performance, which in turn affect the process configuration choice. Capturing these interactions requires detailed modeling of the processing network operations.

[1]A glossary explaining the abbreviations used in this paper can be found in online appendix A.

[2]Online appendix B provides more details on LNG and regasification technologies.

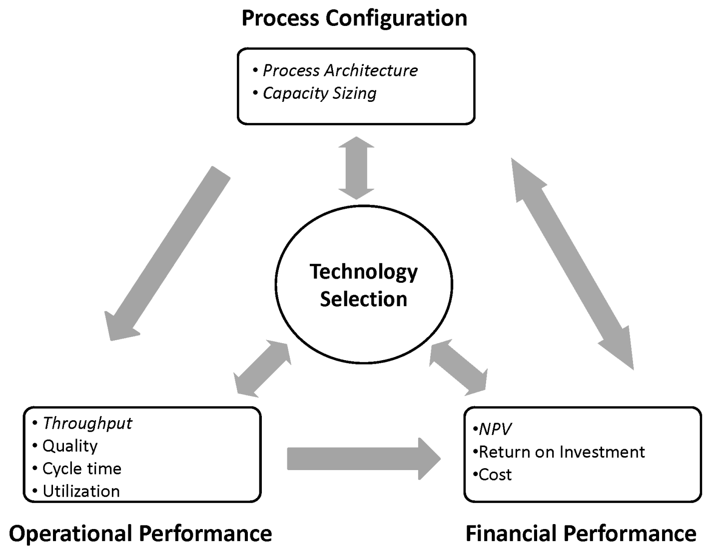


Figure 2: Technology selection dimensions (we use the indicators in italics in our application).

Our objective in this paper is to conduct an analysis of the selection problem between these two technologies. To do so, we engaged executives at Excelerate Energy to develop and apply to data an analytic framework for this technology selection problem. Figure 2 illustrates the main elements of our framework: Process configuration and operational and financial performance. Process configuration includes the choice of a process architecture and the capacity levels of its resources. In particular, the process architecture determines the organization of the tasks within a process: decomposed, sequenced or integrated tasks (von Hippel 1990). For a given architecture, modularity measures task independence. Interdependence between tasks decreases as modularity increases (Baldwin and Clark 2000, Gomes and Joglekar 2008). Operational performance refers to the measurable efficiency indicators of a given process configuration, such as throughput, quality, production cycle time, and utilization. Financial performance measures the financial aspect of a given process configuration using indicators, such as net present value (NPV), return on investment, and cost. In this study, we use throughput and NPV as the indicators of the operational and financial performance since they are the most relevant to our LNG application. The three dimensions of process configuration, operational performance and financial performance are often intertwined. Senior executives faced with technology selection choices are sensitive to these dependencies.

The methodologies deployed in our study capture the key features of the emerging and incumbent LNG regasification technologies. We utilize closed queueing network (CQN) and simulation analysis to calculate the operational performance of alternative process configurations for each technology, which we value financially using an NPV model. We then use optimization models to select the capacity levels in a given architecture to minimize the present value of the costs incurred to sustain at least a given throughput requirement. Finally, we compute the NPV of the given throughput requirement by subtracting this cost figure from the present value of its revenue stream. This optimization step integrates the three components of our framework and allows us to determine how they impact the technology choice. We apply our framework to data to study how process configuration, and operational and financial performance affect technology selection decisions. This leads to several contributions.

First, we compare the incumbent technology, which can be deployed only in one architectural option, versus a basic architecture of the emerging technology. This comparison is complicated by the fact that the two technologies display different capacity sizing features: number of ships for the incumbent technology, and number of ships and number of unloading buoys for the emerging technology. Our analysis brings to light a characterization of when each technology is preferred over the other, depending on two critical factors: The throughput and the time to revenue advantage of the onboard technology (TRAOT). This latter effect arises from the fact that the emerging technology may start to earn revenue earlier than the incumbent technology, due to its faster installation time. One notable insight is that contrary to the prevailing wisdom (Jensen 2003, Smith et al. 2004), the less modular, emerging technology can outperform the more modular, incumbent technology in situations of high throughput requirement, provided that TRAOT is sufficiently high. We ascribe this seemingly counterintuitive result to the fact that the current literature and practice have apparently overlooked the possibility of sizing the capacity of the emerging technology by employing multiple unloading buoys [3]. This finding (1) shows that process configuration choices may affect new technology selection decisions, sometimes in unexpected ways, that is, increasing modularity is not always preferable when one considers its net benefit; and (2) challenges the LNG industry to think differently about the emerging onboard technology.

Second, we evaluate whether these conclusions may be affected by deploying the emerging technology under alternative architectural options. Specifically, we measure the relative merits of different ship-to-ship transshipment architectures when using the new technology. Transshipment increases the degree of modularity of an LNG system by partially decoupling LNG transportation from its storage and regasification, at the expense of introducing an additional operational activity

[3] Among two existing offshore deepwater ports, Gulf Gateway consists of a single buoy and subsea pipeline structure and Northeast Gateway consists of a dual buoy and single subsea pipeline structure. Although Northeast Gateway has a dual-buoy design, only one vessel can unload its LNG cargo at a time: Its dual-buoy structure is designed with the purpose of mooring two vessels at the same time to maintain continuous gas flow, instead of unloading two vessels simultaneously.

(the ship-to-ship LNG transfer). Moreover, transshipment can reduce the capital investment costs by allowing the use of LNGCs in transportation instead of more expensive LNGRVs. Thus, its overall benefit is unclear. Our analysis finds that transshipment is unlikely to be beneficial, and when it is, its benefits are likely to be small, due to the reduction in throughput caused by the additional operational activity. This finding confirms our earlier characterization of the comparison between the incumbent and the new technologies, and it qualitatively reinforces our results on the net benefit of modularity. It also provides an answer to the architecture and fleet structure choice challenge currently faced by managers in the LNG industry (Bryngelson 2007).

Third, we complement our analysis by studying the potential impact of our use of stochastic models of throughput on our conclusions. This impact is unclear as the incumbent and the emerging technologies differ in their process configurations, so that their operational activities exhibit different levels of processing time variability. Despite these differences, we find that deterministic models appear to be adequate to support technology selection decisions. However, they may be inadequate in supporting capacity sizing decisions for a given technology, especially for the emerging technology. This insight is particularly important for managers involved in the management of LNG supply chains that employ the emerging technology; that is, we alert these managers to the potential error (capacity, and hence NPV shortfall) that may result from overlooking stochastic variability in the relevant processing times.

While our focus in this study is on a specific segment of the LNG industry, our analytic framework has potential applications for a broader class of technology selection problems. It may be used to evaluate other technology innovations in the LNG industry, such as floating LNG production (Chazan 2009, Tusiani and Shearer 2007, Ch. 5) rather than regasification. It may also be used to compare technologies in other industries; for example in settings where one type is cheaper and requires a shorter time to install, but can sustain a lower production rate; while the other type is more expensive and requires a longer time to install, but offers a higher throughput. Companies often face such tradeoffs when developing new technologies, both in manufacturing and service industries. One example occurs in emerging markets: A company can typically start manufacturing in the short run by using cheaper and labor intensive operations at a lower production rate, or can enter the market with a more expensive automated system that sustains a higher production rate. Such companies face technology decisions as we consider here.

The remainder of this paper is organized as follows: We review the related literature in §2. Section 3 presents our analytic framework that integrates the technology comparison dimensions illustrated in Figure 1. We present the application of our analytic framework and the insights it generates on the issues we investigate in §4. We conclude in §5 by discussing further research avenues. An online appendix provides supporting material.

2. Related Literature

Energy has long been an active area of research in both operations management and operations research. Durrer and Slater (1977) review the operations research literature that deals with petroleum and natural gas production. More recently, Smith and McCardle (1998) consider the problem of valuing oil properties as real options (Dixit and Pindyck 1994, Trigeorgis 1996), and Smith and McCardle (1999) discuss lessons learned in evaluating oil and gas investments in practice. Hahn and Dyer (2008) value an oil and gas switching option that arises in the production of these commodities. Secomandi (2009b) studies the optimal management of commodity storage assets as real options and discusses an application to natural gas storage, a topic also explored by Carmona and Ludkovski (2007), Chen and Forsyth (2007), Boogert and de Jong (2008), and Thompson et al. (2009). Lai et al. (2009) benchmark practice-based natural gas storage valuation heuristics. Secomandi (2009a) investigates the pricing of natural gas pipeline capacity from various perspectives, including the real option approach. Enders et al. (2010) study the interaction between technology and extraction scaling real options in natural gas production. Our work adds to this literature by considering a novel technology selection problem in the LNG industry.

Closer to the industrial domain that we study, Kaplan et al. (1972), Koenigsberg and Lam (1976), and Koenigsberg and Meyers (1980) model the shipping stage of an LNG supply chain. In this paper we use the model of Koenigsberg and Lam (1976) to evaluate the throughput of some configurations of the technologies that we study, but we also develop original models to evaluate alternative configurations of the emerging technology. Lai et al. (2010) develop a real option model to value downstream LNG storage when LNG is regasified using our incumbent LNG regasification technology. In contrast, we focus on the comparison of this incumbent and the emerging LNG regasification technologies. Abadie and Chamorro (2009) use Monte Carlo simulation to value natural gas investments, including an LNG plant, and Özelkana et al. (2009) use a deterministic optimization model to analyze the design of LNG terminals. Rodríguez (2008) develops a real option model to value delivery flexibility in long-term LNG contracts. None of these authors study the technology selection problem that we analyze.

Our analysis brings to light managerial insights into the drivers of this technology selection problem, providing guidance for executives making such technology decisions. Thus, our work is also related to the operations management literature concerned with establishing principles for guiding managerial decisions (Fisher 2007, Graves and Jordan 1995). Within this literature, researchers study technology selection from different perspectives. Krishnan and Bhattacharya (2002) analyze the relation between product design flexibility and technology selection. Fuchs and Kirchain (2009) study the impact of production location on technology choice. Van Mieghem (2003) reviews several papers that deal with capacity management, focusing on the selection between dedicated and flexible technologies by using stochastic capacity portfolio investment models. In contrast, we study the impact of process configuration and operational and financial performance on technology selection, by using an integrated evaluation framework.

Our process configuration definition comprises process architecture and capacity sizing. Henderson and Clark (1990) define architectural innovation as those innovations that change the architecture of a large system without changing its components. One stream of research on architectural innovation focuses on process architecture (reviewed by Smith and Morrow 1999, Browning and Ramasesh 2007), that is, the process activities, their mutual relationships, as well as their relationships with external processes. An essential decision when structuring a process architecture is how to decompose a large process network into smaller elements. The models developed in the process innovation literature to guide this decision emphasize the benefits of increasing modularity. However, modularity does not come for free, as recognized by Baldwin and Clark (2000), who state that in deciding how much modularity to pursue, the value of increased modularity needs to be compared to its costs: Increasing modularity may increase investment cost, as well as capacity installation and processing times in a processing network as in our specific application. Our paper adds to the growing body of process innovation and technology management (Gaimon 2008) research by quantifying the net benefit of modularity that arises in the context of different technology/process configuration choices in a specific application. In particular, we bring to light conditions under which less modular architectures are more profitable than more modular architectures. We show that the operational drawbacks of decreasing modularity in designing a processing network can be mitigated by adjusting the resource capacities.

