

**A SYSTEM DYNAMICS FRAMEWORK FOR DEVELOPING A LIFE
CYCLE COSTING MODEL FOR LIQUEFIED NATURAL GAS
DOWNSTREAM PRODUCTION SYSTEMS**

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ABSTRACT

Purpose of the study: This study proposes a qualitative System Dynamics (SD) framework for developing an LCC estimation model tailored to LNG operations.

Problem Statement: Life Cycle Cost (LCC) models are employed to enable strategic planning and allocation across all phases of LNG production, from feasibility studies to final investment and operational decisions. However, their development is inherently complex due to a spectrum of multifaceted, complex, dynamic, and interactive cost drivers.

Methodology: The framework utilised the Causal Loop Diagram (CLD) concept of SD to identify key LNG production cost-related variables and establish their interrelationship. The causal interactions of the factors were subsequently investigated after identifying the Feedback Loops (FBLs) generated from the developed CLD.

Results of the Study: At least twenty FBLs were identified in relation to activities spanning - feed gas supply, operation, maintenance, transport, and economics covering multiple cost drivers that include feed gas requirement, plant operation, Equipment Availability, Maintenance Action, total Cost of Production, and profitability. The analysis highlighted the LNG process as inherently goal-driven, with system stability and optimization emerging from the ongoing interplay among its interconnected subsystems.

Conclusion and Recommendation: By recognising the nature of these cost factors, this approach lays the groundwork for further expansion towards building a robust simulation model capable of supporting strategic decision-making and enhancing the accuracy of LNG project evaluations.

Keywords: *Life cycle cost, Liquefied natural gas, System dynamics, Causal diagram, Feedback loop.*

INTRODUCTION

A Product cost estimation model is an instrument for predicting the unit cost of a product to be produced in some future period under specified conditions. The importance of accurately assigning a cost to a product has become a critical consideration, as it can make or break the survival of businesses (Lepădatu, 2011; Lessner, 1991). Many budgetary decisions, including those made before actual production, planning, and profitability analysis, are based on such costs. Hence, the process of developing a model for estimating product cost is critical, as a model that overestimates may introduce some avoidable operational cost penalties (Fisher & Krumwiede, 2012; Oluwagbemiga et al., 2014). The same is true for an underestimate. Consequently, accurate costs should be correctly estimated from the time of business conception.

The severity of incurred penalty costs due to inaccurate estimates may vary from product to product, depending on the capital intensity of the business. The more capital-intensive the product, the higher the penalty may be. One such capital-intensive product in Nigeria is Liquefied Natural Gas (LNG). Currently, the industry is a major revenue-generating source for the country. For example, LNG exports in Nigeria produced a positive impact on the economy, leading to a 0.72 % gain in GDP (Udoudo et al., 2023). However, Nigeria, endowed with great natural gas deposits, has been flaring the gas for well over two decades (Adekomaya et al., 2016; Ejiogu, 2013; Elehinape et al., 2022). As a result of the large availability of readily available demand for natural gas and multiple suppliers (GIIGNL, 2025), the market has become increasingly competitive.

This implies that in the future, the Nigerian economy and any LNG export-dependent economy, for that matter, may well depend on how effectively and efficiently the LNG business is conducted. Being an internationally traded commodity with prices strongly influenced by marketplace-perceived supply and demand, as well as other macro-economic realities, competitive advantages can be achieved by the players only if major LNG projects are designed and run to attain the lowest unit cost (Odumugbo, 2010; Vazi & Bridle, 2024).

The totality of LNG supply involves multiple large capital expenditure requiring tasks and activities that cover all the production stages. Due to the high cost of investment and the need to match available demand with existing supply resources, it has become commonplace for potential investors to carry out a life cycle cost estimation of the LNG project to establish its viability before embarking on its large-scale implementation. This activity is of particular importance because

poorly evaluated projects could negatively impact the cost of the project completion, as it did in the case of the Gorgon LNG project (Habibullah & Kikkawa, 2018).

Some of such activities include the feasibility study of the LNG project undertaken towards making the Final investment decision (FID) for the desired project (Songhurst, 2018). In situations where the FID is favourable, focus is then shifted to the construction of the base liquefaction in the form of Greenfield and Brownfield plants (Russell & Adams, 2018). In addition, during the LNG operation phase, there are other concerns in the value-added chain, including those of natural or feed gas transportation and pre-processing, gas-to-LNG conversion operations, as well as LNG transportation and delivery operations. Furthermore, there is also the need to undertake detailed strategic planning regarding equipment conditioning and maintenance during plant operating periods. All these activities have huge cost implications.

This calls for the use of sophisticated product cost estimation models at the business conception stage. One such model, with potential to be a useful decision-support instrument for selecting appropriate LNG plant location, design, procurement strategy, production management, etc., for long-term plant reliability and customer services, is life cycle cost (LCC) estimation.

