sustainability

Review

Sustainable Liquefied Natural Gas Supply Chain Management: A Review of Quantitative Models

Sara Al-Haidous and Tareq Al-Ansari *

Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha 34110, Qatar; salhaidous@mail.hbku.edu.qa
* Correspondence: talansari@hbku.edu.qa

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Abstract: Natural gas is an essential fuel in the transitions towards a sustainable energy future as it is considered a cleaner source of fuel when compared to other hydrocarbon sources. To enable natural gas delivery from the producer to consumers, natural gas is liquified to enhance transportation efficiency and reliability. The main contribution of this paper is to develop sustainable LNG supply chain through a review of different sustainable supply chain management tools and assessing their applicability in managing LNG supply chains. Energy security has evolved to include the protection of the entire energy supply chain and infrastructure rather than a consideration for the availability of resources alone. There is a particular focus on coupling sustainability and resilience/risk as part of the need to develop integrated approaches to manage energy supply chains to deliver cargo at minimal cost and environmental impact, and to ensure that supply chains can overcome vulnerabilities withstanding potential disruptions to the supply chain. Outcomes of this review demonstrate the possibility to develop multi criteria models, which consider sustainability dimensions within the LNG supply chains and to integrate parameters that form part of the annual delivery plan ensuring day to day LNG supply chain planning consider multiple objectives.

Keywords: closed loop; forward loop; optimisation; LNG; resilience

1. Introduction

1.1. Background

Considering climate change and rising energy security concerns, global markets require access to a clean and reliable source of fuel. Natural gas is a clean source of fuel when compared to traditional hydrocarbon sources such as oil and coal and is considered necessary towards the transition towards a sustainable energy future. As a relatively cleaner burning fuel in terms of greenhouse gas (GHG) emission, natural gas is expected to progressively replace high polluting oil and coal fuels for power generation, production of petrochemicals (ammonia, methanol, etc.), and the production of fuels for transportation fuel. Furthermore, natural gas is also a source of hydrogen, generating power within fuel cells with minimal emissions. As such, it can be considered a bridge fuel to clean hydrogen and a renewable energy-based economy [1].

Natural gas is considered one of the cleanest fuels available as it produces non-toxic gases such as carbon dioxide, water vapor, and a few nitrogen oxides upon combustion, unlike other hydrocarbons. Moreover, the process of using natural gas to generate electricity leads to considerably lower GHG emissions when compared to using coal as a fuel on megawatt per hour basis [1]. A study conducted in United States suggests that replacing coal power plants with natural gas power plants could shrink associated with GHG emissions by 22% [2]. Moreover, in most parts of the world, natural gas is widely used in residential units for cooking, drying clothes, space, and water heating purposes. For instance, half of the residential units in the United States used natural gas for heating in 2013, and more than 70% of the new homes contain gas heating systems [3]. In Europe, more than 45% of houses prefer to use gas-fuelled heating appliances [4].

Through rapid technological development, natural gas is now liquefied, to make transport more efficient and reliable through the use of specialised carriers. Considering the economics of scale, the supply chain of LNG is the cheapest per unit of all transport modes. At approximately −162 °C and atmospheric pressure, natural gas has usually transferred into a liquid state. This liquefaction process enables the natural gas to be reduced to about 600 times its original volume, this transformation state enhancing the supply chain transportation efficiency. Ongoing boom-bust cycles have caused prices to fluctuate, but so far, producers have been able to develop new supplies as needed to keep up with demand [5]. As a consequence of global LNG market growth, the complexity of supply chain management (SCM) has become more obvious, which necessitates the need for decision support systems driven by performance indicators that consist of tools in which outputs result can induce changes in operations.