3. Analytic Framework

In this section we describe our analytic framework, illustrated in Figure 3, which integrates the technology comparison dimensions depicted in Figure 2: Process configuration and operational and financial performance. We first discuss the process configuration options considered for an LNG

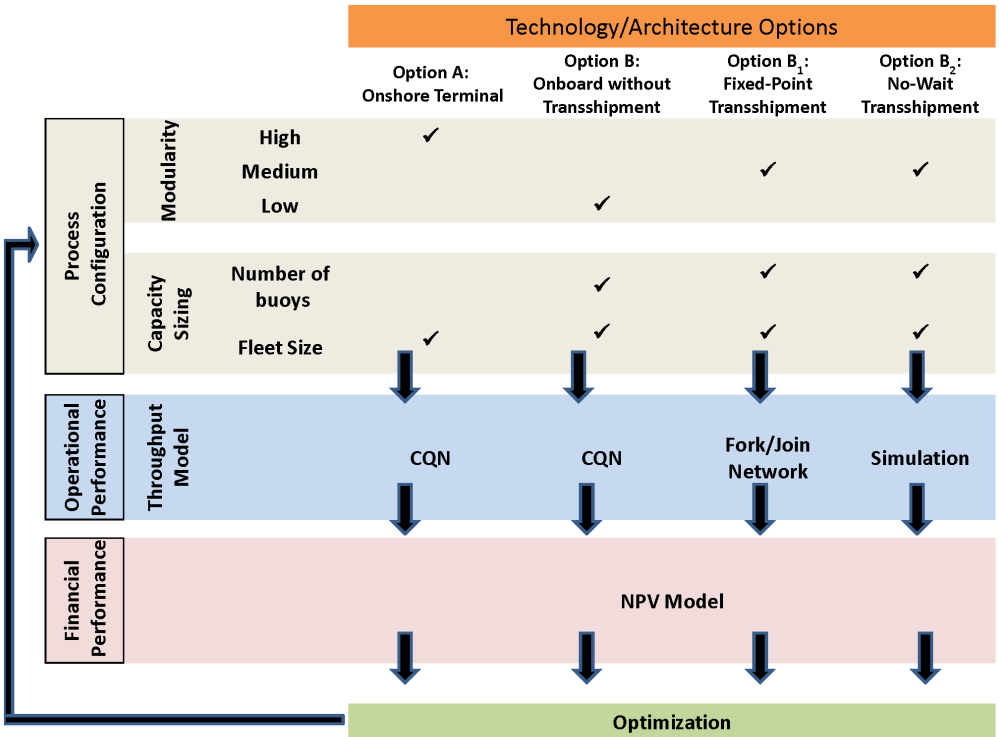


Figure 3: Analytic framework.

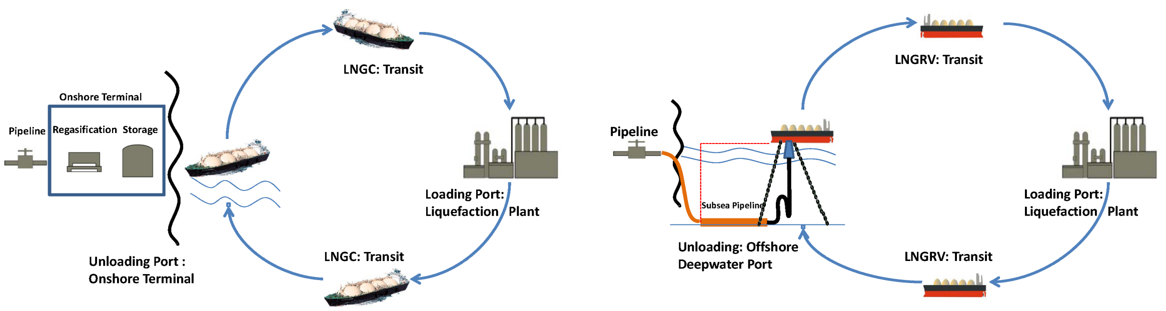
network[4]. Then, we explain the queueing and simulation models used for calculating the throughput (operational performance) of a given LNG process configuration, as well as the NPV model used to value the financial performance of a given process configuration. In the last step of our approach, we optimize the capacity level corresponding to a given technology and architecture option to minimize the present value of the costs incurred to sustain a given throughput requirement. We obtain the NPV of the given throughput requirement by reducing the present value of its revenue stream by this cost figure. We describe each of these steps in detail below.

3.1 Process Configuration Choices

Figure 3 lists the technology/architecture options that we study: Incumbent onshore-terminal technology based system (option A), emerging onboard technology based system without transshipment (option B), onboard system with fixed-point transshipment (option B_1) and onboard system with no-wait transshipment (option B_2).

[4]We determined the specific attributes of each configuration option in collaboration with the managers of Excelerate Energy, a company that is currently operating both LNGCs and LNGRVs, and developing and managing LNG projects with and without transshipment based on the new onboard technology.

We illustrate the LNG chains based on options A and B in Figure 4. In these systems, ships load LNG at the loading port (liquefaction plant), transit to the unloading facility (the onshore terminal in option A and the deepwater port in option B), unload their cargos, and transit back to the loading port. In option A, the decoupled transportation, storage and regasification tasks (as explained in §1) offer high modularity, as listed in Figure 3. On the other hand, in option B, use of the LNGRVs (special vessels) integrates these three tasks, which decreases modularity.



(a) Option A:Incumbent onshore terminal based regasification.

(b) Option B: Emerging onboard regasification without transshipment.

Figure 4: Technology/Architecture options A and B.

Figure 5 displays the LNG chains that feature transshipment based architectures with the emerging onboard technology (options B_1 and B_2 in Figure 3). These architectures use two types of ships: LNGCs and LNGRVs. LNGCs deliver LNG cargos from the loading port to the transshipment location (TL), then transfer their cargos onto LNGRVs that are used in shuttle service between the TL and the unloading deepwater port. Transshipment allows partial decoupling of transportation from the storage and regasifications tasks. Thus, options B_1 and B_2 are characterized as having medium level of modularity in Figure 3. With fixed-point transshipment (option B_1), transshipment occurs at a predetermined point located upstream of the deepwater port, either in the open ocean or in a protected environment. Transshipment occurs between an LNGRV and an LNGC, if they are at the TL at the same time; otherwise a ship that is at the TL must wait until the arrival of a ship of the other type. With no-wait transshipment (option B_2), we assume that ships keep sailing until they meet, instead of waiting at the fixed TL for the arrival of a ship of the other type.

3.2 Operational and Financial Performance Models

We now describe the models we use for calculating the throughput and NPV of the configuration choices explained in §3.1.

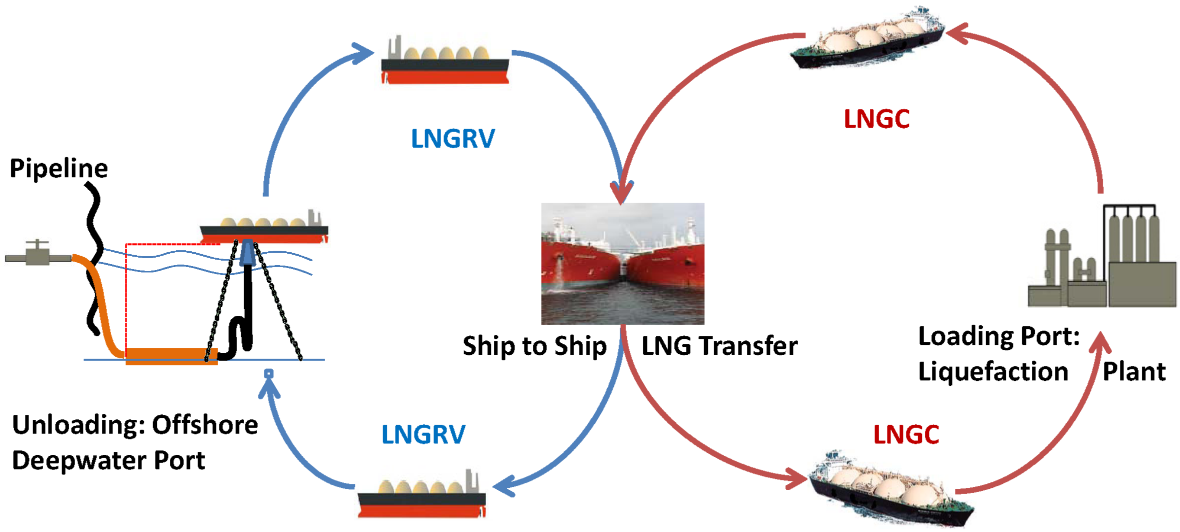


Figure 5: Transshipment based configuration of the emerging onboard technology (Options B_1 and B_2).

Onshore-Terminal and Onboard Systems without Transshipment - Options A and B. Following Koenigsberg and Lam (1976), Koenigsberg and Meyers (1980), and Wang (2008) we model the systems corresponding to options A and B as CQNs. Figure 6 represents the process flow in the corresponding CQNs. We model the loading and unloading processes as first-come-first-serve (FCFS) exponential queues, and the transit processes as ample-server (AS) stations with service time distributions having rational Laplace transforms. Under these assumptions, each CQN has a closed product-form stationary distribution (Baskett et al. 1975).

Let I be the total number of blocks (four blocks in Figure 6). We denote the number of ships in block i as n_i. The state of the shipping system is the array $n = (n_i, i = 1, \ldots, I)$, and satisfies $\sum_{i=1}^{I} n_i = N$, where N is the total number of vessels. Let λ_i and μ_i be the arrival rate and service rate of block i, respectively. Denote $\pi(n)$ as the steady state probability that the system is in state n. Following Baskett et al. (1975), $\pi(n) = \Gamma \prod_{i=1}^{I} \gamma_i(\lambda_i, \mu_i, n_i)$, where Γ is a normalizing constant chosen to make these probabilities sum to 1 and $\gamma_i(\cdot)$ is computed as follows:

$$\gamma_i(\lambda_i, \mu_i, n_i) \quad := \quad \begin{cases} (\frac{\lambda_i}{\mu_i})^{n_i}, & \text{If block } i \text{ is FCFS,} \\ \frac{1}{n_i!}(\frac{\lambda_i}{\mu_i})^{n_i}, & \text{If block } i \text{ is AS.} \end{cases} \tag{1}$$

In an onboard technology based system, there can be multiple unloading buoys/subsea-pipelines at the unloading port to enable unloading multiple vessels at the same time. In this case, station 1 (the unloading port in Figure 6) has multiple servers (buoys/subsea-pipelines), and $\gamma_1(\lambda_1, \mu_1, n_1)$