The LCC estimation is an all-product-lifespan-activities process to costing that involves the analysis of the costs of a system over its entire life span to quantify its total cost of ownership (Dhillon, 2010; Emblemståg, 2003; Farr & Faber, 2019). The process allows for the creation of scenarios based on assumptions about future cost drivers in the areas of research and development, construction, production, operations, maintenance, retirement, and disposal. These costs are incurred at different times in the life cycle of the system. The scope and complexity of the life cycle cost analysis, the ability to predict future costs, and the significance of the future costs to the decision being made by the organization are generally dependent on the complexity of the operating system (Emblemståg, 2003; Farr & Faber, 2019).

Developing an LNG life cycle cost estimation model with desired accuracy is, however, an intractable process. It is made complex by the nature of the LNG operation structure, which has many interrelated business processes, a long product life span, and whose activities are usually impacted by unpredictable, risky events. Historically, such cost estimation models are usually mathematical, statistical, and/or simulated (Sievanen & Tornberg, 2002; Tagliaferri et al., 2017; Tamura et al., 2001).

As earlier inferred, model accuracy is the main criterion for selecting suitable models. However, model accuracy is a concept that depends on a large number of factors ranging from data attributes to a variety of product-related man-machine activities. Perhaps, the complexity of the concept and its implications for model development may be better appreciated when some of these factors are outlined. Derived from the LNG value chain, the following are some of such factors: (i) Business conception activities including market survey; (ii) Business partnership transaction activities; (iii) LNG Plant design and construction activities; (iv) Personnel acquisition activities; (v) Material supply activities; (vi) LNG Production activities; (vii) LNG management activities; (viii) LNG Facilities maintenance activities; (ix) LNG Facilities expansion activities; (x) Product storage and distribution activities; (xi) Product retirement activities; (xii) Product life span (xiii) Uncertainty of future events and (xiv) Causal factor interactions.

In addition, the type of Mathematical/statistical/simulation model applied may affect accuracy. It may be noted that the accuracy of a model will depend largely on the extent to which it can capture information on all the aforementioned factors. The more factors incorporated in a model estimating structure, the higher its likelihood to increase its degree of accuracy and vice versa. Thus, a model developer should capture as many relevant factors as possible in a single model.

Unfortunately, most mathematical, statistical, simulation, and even knowledge-based models have limitations. Hence, the chance of a single model accounting for all possible factors is slim. Many static and deterministic mathematical models account mostly for data captured on the activities, but fail to reflect time-based changes, uncertainty, feedback information, delays, and factor interactions (Glerum, 2014; Kowgier, 2022). Statistical models are, however, able to cater to the activities and uncertainty but are weak in accommodating time-based changes, the incorporation of timely feedback data, and interactions. Simulation models that incorporate mathematical and statistical functions have been found to accommodate more factors, including time-phased activities, environmental changes, uncertainty, feedback, and some degree of factor interactions.

It is worth noting that previous LNG cost and related estimates were made as projections of historical annual operating cost data using either time series analysis, regression analysis, or statistics combined with engineering economic tools (Asa & Nautwima, 2025; Budiyanto et al., 2023; Hönig et al., 2019; Raj, Suman, et al., 2016). The implicit assumption is that previous LNG operations are satisfactory, therefore advantageously replicable for the future. This, of course, may not hold given the increasing influences of uncertainties and global competition over time.

Future operating conditions may require new adaptive operating and management strategies for improvements and survival. For example, the use of timely operating feedback data for effective LNG plant control decisions. This is a feature lacking in some of the reported approaches. Besides, product unit cost behaviour may display transient and convergence characteristics with time. It is when the cash flow rate, wellhead gas supply rate, manpower supply rate, steady plant supply rate, and energy supply rate are balanced that unit cost may converge to a minimum value. Hence, these resource flow rates are desirable operating parameters. They give rise not only to minimum unit cost but also to maximum LNG plant production flow rate. Of course, a process capable of determining these values may also require knowledge of causality-based interrelationships between LNG production factors. It thus appears obvious that, in the process of accurate LNG cost estimation, the following issues require attention:

- (i) Establishment of the causality-based relationship between a set of LNG process governing factors;
- (ii) Development of a decision-support model for the timely provision of LNG operating data feedback for automatic process control; and
- (iii) Determination of desirable LNG operating resource flow rates.

One approach that easily combines various types of mathematical and statistical functions, computer logic, and usually gives birth to continuous event simulation models is System Dynamics. Thus, it is intuitively appealing to apply systems dynamics modelling principles to model all the LNG serially related activities, parallel operating facilities, life cycle events and the associated environmental time-based changes as operating cost contributors. This work is an attempt to develop a framework for LNG life cycle costing model using a qualitative systems dynamics approach to (i) identify basic LNG life cycle cost-related variables and parameters and (ii) determine the interrelationships among the identified variables and parameters.

Since the LCC analysis for LNG production plants is complex and involves many interacting and feedback cost factors, a systematic approach to its estimation possesses the capability to recognise both the effects of cost factors on one another and on the complete system towards the attainment of the goal of the project owner. It is expected that this work will serve as a foundation for the development of a robust simulation model for the evaluation of the LCC of LNG projects.