Supply chain management is related to the entire flow of goods or services beginning from product development, sourcing, production, and logistics. SCM involves optimising the interconnection between the entities across the supply chain that can span across the globe to satisfy customer requirements in terms of cost and on-time delivery. As such, effective SCM extends beyond logistics and requires the integration between business operations and supply chain. Essentially, SCM aims to provide the necessary level of customer service to a specific segment with less amount of required resources [6]. Supply chains are classified into forward and closed-loop supply chain management. The forward supply chain is a system whose essential parts include the following; suppliers of material, production facilities, distribution services, and finally, the customers who is connected by the feed-forward flow of materials and information [7]. It is characterised by a supply chain in which there is no flow back from any stage to the previous steps, essentially an 'open loop supply chain' [8]. In contrast, closed-loop supply chain management requires a flow back from any stage to the previous steps. This kind of supply chain is more complex and requires more effort to control both forward and reverse logistics simultaneously. Within LNG supply chains, deterministic models are used to reduce randomness and involve the use of mathematical formulations to acquire a set of optimal solutions. From the sustainability perspective, optimal solutions involve environmental and economic objectives within the LNG annual delivery plan and the constituting variables. However, if uncertainty is introduced to the problem, stochastic approaches can be used to provide a measure for system robustness and resilience and robustness within the management of supply chains.

1.2. Review Structure

The main contribution of this review is to understand the tools and theory that can contribute towards the development of sustainable LNG supply chains. This will be conducted through a comprehensive review of different sustainable supply chain management tools and models, which have been conducted in various applications and assess their applicability in managing LNG supply chains. There is an additional focus on the coupling of sustainability and resilience/risk as part of the need to develop integrated approaches to manage energy supply chains. This is because the understanding of energy security has evolved to include the protection of the entire energy supply chain and infrastructure, rather than a consideration for the availability of resources alone. It ensures that supply chains deliver cargo at minimal cost and environmental impact, on schedule, and to ensure that supply chains can overcome vulnerabilities withstanding potential disruptions to the supply chain. In this regard, supply chain resilience is sufficient to address the difficulties faced by complex global supply chains in terms of vulnerabilities, uncertainties, and unforeseen disruptions. This review highlights the usefulness of integrating sustainability and resilience characteristics in the decision-making process across the different levels of supply chains. Furthermore, a comprehensive discussion on potential deterministic and stochastic methods that are used to evaluate sustainability dimensions within supply chains, namely economic, environmental, and social, in addition to the nature of the supply chain, i.e., forward or closed-loop supply chain management. Finally, this review provides insight into the necessary integration of sustainability dimensions and the possibility to use both deterministic and stochastic approaches within LNG supply chains.

The methodology implemented in this review paper involves a comprehensive discussion of peer reviewed and journal articles that are available in public, in the English language only, and published in recognized databases such as ScienceDirect, ResearchGate, MDPI, and Springer for the last 20 years. The main approaches reviewed as part of this study include mixed integer linear programming (MILP), discrete event simulation, quality function deployment, quantitative modelling approach, multi-criteria decision, and global optimisation algorithms. These tools have generally been used to evaluate sustainable supply chains because they are able to consider multiple objectives, which is necessary in the analysis of complex systems.

In addition to describing LNG supply chains, the next sections of this review highlight the conceptual basis of SCM and the possible intersection with the quantitative models considered. This review will form the basis of the future perspectives in the development of LNG supply chains.

The search for relevant journal papers is conducted using specific keywords that are related to the topic of review. This includes keywords and phrases that have appeared in the title or abstract of the searched papers, such as sustainability, supply chain, quantitative models, deterministic, and stochastic models. In this study, 31 papers are selected for the review, and 13 additional papers are mainly focused on the LNG supply chain resulting in a total of 44 reviewed articles and classified in Figure 1 into forward and closed-loop supply chain.