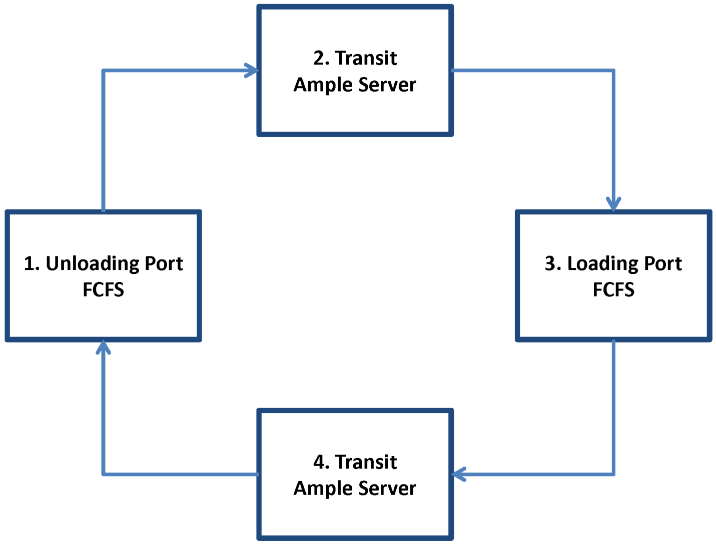


Figure 6: Process flow for options A and B.

becomes $\gamma_1(\lambda_1, \mu_1, n_1)(1/\prod_{a=1}^{n_1} x(a))$, where $x(a)$ is the rate of service at station 1 when there are a vessels at this station relative to the service rate when there is only one vessel at this station, $a = 1$. If there are k servers at station 1, then

$$x(a) \quad := \quad \begin{cases} a, & 1 \leq a \leq k, \\ k, & a > k. \end{cases}$$

Let $\mathcal{N}$ denote all the possible states of the system. Also denote by $\mathcal{N}'$ the set of states in which at least one ship is loading, i.e., $\mathcal{N}' := \{n \in \mathcal{N} : n_3 > 0\}$. Then the throughput rate is:

$$X = C\mu_3 \sum_{n \in \mathcal{N}'} \pi(n), \tag{2}$$

where C is the cargo size of a ship.

The only difference between the onshore terminal (option A) and onboard technology (option B) based systems is the service rate of the unloading block, μ_1; due to onboard regasification, an LNGRV unloads its cargo at a slower rate than an LNGC.

Fixed-point Transshipment Based Onboard System - Option B$_1$. We consider a fixed-point transshipment configuration as a closed fork/join queueing network as depicted in Figure 7. One can think of this system as two conjoined CQNs that are coupled via the transshipment block. Transshipment occurs between an LNGRV and an LNGC if they are at the TL at the same time; otherwise a ship that is at the TL must wait until the arrival of a ship of the other type.

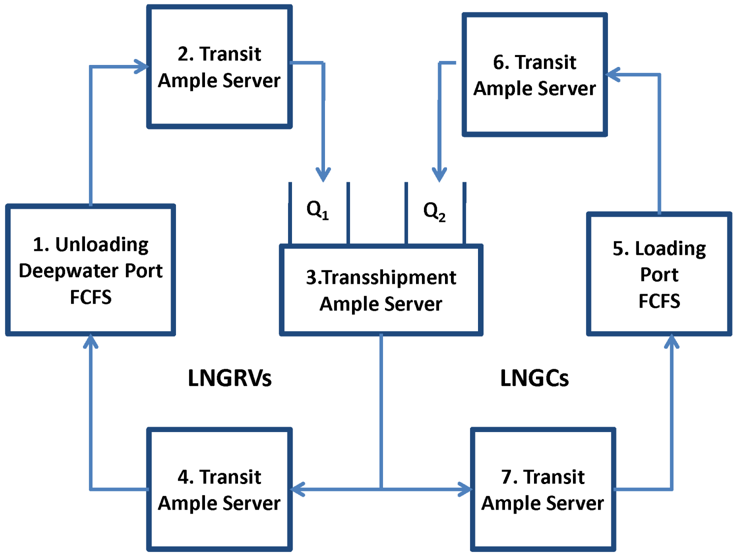


Figure 7: Process flow for option B_1.

We analyze the transshipment network depicted in Figure 7 as a continuous time Markov process. Once again, we denote by μ_i the service rate of station i, $i = 1, \ldots, 7$. Let N_1 and N_2 denote the number of LNGRVs and LNGCs in the system, and $W_1(t)$ and $W_2(t)$ the number of ships in the buffer queues Q_1 and Q_2, respectively, at time t. Because transshipment occurs between an LNGRV and an LNGC as they appear at the TL, it is not possible for both buffers Q_1 and Q_2 to be non-empty. For this reason we denote the number of ships waiting for transshipment at time t using the one dimensional random variable $W(t) := W_1(t) - W_2(t)$; $W(t)$ takes values in $\{-N_2, \ldots, -1, 0, 1, \ldots, N_1\}$. For example, $W(t) = -3$ means that 3 LNGCs are waiting for transshipment at Q_2 and no LNGRV is present at Q_1 for transshipment. There is no ship of either type waiting for transshipment if $W(t) = 0$.

We define $n_i(t)$ as the number of ships at station i in Figure 7 at time t, with the exception that $n_3(t)$ denotes the number of ship *pairs* that are transshipping; $n_3(t)$ can take values in $\{0, 1, \ldots, \min(N_1, N_2)\}$. For $i \in \{1, 2, 4\}$, $n_i(t)$ can take values in $\{0, \ldots, N_1\}$, and for $i \in \{5, 6, 7\}$, $n_i(t)$ can take values in $\{0, \ldots, N_2\}$. The state of the transshipment system in Figure 7 is characterized by the six dimensional array $m := (W, n_1, n_2, n_3, n_5, n_6)$. We find the probability distribution that the system is in state m by modeling it as a continuous time Markov chain.

Let $\mathcal{M}$ denote all the possible states of the system:

$$\mathcal{M} := \{(W, n_1, n_2, n_3, n_5, n_6) : \quad \textstyle\sum_{i=1}^{3} n_i \leq N_1 \text{ and } n_3 + n_5 + n_6 + |W| \leq N_2 \quad \forall\, W \leq 0;$$
$$\textstyle\sum_{i=1}^{3} n_i + W \leq N_1 \text{ and } n_3 + n_5 + n_6 \leq N_2 \quad \forall\, W > 0\}$$

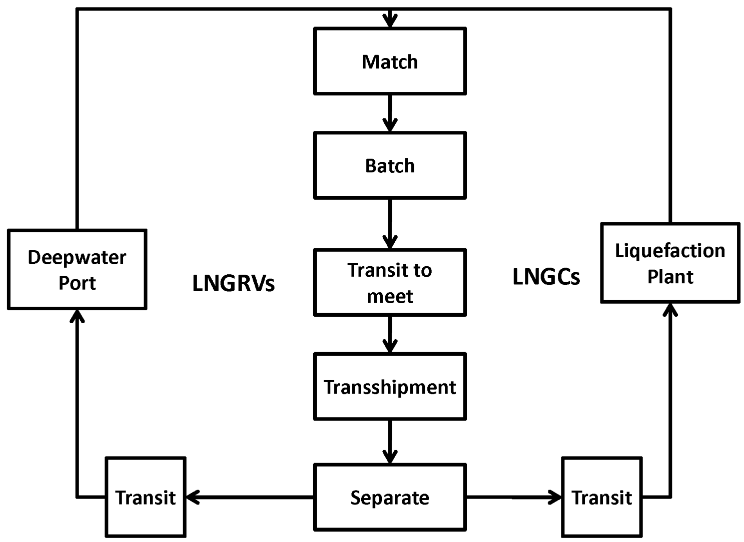


Figure 8: Flow chart of the simulation model of the no-wait transshipment based onboard system.

where we exploit the fact that the number of ships in stations 1 to 4 and buffer Q_1 must sum up to N_1, and the number of ships in stations 3, 5, 6, 7 and buffer Q_2 must sum up to N_2. For each state $m \in \mathcal{M}$, let $\pi(m)$ be the steady state probability that the continuous time Markov chain is in state m; $\pi(m)$ can be computed by solving the global balance equations for all states $m \in \mathcal{M}$ simultaneously with the condition that these probabilities sum up to 1 (see online appendix C).

Let $\mathcal{M}'$ denote the set of states in which there is at least one LNGC at the loading port (station 5), i.e., $\mathcal{M}' := \{(W, n_1, n_2, n_3, n_5, n_6) \in \mathcal{M} : n_5 > 0\}$. Then, the throughput rate of the system is

$$X^T = C\mu_5 \sum_{m \in \mathcal{M}'} \pi(m). \tag{3}$$

No-wait Transshipment Based Onboard System - Option B$_2$. We calculate the throughput of the no-wait transshipment system by Monte Carlo simulation. Figure 8 displays the flow chart of our model. An entity representing an LNGRV or an entity representing an LNGC flow into a match block immediately after they leave the unloading deepwater port and the liquefaction plant, respectively. When an entity arrives at the match block, it is placed in one of two associated queues, one for each vessel type. Entities remain in their respective queues until a match occurs. We record this waiting time in the match block queue to obtain the distance traveled by the matching vessel before the match occurs.

Once a match exists, one entity from each queue is released. After the vessels leave the match block, they flow into a batch block to form a single entity representing the paired vessels that will transship. Batched entities are delayed in the transit-to-meet block for the remaining time required to meet, which is equal to half the difference between the one way transit time and the previously recorded time waited in the match block. Then, the batched entity is delayed in the transshipment block for the time required by the ship-to-ship LNG transfer. When this transfer is completed, the batched entity is separated into its component entities in the separate block. Upon leaving the separate block, the entities representing the LNGRV and the LNGC are delayed in their respective transit blocks for the time required for sailing from the location where transshipment is performed to the deepwater port and the liquefaction plant, respectively.

We use the ARENA simulation software to calculate the throughput, selecting the simulation run times and number of replications such that the throughput rate becomes insensitive to the simulation length and the half-width of a 95% confidence interval is at most 0.5% of the mean.

NPV model. We use the throughput levels calculated above to obtain the NPV generated by each process configuration option. We calculate the NPV as the present value of the revenue generated during a given time horizon minus the operational and capital investment costs incurred during the project lifetime. Assuming that the capital investment costs are incurred at time zero, we discount the cash flows over time using a constant annual risk-free rate; that is, we use a risk neutral valuation approach (Smith 2005, Luenberger 1998, Ch. 13). In order to calculate the revenue, we use New York Mercantile Exchange (NYMEX) natural gas futures prices. Since we value the revenue stream using futures prices, using a risk neutral valuation approach is appropriate. Moreover, since the futures prices capture the *current* market view of *future* supply and demand conditions, this approach implicitly takes into account uncertainty in future demand. In addition, we also assume that any regasified LNG can be sold on the natural gas spot market at the prevailing market price at the time of regasification. That is, the amount of natural gas that is vaporized and pumped into the local natural gas pipeline system does not affect the natural gas price. Given the size of the U.S. natural gas market, this is a reasonable assumption.

3.3 Optimization of the Capacity Levels of Each Technology Architecture Option

We optimize the capacity levels of each technology architecture option to minimize the present value of the costs associated with sustaining at least a given throughput requirement. Subtracting this cost figure from the present value of the revenue stream of the given throughput requirement yields its NPV. For the incumbent technology this simply amounts to choosing the smallest number of ships such that this throughput constraint is satisfied.