LITERATURE REVIEW

The LNG industry is concerned with the exploration for and mining of NG, the conversion of NG to LNG, including its distribution and delivery. Thus, the recent emphasis on its LCC is largely tied to the upstream, midstream, and downstream sectors of the industry (Harraz, 2016; Inkpen & Moffett, 2011; Petro Online, 2014). However, this study focuses on the life cycle costing of the downstream sector, and as such, the NG conversion (liquefaction) and transportation activities are further discussed.

Liquefaction is the process of converting natural gas through heat removal over a wide temperature range. For any liquefaction process to be successful, a functional liquefaction plant located onshore and offshore facilities must be available (Gallagher, 2018; Songhurst, 2018). As a result of the scale of the NG conversion operation, coupled with the corresponding energy requirements and process efficiency, all conditions that affect liquefaction operations and plant construction must be carefully considered. Some of such conditions include have been classified into technical [process type, efficiency, reliability, site conditions, environmental impact) and economic conditions (upfront capital expenditure [CAPEX] and operating expenditure [OPEX] over the expected plant lifetime] (Castillo et al., 2010; Khan et al., 2017).

Another important aspect of the LNG downstream value chain is transportation. It entails the distribution of products to consumers. In recent times, a rough estimate of the cost of carrier charter has been estimated to be as high as 20 to 50% of the delivery price of LNG (Bipul, 2016; Eikens, 2020; Molnar, 2022; Shakirov, 2020). As such, a thorough estimate of LNG shipping cost is crucial as it is critical in driving decisions regarding the life cycle cost (LCC) of LNG projects.

Life cycle cost models are methodologies that produce cost estimates as outputs formulated based on a set of mathematical or statistical relationships and are differentiated based on the linearity and non-linearity characteristics of the costing methods. They can be classified as Linear Homogeneous, Optimisation, Quasi-Dynamic, Estimation, and Dynamic models.

Linear Homogeneous models, also called ‘constant returns to scale’ models, refer to LCC models in which the model output is proportional to the inputs and, as such, is scaled equally to the latter (Seuring et al., 2008). The Optimisation LCC models, on the other hand, are those in which the LCCs are done using optimisation approaches. These approaches could be mathematical programming or heuristics. The quasi-dynamic LCC models refer to those models that act as a

compromise between static (steady-state) and dynamic models. They may include time series, Markov chains and Markov processes (Research And Technology Organisation, 2007).

The dynamic model category involves the use of simulation methodologies such as Monte-Carlo methods, system dynamics and discrete event simulation to explain system costs that develop over time (Research And Technology Organisation, 2007).

The literature reveals that LNG LCC models are sparse. It could be speculated here that this sparsity could be attributed to the scope of the costing process, which is mainly client-contractor specific. As such, there may be a desire by the clients and contractors to keep information outside the public domain. Nonetheless, a few attempts observed to have been made in this area and are highlighted here.

One of such provided the basis for the integration of various LNG cost elements, with emphasis placed on the use of time value of money and internal rate of returns as system evaluation parameters (Coyle et al., 1998; Kawauchi & Rausand, 1999). Another analysis of the Nigerian LNG project as a new entrant into the global LNG supply market, with a focus on upstream, midstream, and downstream sectors of the project, using global liquefaction (Agbon, 2000). Hirschhausen et al. (2008) carried out a lifecycle-based financial viability analysis of an LNG regasification terminal based on factors such as investment costs, LNG volume regasified per annum, NG and LNG prices, as well as considerations for annual price increases, staffing, and interest rate.

Omar (2016) undertook an LCC analysis of a liquefaction process in Malaysia, with the major focus being the chemical and thermal process costs of LNG conversion. Similarly, Raj, Ghandehariun, et al. (2016) undertook a 25-year techno-economic assessment of a 2-train, 10 MTPA LNG facility in Canada. Nagi et al. (2016) undertook a time-value-of-money-influenced economic comparative analysis of LNG technology and gas-to-liquid (GTL) technology of the Nigerian natural gas production environment based on multiple technical and economic factors. The study results concluded that the LNG production venture was profitable. However, the input data utilised were mainly obtained as estimates rather than from actual source extraction.

A costing analysis based on the use of capital budgeting methodology was used to determine the profitability of the oil and gas investment project in Vietnam (Mentari & Daryanto, 2018). Hönig et al. (2019) carried out a techno-economic evaluation of commercial LNG production in the

European Union (EU). The technical evaluation procedure involved a quantitative analysis of the NG purification and liquefaction processes. The economic analysis involved an assessment of the viability of the LNG production operation. Da Silva Sequeira (2019) undertook an economic viability study of the life cycle of the LNG business in comparison to that of the gas-to-liquid (GTL) process using the Monte Carlo simulation method with consideration for 12 LNG technical and operational factors.

The author observed from the conclusions of the highlighted works that the economic performance of LNG production was mostly affected by the CAPEX, product selling price, feed gas price, and plant efficiency. Further results revealed that the LNG projects investigated were more profitable and attractive (in terms of the NPV and profitability index) as the plant capacities were lower.