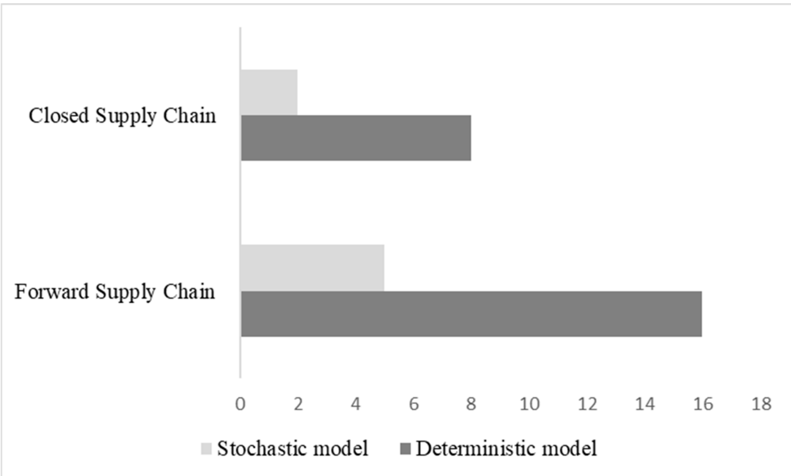

Figure 1. Number of published articles focusing on the application of the listed approaches.

2. LNG Supply Chain Management

Harmonious development across natural and built systems should consider how resources are extracted, processed, transported, and utilised. Understanding the three interconnected domains or pillars of sustainable development according to the triple bottom line (environment, economic, and social) and the way they relate to LNG supply chains is the basis of this study. The LNG supply chain illustrated in Figure 2, consists of extracting natural gas offshore and onshore, subsequent transfer through piping to processing plants where it is liquefied and stored, transported overseas in specially built tanks to a receiving terminal. At the receiving terminal, the LNG is returned to its gaseous state, where it is distributed through the pipeline to power stations and other natural gas consumers [9].

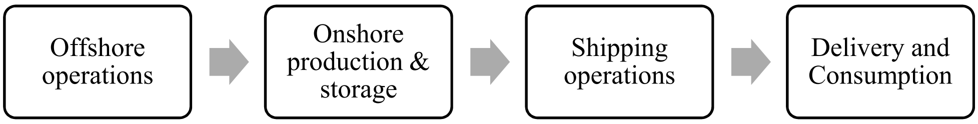

Figure 2. Main segments within LNG supply chains.

LNG Planning Levels

Maritime transportation challenges have unique practical and theoretical perspectives. From a practical perspective, maritime transportation is well aligned with economies of scale, promoting it as the cheapest per unit of all transport modes suitable for substantial industrial activities. From a theoretical perspective, solving maritime transportation problems optimally and within reasonable time frames may be problematic. In doing so, it is essential to consider the three LNG supply chain planning levels which operate at different time horizons.

Strategic planning is usually connected with political and social implications and is concerned with the rules and regulatory governance. In general, this level is uncertain because it is less data-intensive and requires lower quantities of information to represent the overall goal and vision of the supply chain. The annual delivery program (ADP) is situated in the tactical planning level. Fundamentally, the producer is obligated to deliver a certain quantity of LNG cargo to the customer annually as part of mutually agreed long-term contracts. These contracts have a duration of several years and indicate the annual delivery requirements. Furthermore, within delivery agreements, annual cargo spreads are determined, whether they are spread equally or linked to seasonal patterns. In this regard, actual delivery dates are determined to specify specific times or periods where customers can accept deliveries. As such, the LNG producer will need to develop multiple ADP's which operate in parallel and ensure that the needs of all customers are satisfied. The operational planning level consists of technical and logically oriented decisions. In terms of resource management, this stage is associated with analysing sectors from a process system perspective where risks and efficiencies are introduced. As such, fluctuations exist in LNG production due to planned or unplanned shutdown and seasonality in market variations, which impact LNG inventory. However, in order to operate in tandem with market dynamics, it is important that ADP's evolve to consider sustainability and resilience.

3. Sustainable Supply Chain Management

Sustainability is related to meeting the needs of the present without conceding the ability of future generations to meet their own needs. It is a process of maintaining change in a balanced and economically sound natural and built environment to meet human needs and aspirations. In the late 1990s, the integration between sustainability and supply chain management research gained prominence amongst scholars in the field [10]. Sustainability consists of balancing economic, environmental and social objectives which may conflict during the design and operation of supply chains. For instance, social sustainability aims to ensure the needs of the population are met. Whilst, economic sustainability is related to optimising the supply chain to minimise the total cost and to increase profits. Finally, environmental sustainability is associated with minimising the consumption of non-renewable resources and wastes, and limiting environmental impacts associated with the supply chain [11]. As such, developing an understanding for the sustainability dimensions and their interactions with supply chains is necessary.