For the emerging technology, optimization is more involved. In an onboard technology based LNG chain without transshipment, there can be multiple unloading buoys/subsea-pipelines at the deepwater port to enable unloading of multiple vessels at the same time. Thus, a given throughput requirement can be sustained by multiple combinations of buoys and vessels. For every fleet size, we evaluate all the combinations obtained by increasing the number of unloading buoys from one up to the point when an additional buoy does not increase throughput. Then, among these configuration options, we pick the one that minimizes the present value of the costs incurred to sustain at least the given throughput requirement.

For the transshipment based configurations, for a given fleet size-unloading buoy combination, we also evaluate all the possible fleet structure options, that is, the number of LNGC and LNGRV combinations. Among these configuration options, we pick the one that minimizes the present value of the relevant costs and is feasible, and compute the NPV accordingly.

Notice that the design of the fixed-point transshipment based network described in §3.1 also involves the selection of the transshipment location, which affects the system's throughput. For a given capacity level (number of buoys, LNGRVs and LNGCs), we approximate the optimal transshipment location to maximize the system's throughput by solving a *deterministic* version of the network. To do so, we first decouple the network in Figure 7 into two independent loops: Loop 1 (stations 1, 2, 3 and 4) and loop 2 (stations 5, 6, 3 and 7), where LNGRVs and LNGCs are respectively in service. Such a decomposition is possible due to our deterministic assumption and the fact that at optimality the networks will be perfectly coordinated.

The throughput of loop 1 can be calculated as follows. Let u and τ be the travel times between the unloading deepwater port and the transshipment location, and the unloading deepwater port and the loading port, respectively. The parameter c_i represents the capacity of station $i = 1, 3$. The function $c_i(u)$ represents the capacity of station $i = 2, 4$. For the FCFS station 1, $c_1 = k\mu_1$, where k is the number of unloading servers (buoys) and μ_1 is the service rate of station 1; for the AS transit stations (2 and 4), $c_i(u) = N_1/u$; and for the AS transshipment station 3, $c_3 = N_1\mu_3$. The capacity of loop 1 is $R_1(u) := \min(c_1, c_2(u), c_3, c_4(u))$. Let $D_1(u)$ denote the demand rate of the LNGRVs in the system: $D_1(u) := N_1/(2u + 1/\mu_1 + 1/\mu_3)$. The throughput of loop 1 is the minimum of the bottleneck capacity and the demand rate: $X_1(u) = \min(R_1(u), D_1(u))$. The throughput of loop 2, $X_2(u)$, can be calculated in an analogous manner. That is, $X_2(u) = \min(R_2(u), D_2(u))$ where $R_2(u) := \min(c_5, c_6(u), c_3, c_7(u))$ and $D_2(u) := N_2/(2(\tau - u) + 1/\mu_5 + 1/\mu_3)$. Then the throughput of the deterministic transshipment based network is the minimum of those of loop 1 and loop 2:

$$X_d^T(u) = \min(X_1(u), X_2(u)). \tag{4}$$

Our goal is to find a transshipment location that maximizes the deterministic transshipment based network's throughput $X_d^T(u)$. This problem can be equivalently formulated as finding an optimal solution to the following problem:

$$\begin{aligned} \max_{u} \quad & X_d^T(u) \\ \text{s.t.} \quad & 0 \leq u \leq \tau, \end{aligned}$$

where the constraint states that the transshipment location should be between the unloading deepwater port and the loading liquefaction port. A value u that maximizes $X_d^T(u)$, denoted by u^*, can be found as follows.

For all feasible u values, $0 \leq u \leq \tau$, since $c_2(u) = c_4(u) > D_1(u)$ and $c_6(u) = c_7(u) > D_2(u)$, equation (4) reduces to

$$X_d^T(u) = \min(k\mu_1, N_1\mu_3, D_1(u), \mu_5, N_2\mu_3, D_2(u)).$$

Define $R^T := \min(k\mu_1, N_1\mu_3, \mu_5, N_2\mu_3)$ and $D^T(u) := \min(D_1(u), D_2(u))$. With these definitions, our problem can be equivalently formulated as

$$\begin{aligned} \max_{u} \quad & \min(R^T, D^T(u)) \\ \text{s.t.} \quad & 0 \leq u \leq \tau. \end{aligned}$$

Because $D_1(u)$ and $D_2(u)$ are strictly decreasing and increasing functions of u, respectively, the unconstrained u value that maximizes $D^T(u)$, denoted by u', should satisfy $D_1(u') = D_2(u')$:

$$u' = \frac{(2\tau + \frac{1}{\mu_5} + \frac{1}{\mu_3})N_1 - (\frac{1}{\mu_1} + \frac{1}{\mu_3})N_2}{2(N_1 + N_2)}.$$

Define u^* as

$$u^* \quad := \quad \begin{cases} u', & \text{If } 0 \leq u' \leq \tau, \\ 0, & \text{If } u' < 0, \\ \tau, & \text{If } u' > \tau. \end{cases} \tag{5}$$

If the deterministic transshipment network is demand constrained, that is, $D^T(u^*) < R^T$, then u^* is the unique optimum. Otherwise, there are multiple optimal solutions which always include u^*, our chosen one. Although u^* is provably optimal only for the deterministic network, by using an exhaustive search, we find that it is also optimal for the stochastic network considered in all of our numerical experiments reported in §4.3.

Table 1: Units of measurement and conversion factors

bcf		Billion Cubic Feet
cm		Cubic Meter
bcf/d		Billion Cubic Feet per Day
MMTPA		Million Tons per Annum
MMBTU		Million British Thermal Units
NM		Nautical Mile
1 Knot	=	1 NM per Hour
1 bcf	=	1,100,000 MMBTU
1 MMTPA	=	0.128 bcf/d
1 cm	=	0.0000215 bcf

4. Application of the Analytic Framework

We apply our analytic framework by conducting a numerical study based on financial and operational data. Some of the parameter values used in our study are determined in concert with the managers of Excelerate Energy. Others are taken from the existing LNG literature. Table 1 reports the relevant units of measurement and conversion factors.

4.1 Numerical Values for the Relevant Parameters

We consider an integrated LNG chain with a 25 year lifetime, the length of a typical LNG project (Flower 1998). Our LNG chain has one liquefaction facility and one regasification facility. With the incumbent technology, we assume that the regasification terminal is located at Lake Charles, Louisiana, which indeed hosts an onshore LNG terminal operated by Trunkline LNG. We also assume that the offshore facility is located nearby; for example, the Gulf Gateway offshore deepwater port operated by Excelerate Energy is located 100 miles off the Louisiana cost. We assume that the liquefaction plant is located in Egypt, one of the major LNG exporters (Smith et al. 2004). The distance between Egypt and Lake Charles is approximately 7,000 NMs.

We use the following parameters in our study.

Shipping: We consider a homogeneous ship cargo size of 3 bcf, which is common in the LNG industry (Flower 1998). We assume a shipping speed of 19 knots (Cho et al. 2005, Flower 1998, p. 100). With this assumption, a one-way trip between the regasification facility and the liquefaction plant takes approximately 15 days, on average.

Liquefaction Plant: Following Wang (2008), we consider the service time at the liquefaction plant (loading port) to be exponentially distributed with mean 1 day. The service time is the time required by a vessel for entering the loading port, loading 3 bcf of LNG, completing the required paperwork, and leaving the port.

Onshore Terminal: We assume that the regasification capacity of the conventional onshore terminal is 2 bcf/d, which is consistent with the capacity of some of the onshore terminals in the U.S., including Lake Charles. We set the service time at the onshore terminal (entering the port, unloading 3 bcf of LNG into the storage tanks, completing the required paperwork, and leaving the port) as exponentially distributed with mean 1 day (Koenigsberg and Lam 1976). Following Lane (2008), we let the LNGC capital cost be $250M and the onshore terminal cost be $1.5B (M and B denote million and billion, respectively).

The capital cost of an onshore terminal varies considerably depending on factors such as storage and vaporization capacity, cost of real estate, geological structure, local labor and construction costs, and marine environment (Tusiani and Shearer 2007). Thus, different cost figures are reported in the literature. For instance, Smith et al. (2004) state that a 1 bcf/d regasification terminal costs $0.5B, and EIA (2003) states that the cost of a terminal can range from $0.1B to $2B depending on its regasification capacity. Therefore, we also conducted an analysis including the cost of the onshore terminal as a function of its regasification capacity, consistent with these cost figures. We found that our conclusions did not change from those with the fixed cost of $1.5B. Thus, the results reported in §4.2 were obtained by fixing the terminal cost to be $1.5B for all throughput levels.

Tusiani and Shearer (2007) report that the construction time for an LNG terminal does not generally vary with the size of the facility. Rather, it is determined by the construction schedule for the storage tanks, the most time-consuming and expensive components of a terminal, and it may take between 2 and 5 years. We assume that it takes 5 years to construct the onshore terminal, but in §4.2 we explain how our conclusions change when reducing the construction time of this terminal.

Deepwater Port: We assume that the LNG regasification rate of an LNGRV is 0.5 bcf/d (Energy Bridge Fact Sheets 2008). We set the service time at the deepwater port (mooring, connecting with submerged buoy, vaporizing 3 bcf of LNG, and leaving the port) as exponentially distributed with mean 7 days (Lane 2008). We let the capital cost of an LNGRV be $275M (Lane 2008). We assume that each buoy/subsea-pipeline structure (each server) at the deepwater port costs $70M, and that it takes 1 year to construct the deepwater port (Gulf Gateway Fact Sheets 2008), independent of the number of buoys in the deepwater port. The LNG transshipment service time is taken to be 2 days on average (Lane 2008), and is assumed to be exponentially distributed with this mean.

Operational Cost: This cost has three components: Liquefaction, shipping, and regasification costs. Following Wang (2008), we assume that the liquefaction plant operating cost is $8M per MMTPA. According to Lane (2008), the shipping cost is $47.851M per ship per year (this includes

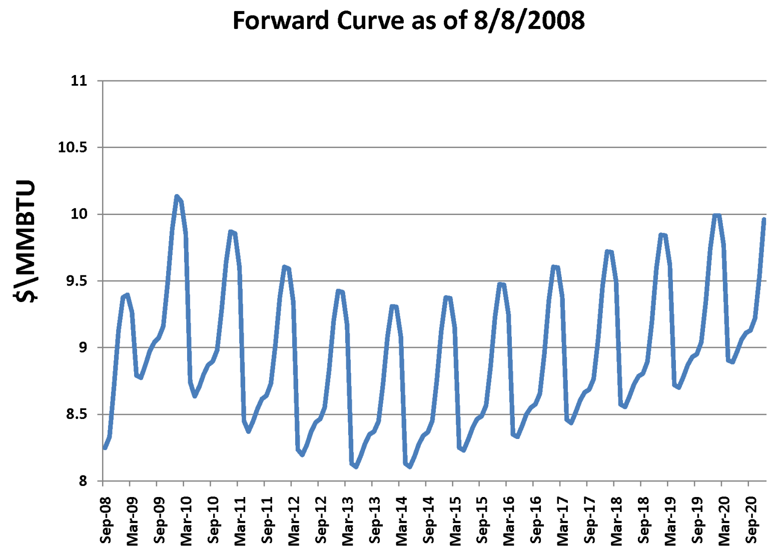


Figure 9: NYMEX natural gas futures prices.

fuel and crew costs). Finally, we take the regasification variable cost as \$0.0285 per MMBTU with a 1.69% fuel loss (Wang 2008).