From the highlights of the LNG LCC models, it is clear that although the authors recognized the complex, dynamic, and transient nature of the LNG production environment, virtually all quantitative cost estimate methods used for analysis were either deterministic models, statistical, or time series. However, the nature of the LNG system requires a thorough understanding of the cause-and-effect behaviour of the factors affecting such systems, and how they relate and interact within the dynamic environment.

These interactions may not be clearly understood with the costing models previously used for LNG LCC. In addition, it is already well understood that dynamic systems, such as those for LNG production, are incorrectly defined without the presence of feedback (Adekoya & Gidiagba, 2024; Ashkanani & Kerbache, 2023; Borelli et al., 2021; Hu et al., 2014). These feedback features, which can serve as decision support systems and potentially influence new adaptive operating and management strategies, aiding organisational improvement and survival in the LNG production environment, are lacking in the use of the reported models.

It is also clear from the literature that the outcomes of the profitability and LCC analysis from the previous reports provide useful information for LNG investments. However, little focus was placed on specifically understanding the degree to which the availability and reliability of the liquefaction equipment and shipping vessels impacted LNG process efficiency. This may have been due to the limitations inherent in the Life cycle costing approaches deployed in the reported works.

System dynamics (SD) is a time-based modelling method that captures the activities of a system over time (Kunc, 2024; Sterman, 2000; Wang et al., 2021). It allows the inflow and outflow of information and materials through states described in time. Some of its major characteristics include its structural allowance for the development of flow and state control behaviour, and its long scope of study. The method also possesses the ability to analyse systems characterised by non-linearity, uncertainties, and transience based on causal relationships, interactions, and feedback (Fabolude et al., 2025; Hamoudi et al., 2021; Hoffmann et al., 2025). System dynamics has been highly recommended for LCC analysis, and the methodology is considered appropriate for improving the limitations of the reported models (Pinto et al., 2019; RTO, 2007). This is because of its ability to incorporate factors of causality and feedback, as well as the provision of a larger pool of information. However, the use of this approach in LNG life cycle costing appears sparse. This, alongside the previously highlighted gaps, motivates this study.

METHODOLOGY

Before developing the conceptual framework for the life cycle costing of liquefied natural gas downstream production systems, secondary information obtained from the literature was used to study LNG production procedures and practices in ten LNG production plants located in various parts of the globe. Afterward, a real-time LNG production firm operating in Nigeria was considered. After permission was sought and approval obtained, two months were spent observing the firm's real-time production activities.

In addition, personal interactions and interviews were conducted with seven randomly selected plant engineers responsible for LNG production management and administration. Using the information obtained from these activities, three sectors were identified to exist in the LNG system. The identified sectors (Table 1) comprise specific units, including financial, production, and maintenance management, which are responsible for managing various activities within the plant to ensure plant availability and, in effect, an optimal production process. The structure of the LCC for an LNG plant was subsequently developed based on three optimisation goals, which are: (1) Maximisation of equipment availability, (2) Maximisation of the volume of LNG produced, and (3) Minimisation of the total LNG production cost

The developed LCC framework for LNG production is described in the Causal Loop Diagram (CLD) [Figure 1]. The CLD illustrates various operational and decision-making activities essential for the operation of the LNG process, their interdependencies, and the corresponding impact on the LCC of the process.

The framework describes the start of the LNG process from the point of capital (equipment) acquisition and the availability of a budget for operational expenses (Table 1). These are the two activities on which all production, maintenance, and product supply operations depend for a successful LNG business process. On the condition that feed gas (raw materials) made available from upstream activities, the conversion process of the feed gas into the final product is completed using acquired equipment, dependent on the availability of a qualified hired operations workforce personnel (Human resources).

Plant operations, however, are dependent on the availability of equipment. The task of ensuring equipment availability is the responsibility of the maintenance personnel (Human Resources). The maintenance personnel are responsible for carrying out various maintenance actions on the deteriorating/degraded equipment to ensure a continuous LNG production process. This will be evidenced by a reduction in equipment deterioration and, by extension, equipment and plant availability.

The LNG production process will be incomplete without consideration for the product transport (Figure 1). Typically, in such systems, depending on the scale of LNG produced, the product can be transported using different transportation modes, including trucks/rails and by sea (USDA & USEA, 2016). Distribution of small-scale LNG products is usually carried out by trucks/rail. This is especially necessary where demand centres are remotely located or access/construction by pipelines is impractical.

Table 1: LNG production system breakdown into various sectors, specific units within the sectors and the activities for which they are responsible

LNG Sectors	Specific Units	Activities
Financial	1. Budgeting/Funding	1. Estimation of costs (initial and running) related to plant location,
Management	2. Economic Analysis	upstream facilities, liquefaction, construction, bulk materials, maintenance, feed gas supply, and LNG production (CAPEX and OPEX).
		2. Identification of cost drivers and LCC estimation

		3. Determination of unit LNG production cost and cost of deferred production.
		4. Determination of periodic profits/losses obtained from the LNG operations
		5. Estimation of various operational economics evaluation indices.
Production	1. Liquefaction operation	1. LNG production from feed gas
Operation	2. Production personnel management	2. Production Process monitoring
	3. Shipping	3. Securing the required manpower for operational activities.
Equipment	1. Equipment maintenance	4. LNG transportation from production to the point of demand
availability	operation	1. Maintenance of equipment and production units
Management	2. Maintenance personnel management	2. Equipment and monitoring, and conditioning
	3. Inventory management	3. Installations and modifications
		4. Ordering, storage, and supply of materials and equipment spares for operations and maintenance services.