The incorporation of sustainability objectives into business practices is a dynamic research avenue in the area of SCM. There is a vast quantity of businesses that have begun to embed sustainability in their processes. However, there remains a challenge to integrate sustainability across the whole supply chain [12]. As such, in the context of sustainability, several research challenges need to be overcome in supply chain design, which includes but are not limited to multi-scale, multi-objectives, and multi-stakeholder challenges. Ultimately, in the development of sustainable supply chain management (SSCM), two main objectives should be achieved; (1) performance assessment of SSC and

(2) integration of sustainable dimension operations [13]. A review of the integration of sustainability dimensions in the supply chain design and assessment is provided below.

3.1. Environmental Dimensions

A high performing supply chain from an environmental perspective alludes to efficient resource utilisation, the reduction and recycling of waste, and mitigation of emissions and pollution [14]. Environmental sustainability can assess by considering resource efficiency (energy and material), water and waste management, emissions, land use, environmental compliance, and supplier assessment [14]. A comprehensive review of how environmental sustainability practices are diffused across the supply chain is presented by Pimenta and Ball [15]. The review was conducted based on the three-main upstream SCM activities; management of purchasing, assessment of performance, and cooperation. The integration between industrial ecology and industrial symbiosis to develop a conceptual framework for environmental SSC developed by Leigh and Li [16]. Furthermore, Acquaye et al. [17] analysed the carbon footprint by developing a robust, sustainable environment performance model that is reinforced by an industrial lifecycle thinking approach. Life cycle assessment (LCA) is a tool used extensively to study and evaluate environmental impacts for a certain product or process throughout their lifecycle [18], from raw material extraction through to processing, transport, use, and finally disposal [19]. Society of Environmental Toxicology and Chemistry, defined the following four distinct stages of LCA [20]:

- Define the goal of the assessment and scoping of the study;
- Prepare the inventory of input and output for the processes that occur in the product's life cycle;
- Assess the impact where the results of the inventory are transformed into an environmental impact profile for the product system;
- Interpret the impact according to the defined goal and scope of the study, including a sensitivity analysis of key elements in the assessment.

3.2. Economic Dimensions

Economic and environmental dimensions are directly related to one and other, such as the recent empirical and theoretical analysis of the Porter hypothesis [21]. Economic performance metrics mainly pertain to financial returns or accounting-based metrics [22]. Economic sustainability predominately outlines the continuity, distribution, and flow of financial resources across an organisation's stakeholders, and the impact on the environment and society [23]. The economic performance of such systems can be measured by considering stability and profitability, income distribution, market competitiveness, and sustainability expenditures [23]. Green supply chains form as a result of positive influence from environmental objectives leading to systems that are economically stables and consider environmental sustainability dimensions [24]. Furthermore, complimentary economic assessment of systems that have an environmental basis can be conducted through life cycle costing (LCC). As a natural extension to LCA, LCC is used to estimate the total costs of a product or process over their lifecycle [18], including capital investment and operating expenses during the product's estimated lifetime.

3.3. Social Dimensions

From a social perspective, research in this area is limited when compared to environmental and economic analysis. Social sustainability is a critical pillar because it addresses the long-term survival of the organisation, and the need to manage its responsibilities towards its social and human capital [25]. Multiple dimensions can be considered when enhancing social sustainability within supply chains, which can be categorised into six attributes related to human rights and anti-corruption, human resources, health and safety, training and education, consumer issues, and social compliance [25]. However, social sustainability is one of the most challenging pillars because of the difficulties in measuring practical impacts and outcomes [26,27]. Incidentally, the Global reporting initiative defined four sub-categories of social sustainability classified into labour practices and decent work, human rights, society, and product responsibility.