Revenue: We use NYMEX natural gas futures prices as of 8/8/2008 (Figure 9) for calculating the relevant revenue figures. For each trading day, NYMEX futures prices are available for maturities of 148 months in the future. To estimate the futures prices for the months beyond the last available maturity, we replicate the prices of the last 12 available months. We set the annual risk-free interest rate as 1.7%, the three-month U.S. Treasury rate as of 8/8/2008.

4.2 Comparison of the Two Regasification Technologies (Option A vs B)

In this subsection we analyze under which conditions each regasification technology should be adopted. We consider throughput requirements up to and including 2 bcf/d.

The dashed line in Figure 10 shows the difference between the present values of the total costs of the onboard and onshore regasification systems; we obtain this difference by subtracting the capital and operating costs of the onshore system from those of the onboard system[5]. The capital cost is the investment required for building the unloading and regasification facilities, and the vessels. The operating costs include the liquefaction, shipping, and regasification costs, as explained in §4.1.

[5]The jittery pattern of the cost difference line is caused by the integer-valued fleet size difference between the onboard and onshore systems. The magnitude of each peak corresponds to the capital and operating cost of an additional vessel required by the onboard system compared to the onshore system to sustain the throughput interval in which the peak occurs. This fleet size difference also creates the jittery pattern of the NPV difference line in Figure 10.

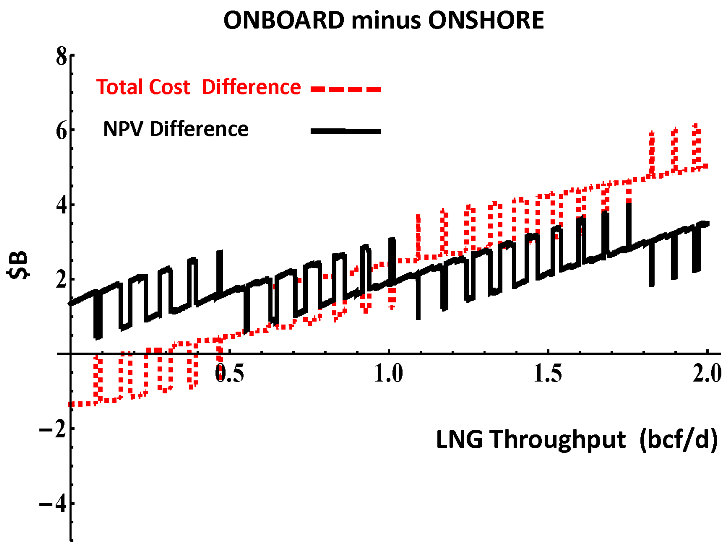


Figure 10: Technology comparison: The NPV and costs difference of the onboard and onshore-terminal systems with high TRAOT.

The cost difference line in Figure 10 shows that for "low" throughput levels - less than 0.5 bcf/d - the onboard technology's cost is lower than that of the onshore technology, due to the lower capital investment required to build the offshore deepwater port. But to sustain higher throughput levels, the onboard technology system needs several unloading buoys and more vessels than the onshore technology system, due to its lower unloading rate. The capital investment for multiple unloading buoys and the capital and operating costs of the extra vessels diminish one of the onboard system's main competitive edges, the lower capital investment required by the deepwater port. Thus, the total cost of the onboard system becomes significantly larger than that of the onshore system for "high" throughput levels - more than 0.5 bcf/d. But what about NPV?

The solid line in Figure 10 displays the difference between the NPVs generated by the two systems; we obtain this difference by subtracting the NPV of the onshore system from the NPV of the onboard system. We find that for *all* throughput levels, the onboard technology based system generates significantly more NPV than the system based on the onshore terminal, although the cost of the former system is much higher for high throughput levels. This result holds due to the shorter time required for building an onboard regasification facility compared to onshore terminals (recall that we assume it takes one year to complete the deepwater port and five years to construct the onshore terminal). Thus, the onboard technology based system starts generating revenue four years earlier. As shown in Figure 10, for high throughput requirements, although the total cost of

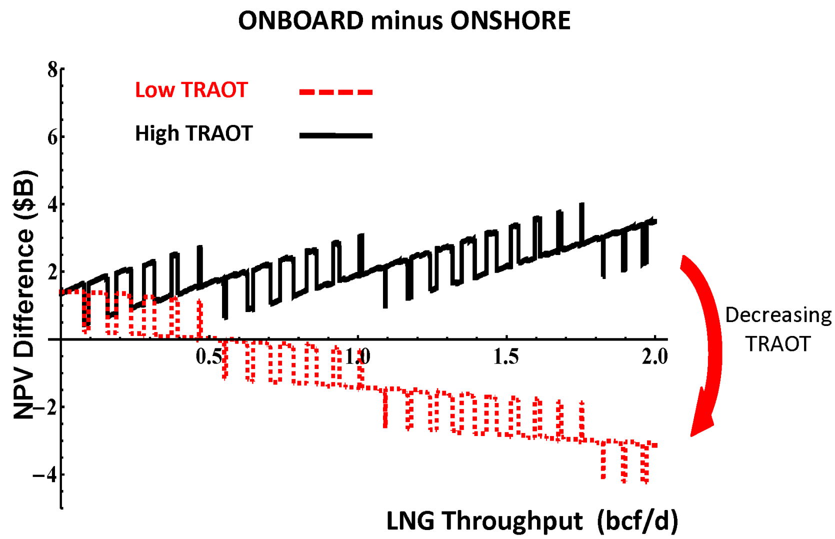


Figure 11: Technology comparison: The TRAOT effect.

the onboard system is greater than that of the onshore-terminal system, the former system is more profitable due to its advantage in its revenue generation timing, which we label TRAOT.

Of course, the NPV difference displayed in Figure 10 is specific to the parameters used in our study. In practice, TRAOT is determined by operational parameters and market conditions, such as the permitting process and facility construction time, availability of the vessels and LNG supply, natural gas futures prices, and interest rates. For instance, it may take less than 5 years to build the onshore terminal. Alternatively, due to idiosyncrasies in the LNG industry, building LNGRVs, which use onboard regasification technology, may take more than the year we assumed. In this case, the revenue generation of the onboard technology based system will be delayed until the LNGRVs are completed. Moreover, due to economic downturns, the natural gas prices or interest rates can decrease to levels lower than those that we use. In these cases, TRAOT would be smaller than what displayed in Figure 10, so that the NPV difference would decrease as illustrated in Figure 11, making the incumbent technology more profitable than the emerging technology for high throughput requirements.

Our analysis reveals the existence of a frontier that partitions the throughput (operational performance) and TRAOT (financial performance) space into two regions in which each of two technologies dominates the other. In other words, by simultaneously considering these dimensions, we derive conditions specifying when each technology should be adopted, as illustrated in Figure 12:

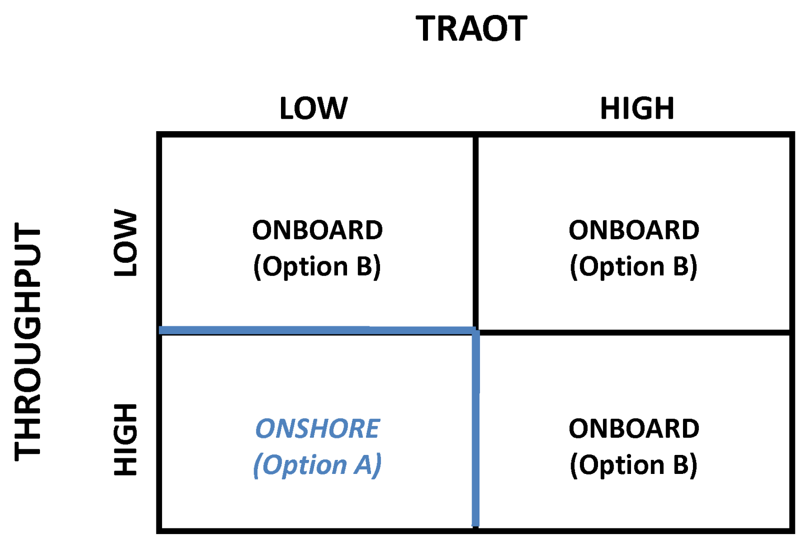


Figure 12: Insights for regasification technology choices.

- If the throughput requirement is low, an onboard technology based system is always more profitable than an onshore-terminal based system due to its lower capital investment cost.
- If the throughput requirement is high, the technology adoption choice depends on TRAOT. Although the onboard system's total cost is greater than that of the onshore-terminal system for high throughput levels, the extra NPV obtained by the former system, thanks to its potential to generate revenue earlier, may still make the onboard system more profitable.

The former finding is consistent with the literature (Jensen 2003, Smith et al. 2004). The latter finding contrasts with those obtained by Jensen (2003) and Smith et al. (2004): These authors state that the emerging onboard technology is well-suited for seasonal and occasional usage, that is, the low throughput case; they also report that the incumbent onshore technology is more profitable than the emerging onboard technology in the high throughput case. We demonstrate that the onboard technology can also be preferred to sustain high throughput, provided the TRAOT advantage is high. In other words, by neglecting the effect of TRAOT, the extant literature fails to identify a situation (high TRAOT, high throughput) in which the onboard technology can dominate the onshore technology.

Indeed, it is surprising that the less modular onboard technology, which features a longer time for vessel unloading, may outperform the more modular onshore technology in a situation of high throughput. The reason for this apparently counterintuitive result is that the extant literature

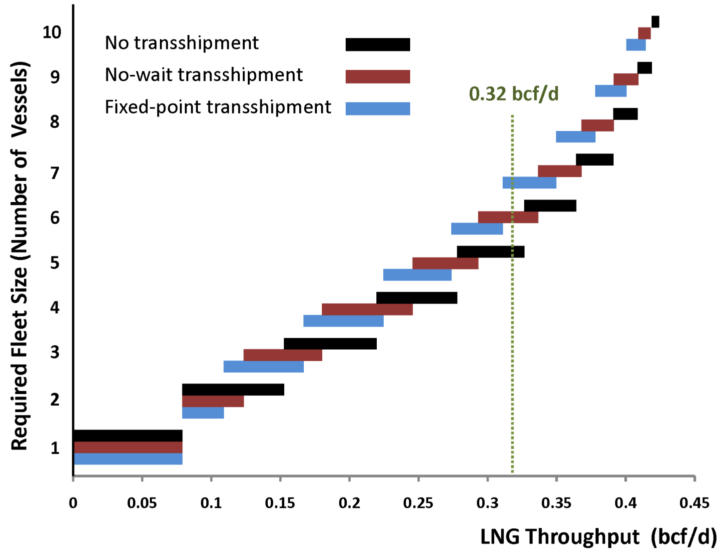


Figure 13: Number of vessels required by the onboard systems with and without transshipment to sustain a given throughput.

and practitioners have seemingly ignored the possibility of configuring the onboard technology using multiple unloading buoys, as we model in this paper. This process configuration choice overcomes the disadvantage of slower unloading rates of the onboard technology (or equivalently the disadvantage of decreasing modularity) and together with higher TRAOT is able to outperform the onshore technology at higher throughput requirements. Thus, our analysis challenges the LNG industry to think differently about the emerging onboard technology.