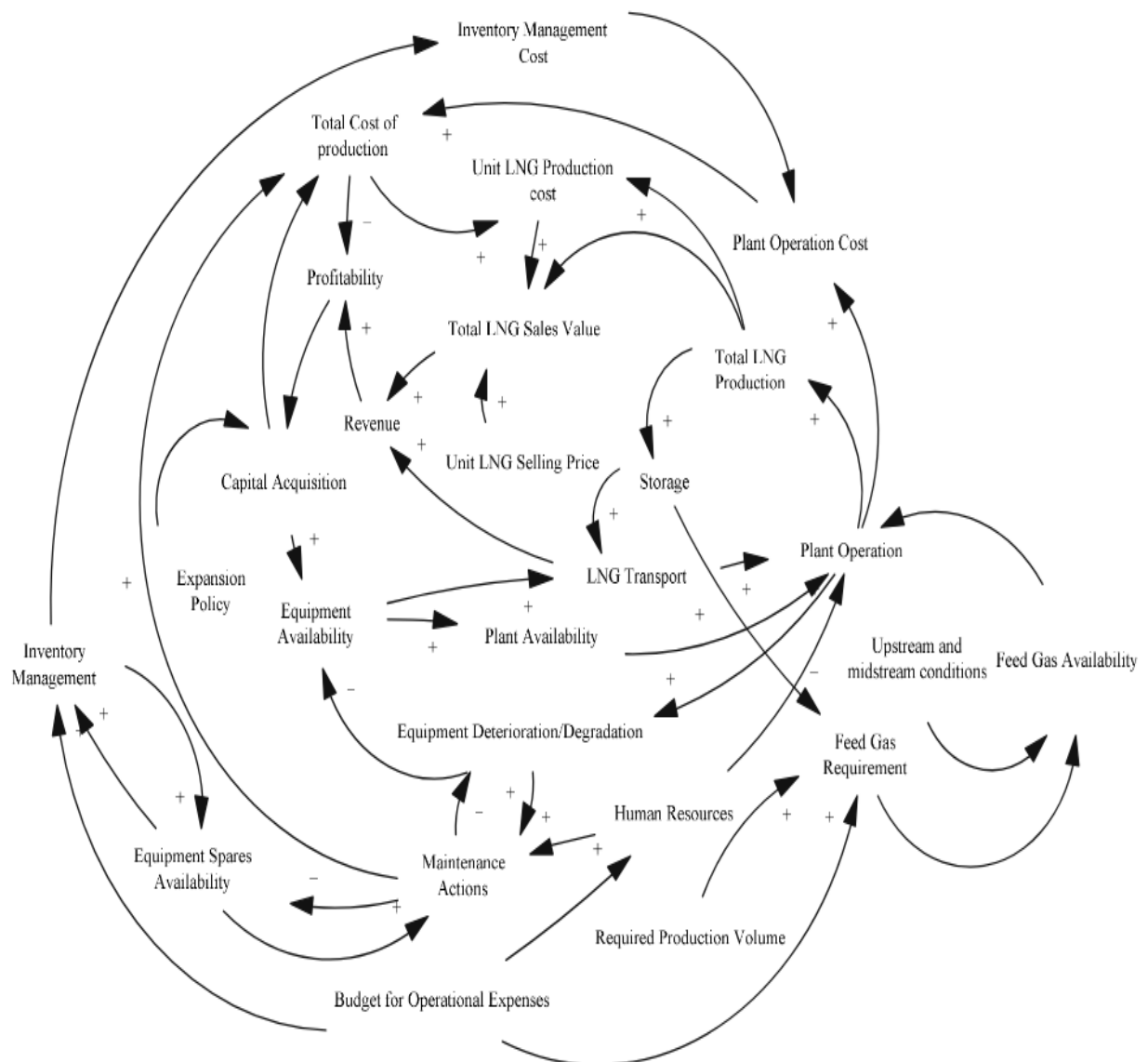


Figure 1: Causal Loop Diagram of the Life Cycle Costing Model for Liquefied Natural Gas Production Systems

Concerning large-scale LNG production, where product demand is primarily concerned with export or offshore LNG delivery, the most convenient means of transport is via sea routes (Raj, Ghandehariun, et al., 2016; Sinha & Wan Nik, 2012; Tu, 2019). This process involves the use of shipping vessels that have been designed specifically for LNG carriage and transport across sea routes. These types of shipping vessels, called LNG carriers, are typically very large double-hulled and insulated sea vessels due to the peculiar nature of the transported product.

In this framework, the possibility of LNG being shipped is dependent on the availability of the vessels on the one hand and the availability of the finished product on the other. Vessel availability will strongly depend on several factors, including the charter cost, type

of propulsion system, number of vessels required to ship available LNG, and ship maintainability.

The framework also considers spare parts replacement and their availability through inventory management, regarding how they affect downtime and, in effect, the LNG production process (Table 1). It can be seen from the causal diagram (Figure 1) that maintenance actions reduce the availability of equipment spares. This triggers an inventory management decision on part orders conditioned on the availability of implementable operational budget appropriated for such purpose.

The LCC of the LNG production system is analysed in terms of the product unit and total cost of production, where the latter can be observed to be influenced by the cost of all plant operations and, in this case, the costs of capital acquisition, feed gas, human resources, spares management, equipment maintenance, shipping cost, and vessel maintenance. Furthermore, project profitability was also given due consideration. This was modelled to ascertain the viability of the venture based on the completion of LNG production (conversion – shipping).

Thus, the project profitability is influenced by the revenue and the total cost of LNG production (Figure 1). It can be further observed that profitability (perceived or actual) can further drive LNG production expansion, dependent on the expansion policies of the business owners. A clear example of this can be found in the Nigerian LNG project, which has implemented multiple expansion phases via the addition of more than four LNG trains over the twenty-five years of its operation. It can be speculated that one of the driving factors for this lies in the profitability of the venture, given that dividends, an indication of profits, have been paid annually since 2004 to stakeholders.

The interrelationship existing among some of the identified life cycle cost quantities was investigated by focusing on the feedback loops (FBL) that were created in relation to the quantities.

RESULTS AND DISCUSSION

From the developed causal diagram (Figure 1), more than twenty feedback loops (FBLs) were identified in relation to the operation, maintenance, supply, and economics of the LNG venture. However, for discussion, seven FBLs identified in relation to Raw material usage (Feed Gas Requirement), Production (Plant Operation), Maintenance (Equipment

Availability, Maintenance Action and Effective Inventory Management), economics (Total Cost of Production and profitability) [Table 2 and Figure 2] are discussed.

Table 2: LNG life cycle cost parameter interrelationship for Total Cost of Production Feedback Loops

Feedback Loop	Interrelationship (s)
Equipment Availability (EA1)	Equipment Availability-->Plant Availability-->Plant Operation-->Equipment Deterioration/Degradation-->Equipment Availability
Equipment Availability (EA2)	Equipment Availability-->LNG Transport Plant Operation-->Equipment-->Deterioration/Degradation-->Equipment Availability
Feed Gas Requirement (FGR)	Feed Gas Requirement-->Feed Gas Availability Plant Operation-->Total LNG Production-->Storage-->Feed Gas Requirement
Effective Inventory Management (EIM)	Effective Inventory Management --> Maintenance Management Cost -->Plant Operation Cost -->Total Cost of production --> Profitability --> Capital Acquisition --> Equipment Availability --> LNG Transport Plant Operation --> Equipment Deterioration/Degradation --> Maintenance Actions --> Equipment Spares Availability-->Effective Inventory Management
Maintenance Actions (MA)	Maintenance Actions-->Maintenance Management Cost-->Plant Operation Cost-->Total Cost of production-->Profitability-->Capital Acquisition-->Equipment Availability-->LNG Transport-->Plant Operation-->Equipment Deterioration/Degradation-->Maintenance Actions
Profitability (P1)	Profitability-->Capital Acquisition Equipment Availability-->LNG Transport Plant Operation (PO)-->Equipment Deterioration/Degradation-->Maintenance Actions-->Equipment Spares Availability-->Effective Inventory Management-->Maintenance Management Cost-->Plant Operation Cost-->Total Cost of production-->Unit LNG Production cost-->Total LNG Sales Value Revenue-->Profitability
Profitability (P2)	Profitability-->Capital Acquisition-->Equipment Availability-->Plant Availability-->Plant Operation-->Equipment Deterioration/Degradation-->Maintenance Actions-->Maintenance Management Cost-->Plant Operation Cost-->Total Cost of production--> Profitability
Storage (S)	Storage-->Feed Gas Requirement-->Feed Gas Availability-->Plant Operation-->Total LNG Production-->Storage
Total Cost of production (TCP1)	Total Cost of production-->Unit LNG Production cost-->Total LNG Sales Value-->Revenue-->Profitability-->Capital Acquisition-->Equipment Availability-->LNG Transport-->Plant Operation-->Equipment Deterioration/Degradation-->Maintenance Actions-->Equipment Spares Availability-->Inventory Management-->Maintenance Management Cost-->Plant Operation Cost--> Total Cost of production
Total Cost of production (TCP2)	Total Cost of production-->Unit LNG Production cost-->Total LNG Sales Value-->Revenue-->Profitability-->Capital Acquisition-->Equipment Availability-->LNG Transport-->Plant Operation-->Equipment Deterioration/Degradation-->Maintenance Actions-->Maintenance Management Cost-->Plant Operation Cost--> Total Cost of production