4.3 The Benefit of LNG Transshipment with the Emerging Technology (Comparing options B, B_1 and B_2)

In this section, we compare options B, B_1 and B_2 to study the merit of ship-to-ship LNG transshipment, a configuration aspect in the deployment of the emerging onboard technology that companies such as Excelerate Energy and Höegh LNG are currently exploring as a way to improve the profitability of this technology. Transshipment allows a firm to configure a fleet of ships as a mix of LNGCs and more expensive LNGRVs. Such a configuration can reduce capital investment cost and partially decouple the transportation from storage and regasification (which increases modularity). We examine the *net benefit of transshipment* in terms of improved profitability of an onboard technology based system, evaluating how our conclusions on technology selection presented in §4.2 may be affected by alternative transhipment based architectures of the emerging onboard technology.

First, we investigate how transshipment (equivalently increasing modularity) can impact the

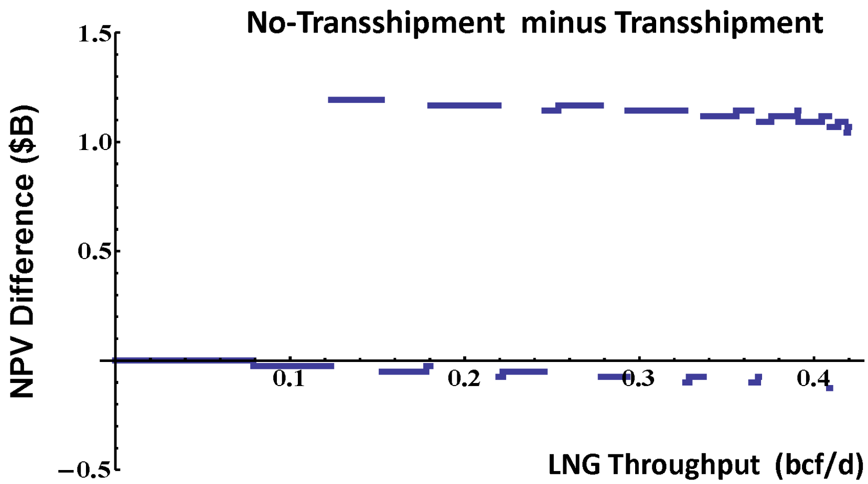


Figure 14: NPV benefit of LNG transshipment.

operational performance of a system using new onboard technology. Figure 13 presents the number of vessels needed to sustain a given throughput by systems with and without transshipment, serving a deepwater port with one unloading buoy (our findings remain similar for systems with multiple buoys). We find that the transshipment based systems (fixed-point and no-wait) may require more vessels than the system without transshipment in order to sustain a given throughput level. This is due to the additional time required for the ship-to-ship LNG transfer and the synchronization of ships (the waiting time at the transshipment location) in the transshipment based systems. For instance, Figure 13 shows that in order to supply 0.32 bcf/d, the system without transshipment requires 5 ships, the no-wait transshipment system requires 6 ships, and the system with fixed-point transshipment requires 7 ships. We also find that for a given fleet size, configuring the shipping network as a no-wait instead of a fixed-point transshipment system may significantly increase LNG throughput (up to 13.2%). However, even this system will never outperform the system without transshipment in terms of throughput.

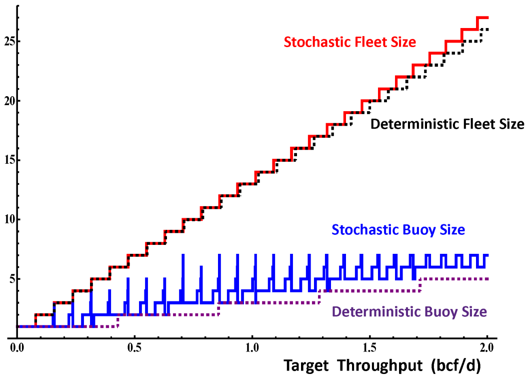
Having quantified the throughput loss due to transshipment, we measure the tradeoff between the capital investment savings obtained by replacing expensive LNGRVs with less expensive LNGCs and the cost of the throughput loss. Figure 14 displays the difference between the NPV of the systems without and with transshipment; we consider a no-wait transshipment network since it dominates the fixed-point transshipment network as shown above. We obtain this difference by subtracting the NPV of the system with transshipment from the NPV of the system without transshipment. For most throughput levels, the latter system generates significantly more NPV than the former system, as a system with transshipment typically requires more vessels than a system without transshipment. The capital and operating costs of these extra vessels exceed the savings brought about by using cheaper LNGCs in the transshipment network. For some throughput levels, transshipment does pay off in terms of NPV, but this benefit is marginal.

Thus, our analysis suggests that LNG supply chains based on onboard regasification technology should be developed, when possible, only using dedicated LNGRVs, rather than as a mixture of these and conventional LNGCs. The use of transshipment should only be considered as a way to circumvent capacity restrictions due to insufficient availability of LNGRVs in the market. This finding provides an answer to the process architecture and fleet structure choice challenge faced by LNG companies using or planning to use emerging onboard technology (Bryngelson 2007). We show that if increasing modularity increases the processing time in a processing network (by introducing additional tasks and/or increasing the interdependence within a module), the cost of throughput loss should be justified against the benefits of modularity. Our analysis also reveals that the insights on technology selection presented in §4.2 are not affected by the possibility of using the transshipment architecture. In other words, we illustrate an example where process configuration does not impact the technology selection decision.

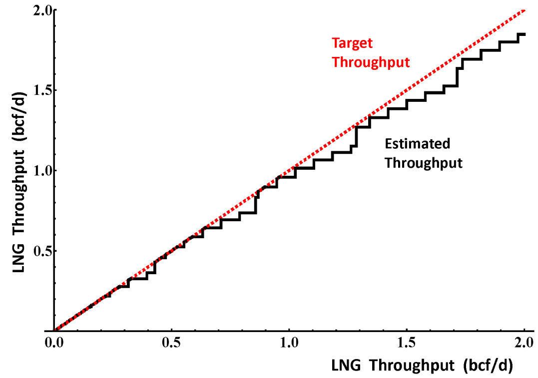
4.4 The Potential Impact of Stochastic Modeling

In this subsection we quantify the potential impact on our conclusions of using our stochastic modeling approach, based on exponentially distributed processing times, by replicating our analysis using deterministic processing times. Specifically, we investigate the choices of capacity size, technology selection, and how to configure an onboard technology based system assuming all transit, loading and unloading times are deterministic. The exponential and deterministic processing times should be interpreted as two extreme cases. In reality, the variability in these processing times typically falls somewhere in between 0 (the deterministic case) and 1 (the exponential case); see, e.g., Koenigsberg and Lam (1976) and Kaplan et al. (1972). Below we refer to an exponential stochastic model as simply a stochastic model.

Capacity Sizing. Figure 15(a) illustrates the optimal onboard system configuration (number of buoys and vessels) computed by the deterministic and stochastic models as a function of the throughput requirement. This figure shows that the capacity levels prescribed by the stochastic model are higher than those obtained by the deterministic model for some throughput intervals, a consequence of the congestion that arises in the stochastic model. Fleet sizes are often similar,



(a) Optimal capacity configuration calculated by the deterministic and stochastic models



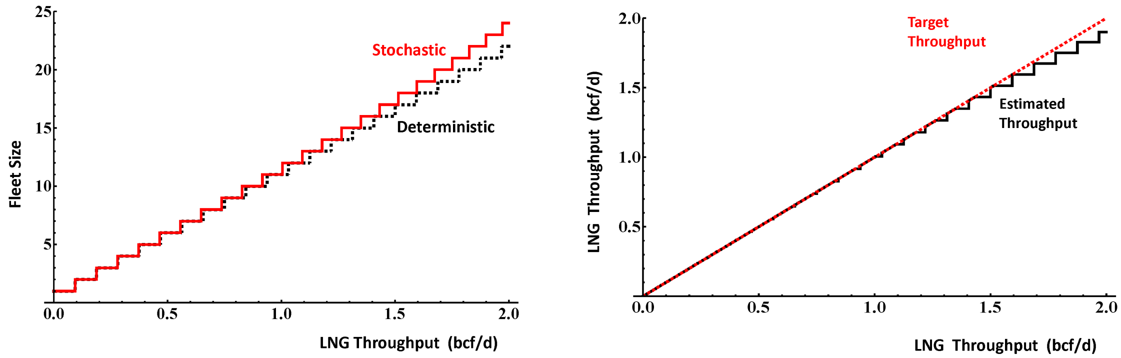
(b) Target and estimated throughput levels

Figure 15: Impact of modeling approach on capacity sizing - Onboard system.

but the stochastic model typically suggests a higher number of unloading buoys. In order to increase throughput, the stochastic model first chooses to install an additional buoy, since the capital and operating cost of an additional vessel is much higher than the cost of an unloading buoy. When adding an extra buoy can no longer increase the throughput, the model has to add an extra ship. This increases the throughput dramatically, so the target throughput can be met with fewer buoys (note that in Figure 15(a) when the number of buoys decreases, this always coincides with an increase in fleet size). Figure 15(b) estimates the throughput levels of the deterministic model's recommendations using our *stochastic* model. The gap between the target and estimated throughput levels can be as large as 17.29%. Even though these may be considered pessimistic estimates of the throughput shortfalls associated with the deterministic model designs, since processing times' coefficient of variations are likely less than 1, Figure 15(b) suggests that detailed stochastic analysis of a given onboard system design is likely to be important in practice to support capacity sizing choices.

Figure 16 is analogous to Figure 15 and relates to the onshore system. Although the throughput shortfall is still present and can be as large as 7.86%, it appears to be smaller than in the onboard technology case for all the considered throughput levels, due to the shorter unloading times. Thus, in the onshore case detailed stochastic analysis, while still advisable, is likely to be somewhat less crucial than in the onboard case for aiding capacity sizing decisions.

Technology Selection. We next elaborate on the potential impact of stochastic modeling on the estimated throughput cost and technology selection. Figure 17(a) depicts the costs of throughput for the onshore and onboard systems calculated by the stochastic and deterministic



(a) Fleet sizes calculated by the deterministic and stochastic models

(b) Target and estimated throughput levels

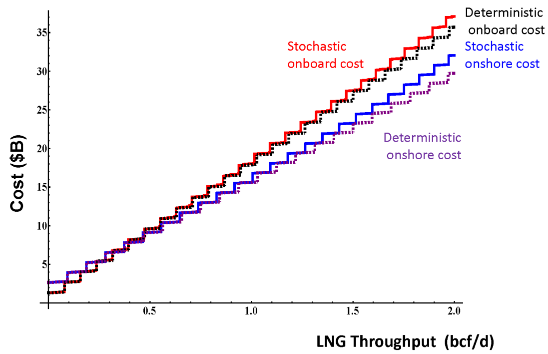
Figure 16: Impact of modeling approach on capacity sizing - Onshore system.