Total Cost of production (TCP3)	Total Cost of production-->Unit LNG Production cost-->Total LNG Sales Value--> Revenue Profitability-->Capital Acquisition-->Equipment Availability-->Plant Availability Plant Operation-->Plant Operation Cost-->Total Cost of production
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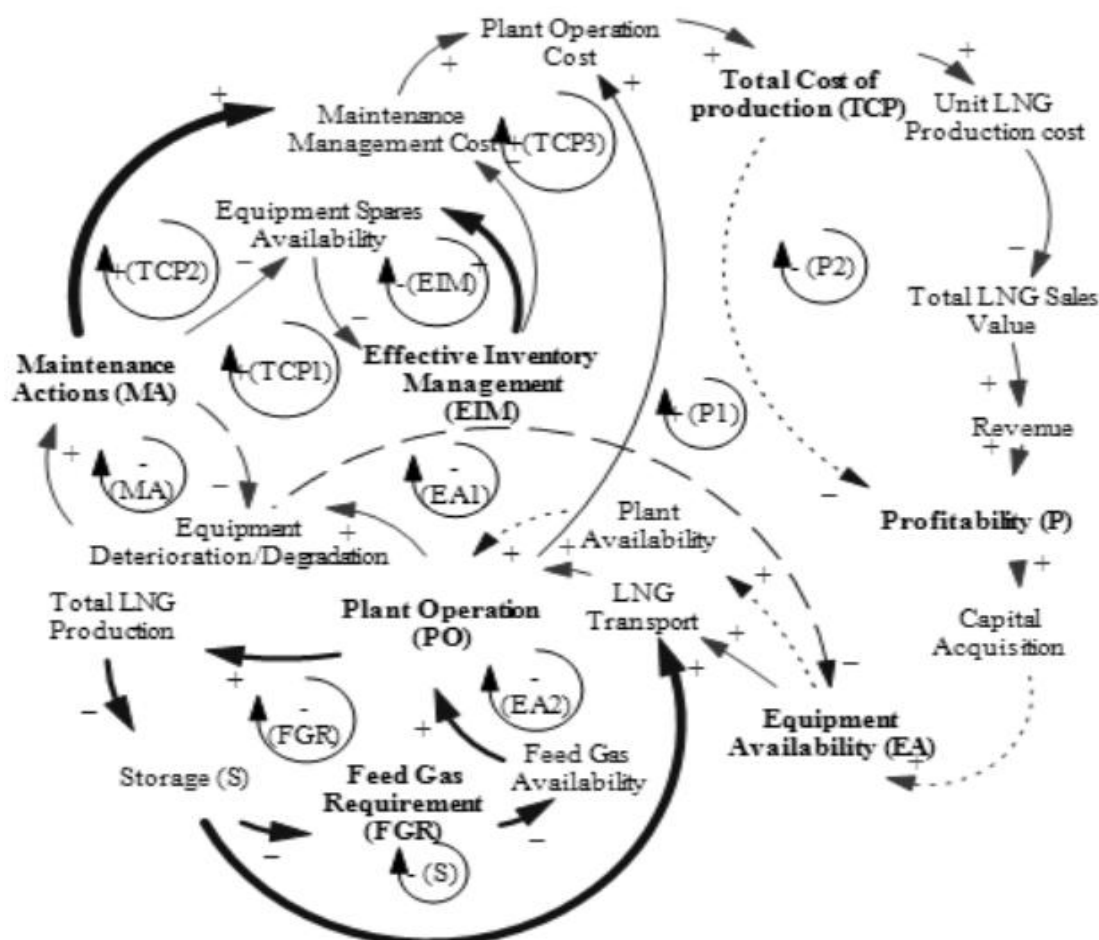


Figure 2: Feedback loop information for various LNG LCC-related quantities

(i) Feed Gas Requirement

Regarding the FGR balancing FBL scenario, we observe how FGR drives the need for feed gas supply and availability for production purposes. If adequate feed gas is available, increased plant operations are possible, subject to the availability of the LNG plant and shipping vessels. This leads to an increase in the total LNG production, putting pressure on the availability of the storage facility. A decreasing storage capacity reduces the feed gas requirement and, by extension, the feed gas availability. This implies that there is a need to investigate the impact of feed gas supply from the upstream sector on the viability of LNG projects.

(ii) Plant Operation

Increased plant operation increases total LNG produced. This situation increases the volume of LNG in storage, putting pressure on the need to ship out the finished product. If the shipping vessels and related conditions are favourable and supply contractual agreements are in place, LNG transportation is increased. Thus, it is possible to further model this scenario as two balancing FBLs (-S and -EA2) to describe the conditions that encourage increased LNG shipping as it is affected by plant storage system and shipping vessel availability.

Another FBL scenario affecting plant operation is the negative FBL (-EA1), which shows that an increase in plant operation increases equipment deterioration. This can lead to equipment failure and, by extension, a reduction in plant availability. If adequate maintenance management strategies and policies are not adopted and implemented, the situation can limit further plant operations. This framework can be expanded to study the impact of equipment maintenance on plant availability and LNG production. The impact of maintenance on transport vessel availability and its effect on LNG Production via plant operation (-EA2) can also be studied using a similar concept.