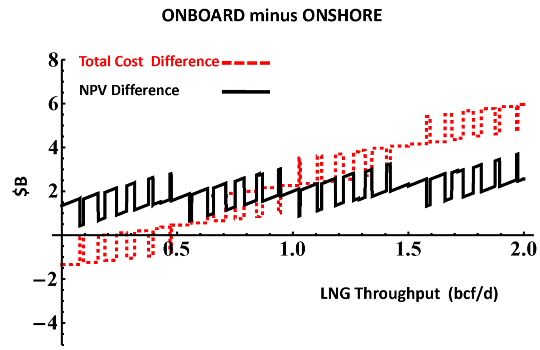
models. Not surprisingly, the costs calculated by the deterministic model are lower than those computed by the stochastic model for both technologies; this is due to the differences in the capacity levels explained above. Likewise, the differences between the costs obtained by the deterministic and stochastic models follow similar trends for both technologies. This is explained by the similarity of the differences in the fleet sizes obtained by the deterministic and stochastic models shown in Figures 15(a) and 16(a), and the fact that a buoy is much cheaper than a vessel.

Figure 17(b) displays the NPV and present values of the total cost differences between the onboard and onshore systems calculated with deterministic models. This figure is very similar to Figure 10, in which these differences are computed with stochastic models. Since the costs of the designs obtained by the deterministic and stochastic models have similar patterns for both technologies, the difference between the relevant costs and NPVs is not significantly affected by stochastic versus deterministic modeling. As a result, the technology selection decision appears to be robust with respect to how one models processing time variability in LNG shipping systems.

Benefit of Transshipment. As in §4.3, we analyze the benefit of transshipment for the onboard technology with one unloading buoy, but now with deterministic models (again, our findings remain similar for systems with multiple buoys). In this analysis, the deterministic model of the transshipment based system consists of equations (4) and (5). Figure 18(a) illustrates the gap between the target and estimated throughput levels when capacity choices are made using deterministic models, but their throughput levels are evaluated with our stochastic models. When there is a positive gap it is typically larger for the transshipment based system, because in such a system vessels face additional sources of variability related to transshipment.

Figure 18(b) presents the difference between the NPVs of the onboard systems with and without



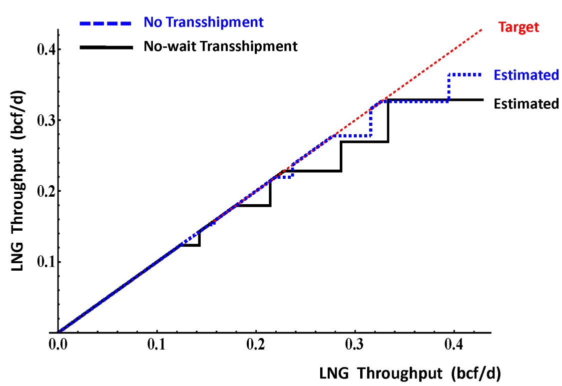


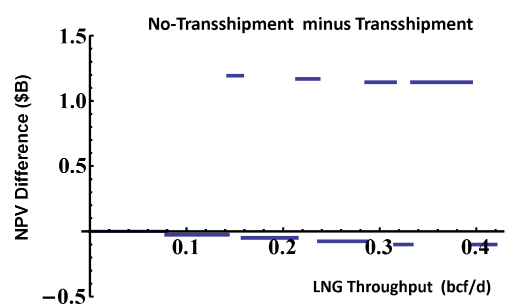
(a) Throughput cost calculated by the deterministic and stochastic models for onboard and onshore systems

(b) Technology comparison using deterministic models

Figure 17: Impact of modeling approach on technology selection.

transshipment obtained by the deterministic models. Compared to the stochastic case (see Figure 14), Figure 18(b) shows that the throughput intervals in which transshipment is beneficial are wider. This occurs because the throughput estimates for deterministic and stochastic models are closer for a system without transshipment than for a transshipment network. Nevertheless, the benefit of transshipment remains marginal. Thus, whether one models stochastic variability is unlikely to change our conclusions regarding the onboard technology configuration choice.





(a) Target and estimated throughput levels for the onboard technology with and without transshipment

(b) Benefit of transshipment with deterministic models

Figure 18: Impact of modeling approach on the configuration of the onboard system.

To sum up, our analysis reveals that although deterministic models are adequate to support the technology and process architecture selection decisions, they may be inadequate to support capacity sizing decisions: Deterministic models can lead to lower investments and missed opportunities since they neglect the impact of process uncertainty. While it is obvious that a stochastic model of throughput provides a lower estimate of the capacity of a processing network than that obtained by a deterministic model, which ignores congestion, we show that the difference in these estimates is significantly higher for the onboard technology than the onshore technology. This insight is relevant to LNG practitioners who, given their familiarity with the incumbent onshore technology, may not want to deploy stochastic models to size emerging networks that use the new onboard technology. Stated differently, we alert practitioners to the potential errors that may result from overlooking stochastic variability in processing times that may lead to under investing in system capacity leading to lower returns.

5. Conclusions

Motivated by current developments, we engaged executives at Excelerate Energy, a company that is currently developing LNG supply chains based on the emerging LNG regasification technology, to develop and apply to data an integrated analytic framework for technology selection in the LNG industry. We analyze the impact of process configuration and operational and financial performance on technology selection, identifying the conditions under which a specific regasification technology and its configuration is appropriate for adoption. We also quantify the potential impact of modeling stochastic variability on the insights we derive. In addition, we measure the tradeoff between the cost and benefits of increasing the modularity of the LNG processing network. We show how the drawbacks of decreasing modularity can be mitigated through operational decisions. Some of our insights attribute a different role to the emerging technology than currently envisioned; others offer new perspectives on pressing issues encountered by those companies that are currently deploying this technology on a commercial scale. The application of our integrated analytic framework provided novel guidelines to executives at Excelerate Energy for their strategic-level planning for capital investments and operating decisions.

Our work could be extended in several directions. In this paper, we focus on technology innovations in the regasification and transportation of LNG. Increased global LNG demand has also led to several technology innovations in the upstream portion of LNG supply chains; for example, floating offshore liquefaction facilities (FOLFs). Companies that are seeking alternatives to conventional onshore natural gas liquefaction plants have expressed growing interest in FOLFs (Chazan 2009, Tusiani and Shearer 2007, Ch. 5). These facilities can offer greater flexibility and lower cost and capacity installation time compared to onshore liquefaction plants (Loo 2009). One could adapt our integrated analytic framework to study the selection of technology for natural gas liquefaction.

We find that increasing modularity can require additional capital investment, and capacity installation and processing time. We study the tradeoff between these three factors and the benefits supplied by increasing modularity in the context of the LNG industry. In general settings there can be additional drawbacks and advantages associated with modularity that need to be identified. One could extend our integrated analytic approach to other domains by enriching it with these additional facets. One could then use our approach to understand the impact of modularity on other processing networks, such as new product development processes, and identify the conditions under which increasing modularity, without additional qualifications, can be used as a general prescription.

We analyze the profit of an integrated LNG chain. However, LNG chains may include multiple parties that manage different stages of the chain, such as LNG producers, shippers, and merchants, who may have conflicting objectives. Our models of different LNG process architecture and/or technology alternatives could be extended to include the perspectives of different parties within a game-theoretic framework. These models could be used to analyze the impact of ownership and contract terms on the architecture and technology choice within an LNG supply chain.

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References

Abadie, L. M., J. M. Chamorro. 2009. Monte Carlo valuation of natural gas investments. *Review of Financial Economics* **18** 10–22.

Baldwin, C. Y., K. B. Clark. 2000. *Design Rules, Volume 1: The Power of Modularity*. MIT Press, Cambridge, MA, USA.

Baskett, F., K. M. Chandy, R. R. Muntz, F. G. Palacios. 1975. Open, closed, and mixed networks of queues with different classes of customers. *Journal of the Association for Computing Machinery* **22** 248–260.

Boogert, A., C. de Jong. 2008. Gas storage valuation using a Monte Carlo method. *Journal of Derivatives* **15** 127–147.

Browning, T. R., R. V. Ramasesh. 2007. A survey of activity network-based process models for managing product development projects. *Production and Operations Management* **16** 217–240.

Bryngelson, R. 2007. Northeast Gateway Energy Bridge deepwater port project status. Available at http://www.northeastgas.org/pdf/r_bryngelson1107.pdf.

Carmona, R., M. Ludkovski. 2007. Valuation of energy storage: An optimal switching approach. Working Paper, Princeton University, Princeton, NJ, USA.

Chazan, G. 2009. Shell plans to build floating gas plant. Wall Street Journal, http://online.wsj.com/article/SB10001424052748704882404574461321132480810.html.

Chen, Z., P. A. Forsyth. 2007. A semi-Lagrangian approach for natural gas storage valuation and optimal operation. *SIAM Journal on Scientific Computing* **30** 339–368.

Cho, J. H., H. Kotzot, F. de la Vega, C. Durr. 2005. Large LNG carrier poses economic advantages, technical challenges. *LNG Observer* **2**. October.

Dixit, A. K., R. S. Pindyck. 1994. *Investment under Uncertainty*. Princeton University Press, Princeton, NJ, USA.

Durrer, E.J., G.E. Slater. 1977. Optimization of petroleum and natural gas production - A survey. *Management Science* **24**(1) 35–43.

EIA. 2003. Energy Information Administration, The global liquefied natural gas market: Status and outlook. U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

Enders, P., A. Scheller-Wolf, N. Secomandi. 2010. Interaction between technology and extraction scaling real options in natural gas production. *IIE Transactions* Forthcoming.

Energy Bridge Fact Sheets. 2008. Available at http://www.excelerateenergy.com/downloads/Excelerate_energybridge.pdf.

FERC. 2009. Federal Energy Regulation Commission, Existing and proposed North American LNG terminals. Washington, DC, USA, http://www.ferc.gov/industries/lng/indus-act/terminals/lng-existing.pdf.

Fisher, M. 2007. Strengthening the empirical base of Operations Management. *Manufacturing and Service Operations Management* **9** 368–382.

Flower, A. R. 1998. LNG project feasibility. *In G. B. Greenwald (ed.), Liquefied Natural Gas: Developing and Financing International Projects*. Kluwer Law International, London, UK.

Fuchs, E., R. Kirchain. 2009. Design for location? The impact of manufacturing offshore on technology competitiveness in the optoelectronics industry. Working Paper, Carnegie Mellon University, College of Engineering.

Gaimon, C. 2008. The management of technology: A Production and Operations Management perspective. *Production and Operations Management* **17** 1–11.

Geman, H. 2005. *Commodities and Commodity Derivatives: Modeling and Pricing for Agriculturals, Metals and Energy*. John Wiley & Sons, Chichester, UK.

Gomes, P. J., N. R. Joglekar. 2008. Linking modularity with problem solving and coordination efforts. *Managerial and Decision Economics* **29** 443–457.

Graves, S. C., W. C. Jordan. 1995. Principles on the benefits of manufacturing process flexibility. *Management Science* **41** 577–594.

Gulf Gateway Fact Sheets. 2008. Available at http://www.excelerateenergy.com/downloads/Excelerate_gulfgate08.pdf.