It can be clearly observed from Figure 2 that plant operations are affected by several FBLs, including -FGR, -EA1, -EA2, -MA, and -EIM. One significant observation of the nature of these FBLs is that they are all goal-seeking in nature. This implies that LNG plant operations are affected by multiple factors that include raw materials, equipment availability, plant and shipping vessel maintenance management factors, seeking to provide stability to the LNG production process. As such, modelling LNG plant operation cannot be done in isolation from these subsystems.

(iii) Maintenance Management

Liquefied natural gas operations require the use of several types of equipment, including heat exchangers, turbines, compressors, shipping vessels, and ancillary equipment. The operational availability and reliability of this equipment affect the cost and profitability of the business. Equipment available ensures continuous production, lowered turndowns, and shutdowns due to increases in system failure rates. It also reduces the likelihood of attaining in terms of LNG production, the expected design capacity. Thus, for this to be

made possible, total maintenance strategies must be adequately implemented (Kwang Pil *et al.*, 2008; Gowid *et al.*, 2014, 2015).

One of the ways of achieving this is through the use of effective maintenance action (MA) and inventory management (EIM) strategies. The FBL of MA describes the balancing impact of various MA policies on equipment deterioration and the corresponding effect of the latter on the former. Clearly, as equipment function degrades due to usage, it signals for increase in MA towards countering the deterioration. However, MA activities, such as corrective and preventive activities, usually require the use of materials/spares if available. This creates demand, supply, and inventory management decision issues. For example, which spares should always be available in the store and which should be ordered when required? What lead time policy should be adopted to enhance effective supply management? Another decision problem would be requiring a solution in understanding the effect of maintenance action in terms of frequency and quality on equipment spares availability. These FBLs observed in the framework possess the potential for expansive modelling and investigation, especially with respect to SD-based characterisation, prediction reliability monitoring of different equipment required for LNG production.

(iv) LNG Production Economics

The LCC of an LNG project will be considered acceptable and worth investing in if the economic performance of the project is satisfactory or acceptable. Economic models that give consideration to production cost, revenue, and profitability are usually deployed to arrive at the state of an LNG project's economic performance. The total cost of production (+TCP) and Profitability FBLs were identified to cater to this aspect of the project.

The +TCP are FBLs that constitute the +TCP1, +TCP2, and +TCP3, that is, positive reinforcing FBLs that account for the cost interactions related to maintenance inventory management, maintenance actions, and plant operation. Within the quantities that make up these FBLs, it is necessary that considerations are given to cost driver quantities, such as shipping costs and workforce management costs. It is worth noting that the +TCP feedback loop also influences sales and revenue (Figure 2). The FBLs are vital for tracking to ensure cost transparency, retrieving feedback from cost data, identifying waste and bottlenecks, and streamlining operations.

The interactions that capture the extent of attractiveness of the LNG project investment and by extension its sustainability are captured by the profitability FBL (+P1 and -P2). The +P1 and -P2 capture the dynamics that affect the interacting quantities, which result in revenue generation and production costs, respectively. As can also be observed in Figure 2, the FBL houses the interactions that influence reinvestment decisions (capital acquisition). This provides the platform for improving production operations, portfolio optimisation, and capacity expansion, improved future profits, and operational efficiency. This is an especially vital feedback loop in a capital-intensive venture such as LNG production.

CONCLUSION

With the goal of overcoming the complexities of existing mathematical models, precise analysis of scenarios, and efficient estimation of vital LNG business parameters, this work proposed a System Dynamics framework for estimating the life cycle cost of LNG production systems. The multilayered approach framework utilised the system thinking approach in the development of a qualitative Causal Loop Diagram (CLD) model with the aim of providing a holistic understanding of the complex interrelationships that exist among LNG production cost drivers. The CLD shows the dynamic interplay between capital investment, operational budgeting, plant operations, human resources, equipment maintenance, and product supply, quantities which are essential for efficient and sustainable LNG production.

The analysis of the developed CLD reveals a complex and interdependent network of feedback loops that govern the operational, maintenance, supply, and economic dynamics of LNG production systems. The ten key feedback loops discussed, spanning feed gas requirement, plant operation, maintenance management, and production economics, highlight the goal-seeking nature of the LNG process, where stability and optimisation are achieved through continuous interaction among subsystems.

Altogether, the framework possesses the potential to serve as a tool for enhancing equipment availability, maximizing LNG output, and minimizing production costs, two key pillars for achieving operational excellence in LNG production.

RECOMMENDATION

The insights from this study affirm that LNG production cannot be modelled or managed in isolation. Instead, a systems-based analysis approach is essential for understanding the dynamic behaviour of LNG ventures and for guiding strategic decisions that enhance efficiency, reliability, and profitability. Based on this, the authors propose that future research could focus on a more detailed analysis of all the subsystems captured in the framework with a view to creating a holistic LNG LCC model that comprises most of the components that support and drive the overall system.

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