Hahn, Warren J., James S. Dyer. 2008. Discrete time modeling of mean-reverting stochastic processes for real option valuation. *European Journal of Operational Research* **184** 534–548.

Henderson, R. M., K. B. Clark. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly* **35** 9–30.

Jensen, J. T. 2003. The LNG revolution. *The Energy Journal* **24** 1–45.

Kaplan, M., R. C. Wentworth, R. J. Hischier. 1972. Simulation and optimization of LNG shipping systems. ASME Transactions of the Petroleum Mechanical Engineering and Pressure Vessels and Piping Conference, New Orleans, September 17-21, 1-11.

Koenigsberg, E., R. C. Lam. 1976. Cyclic queue models of fleet operations. *Operations Research* **24** 516–529.

Koenigsberg, E., D. A. Meyers. 1980. An interacting cyclic queue model of fleet operations. *The Logistics and Transportation Review* **16** 59–71.

Krishnan, V., S. Bhattacharya. 2002. Technology selection and commitment in new product development: The role of uncertainty and design flexibility. *Management Science* **48** 313–327.

Lai, G., F. Margot, N. Secomandi. 2009. An approximate dynamic programming approach to benchmark practice-based heuristics for natural gas storage valuation. *Operations Research* Forthcoming.

Lai, G., M. X. Wang, S. Kekre, A. Scheller-Wolf, N. Secomandi. 2010. Valuation of the real option to store liquefied natural gas at a regasification terminal. Working Paper 2006-E99, Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA, USA.

Lane, M. K. 2008. Vice President - Operations at Excelerate Energy. Personal Communication.

Loo, F. 2009. Preview-LNG industry seeks answers to untried floating LNG. Available at http://www.reuters.com/ article/marketsNews/idUSSP50927120090727?sp=true.

Luenberger, D. G. 1998. *Investment Science*. Oxford University Press, New York, NY, USA.

Özelkana, E. C., A. D'Ambrosio, S. G. Teng. 2009. Optimizing liquefied natural gas terminal design for effective supply-chain operations. *International Journal of Production Economics* **111** 529–542.

Rodríguez, R. Y. 2008. Real option valuation of free destination in long-term liquefied natural gas supplies. *Energy Economics* **30** 1909–1932.

Secomandi, N. 2009a. On the pricing of natural gas pipeline capacity. *Manufacturing & Service Operations Management* Forthcoming.

Secomandi, N. 2009b. Optimal commodity trading with a capacitated storage asset. *Management Science* Forthcoming.

Smith, E. N., J. W. McFarland, J. M. Trapani, S. E. Michaelides, J. R. Moroney, C. W. Nelson. 2004. Liquefied natural gas imports and their impact on the state, regional, and national economies. Entergy-Tulane Energy Institute.

Smith, J. E. 2005. Alternative approaches for solving real-options problems. *Decision Analysis* **2** 89–102.

Smith, J. E., K. F. McCardle. 1999. Options in the real world: Lessons learned in evaluating oil and gas investments. *Operations Research* **47** 1–15.

Smith, J.E., K.F. McCardle. 1998. Valuing oil properties: Integrating option pricing and decision analysis approaches. *Operations Research* **46**(2) 198–217.

Smith, R. P., J. A. Morrow. 1999. Product development process modeling. *Design Studies* **20** 237–261.

Thompson, M., M. Davison, H. Rasmussen. 2009. Natural gas storage valuation and optimization: A real options application. *Naval Research Logistics* **56** 226–238.

Trigeorgis, L. 1996. *Real Options: Managerial Flexibility and Strategy in Resource Allocation*. The MIT Press, Cambridge, MA, USA.

Tusiani, M. D., G. Shearer. 2007. *LNG: A Nontechnical Guide*. PennWell Corporation, Tulsa, OK, USA.

Van Mieghem, J. A. 2003. Capacity management, investment, and hedging: Review and recent developments. *Manufacturing and Service Operations Management* **5** 269–302.

von Hippel, E. 1990. Task partitioning: An innovation process variable. *Research Policy* **19** 407–418.

Wang, M. X. 2008. Supply chain management and economic valuation of real options in the natural gas and liquefied natural gas industry. Ph.D. thesis, Carnegie Mellon University.

Online Appendix

A. Glossary

AS: Ample server.

CQN: Closed queueing network.

FCFS: First come first serve.

FOLF: Floating offshore liquefaction facility.

LNG: Liquefied natural gas.

LNGC: Conventional LNG carrier.

LNGRV: LNG regasification vessel.

NPV: Net present value.

Option A: LNG network architecture using onshore-terminal regasification technology (see Figure 4(a)).

Option B: LNG network architecture using onboard regasification technology without transshipment (see Figure 4(b)).

Option B_1: LNG network architecture using onboard regasification technology with fixed-point transshipment (see Figure 5).

Option B_2: LNG network architecture using onboard regasification technology with no-wait transshipment (see Figure 5).

TL: Transshipment location.

TRAOT: Time-to-revenue advantage of onboard technology.

B. LNG and Regasification Technologies

The journey of LNG begins when natural gas, extracted from underground reservoirs, is sent to a liquefaction facility through a pipeline. At the liquefaction plant, the natural gas is cooled to minus 260 degrees Fahrenheit transforming it into LNG. LNG takes 600 times less space than natural gas, which makes it feasible to transport it over long distances. LNG vessels load LNG at the liquefaction facility and transport it to regasification terminals at remote demand locations. At these import terminals, LNG is warmed back to natural gas, and finally pumped into pipelines and sent to market.

There are two types of LNG import (regasification) terminals: onshore and offshore-onboard. At an onshore terminal an LNGC unloads its LNG cargo to the storage tanks of the terminal as depicted in Figure 1(a). LNG in the storage tanks is then regasified by the regasification unit and pumped into the local natural gas pipeline. At an offshore deepwater terminal (Figure 1(b)), LNG is regasified onboard specialized LNGRVs that connect directly a pipeline. The primary difference between onshore terminals and the offshore-onboard system is the regasification process: At a deepwater port, regasification is done onboard by an LNGRV, whereas at an onshore terminal LNG is regasified by the terminal.

As of October 2009, two offshore-onboard LNG import facilities operate in the U.S., the Gulf Gateway and Northeast Gateway facilities, complementing nine onshore-terminal facilities (FERC 2009). Gulf Gateway is located 100 miles off the Louisiana Cost and has been operational since 2005. Northeast Gateway is located 13 miles off the Boston coast and has been operational since 2007. Both terminals were developed by Excelerate Energy using the onboard LNG regasification and delivery technology called Energy Bridge.

C. Balance Equations for Fixed-point Transshipment based Onboard System Model

We partition the state space $\mathcal{M}$ into subsets according to the type of ship waiting for transshipment: $\mathcal{M}^-$ is the set of states where $W < 0$ (at least one LNGC is waiting for transshipment at Q_2), $\mathcal{M}^0$ is the set of states where $W = 0$ (no ship is waiting for transshipment) and $\mathcal{M}^+$ is the set of states where $W > 0$ (at least one LNGRV is waiting for transshipment at Q_1). Then, letting $\mathcal{I}\{\cdot\}$ the indicator function, the balance equation for each state $m \in \mathcal{M}$ can be formulated as

$\forall\ m \in \mathcal{M}^-$,

$$
\begin{aligned}
&\pi(W,n_1,n_2,n_3,n_5,n_6)[\mathcal{I}\{n_1>0\}\mu_1+n_2\mu_2+n_3\mu_3+(N_1-n_1-n_2-n_3)\mu_4+\mathcal{I}\{n_5>0\}\mu_5\\
&+n_6\mu_6+(N_2-n_3-n_5-n_6+W)\mu_7]\\
&=\pi(W,n_1+1,n_2-1,n_3,n_5,n_6)\mu_1+\pi(W-1,n_1,n_2+1,n_3-1,n_5,n_6)(n_2+1)\mu_2\\
&+\pi(W,n_1,n_2,n_3+1,n_5,n_6)(n_3+1)\mu_3+\pi(W,n_1-1,n_2,n_3,n_5,n_6)(N_1-n_1+1-n_2-n_3)\mu_4\\
&+\pi(W,n_1,n_2,n_3,n_5+1,n_6-1)\mu_5+\pi(W+1,n_1,n_2,n_3,n_5,n_6+1)(n_6+1)\mu_6\\
&+\pi(W,n_1,n_2,n_3,n_5-1,n_6)(N_2-n_3-n_5+1-n_6+W)\mu_7;
\end{aligned}
$$

$\forall\ m \in \mathcal{M}^0,$

$$\pi(0,n_1,n_2,n_3,n_5,n_6)[\mathcal{I}\{n_1>0\}\mu_1+n_2\mu_2+n_3\mu_3+(N_1-n_1-n_2-n_3)\mu_4+\mathcal{I}\{n_5>0\}\mu_5$$
$$+n_6\mu_6+(N_2-n_3-n_5-n_6)\mu_7]$$
$$=\pi(0,n_1+1,n_2-1,n_3,n_5,n_6)\mu_1+\pi(-1,n_1,n_2+1,n_3-1,n_5,n_6)(n_2+1)\mu_2$$
$$+\pi(0,n_1,n_2,n_3+1,n_5,n_6)(n_3+1)\mu_3+\pi(0,n_1-1,n_2,n_3,n_5,n_6)(N_1-n_1+1-n_2-n_3)\mu_4$$
$$+\pi(0,n_1,n_2,n_3,n_5+1,n_6-1)\mu_5+\pi(1,n_1,n_2,n_3-1,n_5,n_6+1)(n_6+1)\mu_6$$
$$+\pi(0,n_1,n_2,n_3,n_5-1,n_6)(N_2-n_3-n_5+1-n_6)\mu_7;$$

$\forall\ m \in \mathcal{M}^+,$

$$\pi(W,n_1,n_2,n_3,n_5,n_6)[\mathcal{I}\{n_1>0\}\mu_1+n_2\mu_2+n_3\mu_3+(N_1-n_1-n_2-n_3-W)\mu_4+\mathcal{I}\{n_5>0\}\mu_5$$
$$+n_6\mu_6+(N_2-n_3-n_5-n_6)\mu_7]$$
$$=\pi(W,n_1+1,n_2-1,n_3,n_5,n_6)\mu_1+\pi(W-1,n_1,n_2+1,n_3,n_5,n_6)(n_2+1)\mu_2$$
$$+\pi(W,n_1,n_2,n_3+1,n_5,n_6)(n_3+1)\mu_3+\pi(W,n_1-1,n_2,n_3,n_5,n_6)(N_1-n_1+1-n_2-n_3-W)\mu_4$$
$$+\pi(W,n_1,n_2,n_3,n_5+1,n_6-1)\mu_5+\pi(W+1,n_1,n_2,n_3-1,n_5,n_6+1)(n_6+1)\mu_6$$
$$+\pi(W,n_1,n_2,n_3,n_5-1,n_6)(N_2-n_3-n_5+1-n_6)\mu_7.$$

The steady state probabilities, $\pi(m)$, can be computed by solving the balance equations for all states $m \in \mathcal{M}$ simultaneously with the condition that these probabilities sum up to 1.