In terms of quantification, two impacts categories are considered within the social aspects of LCA end-point and mid-point analysis [28]. Similarly, a set of quantitative indicators for social sustainability assessment for both end-and mid-point impact categories across the whole supply chain was developed by Popovic et al. [29]. Due to the enormous scope of these impact categories, the work was limited to labour practice, decent work, and human rights end-points only. Furthermore, a framework to support supply chain decisions by assessing social sustainability was developed by Popovic et al. [30]. The application of supply chain social sustainability in upstream and downstream segments of the supply chain was introduced by Mani et al. [31]. In the study, empirical methods to measure supply chain social sustainability was conducted using surveys and interviews for a manufacturing case study in India.

3.4. Developing Sustainable Supply Chains

Multiple factors influence supply chain performance. According to existing research, the most crucial factor is the ability to view the whole supply chain as one large entity working towards a common goal in an integrated strategy considering customer requirements. Through key performance indicators (KPIs), the performance of supply chains is evaluated to reveal gaps between preparation and performance, through which companies can identify the possible areas for improvement. However, practical guidelines that guide the implementation of KPI's are not readily available for SCM practitioners. Chae [32] suggested a practical approach to develop performance metrics development, implying that companies should focus on a small list of KPIs only, which are critical to operations management, customer service, and financial viability. Furthermore, four meta-processes (plan, source, make, and deliver) model should be developed for the primary and secondary KPIs for each of the supply chain operations-reference. A big data architecture conceptual framework, which provides a practical approach to managing supply chain KPIs under a dynamic environment, was proposed by Dev et al. [33]. Upon selection of the relevant KPI's, monitoring and control/optimisation is necessary. Figure 3 represents the primary KPIs and their sub-elements that contribute towards achieving SC objectives.

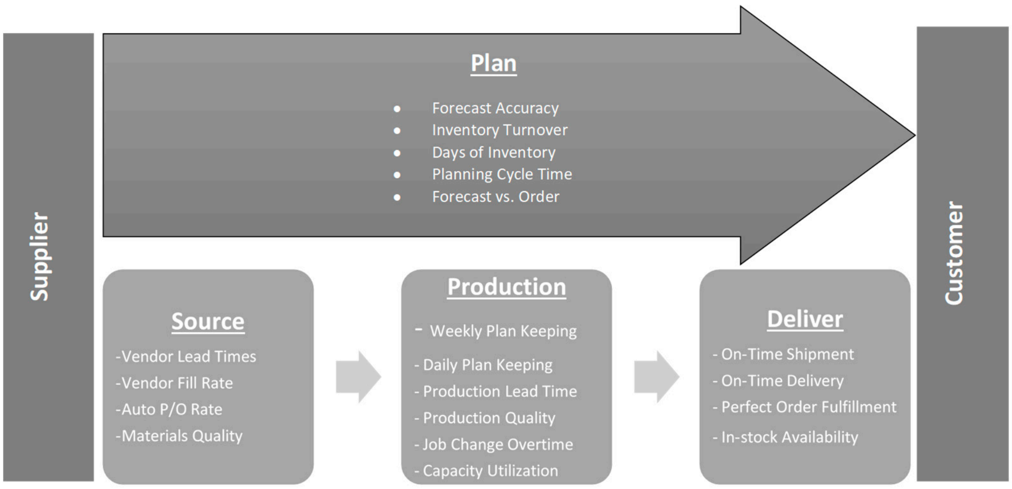

Figure 3. Key performance indicators (KPIs) in Supply chain management [32].

A system of indicators is required to assess the sustainability-related performance of a supply chain in any or all of the dimensions of sustainability. Indicators are suitable in representing complex systems such as SC or SSC and can be categorised as: quantitative and qualitative [34,35], financial and nonfinancial [36,37], absolute and relative [38], and based on different planning levels (i.e., strategic, tactical, and operational) [39,40]. Sustainability performance indicators are used to measure the performance of SSCM [41] and evaluate an organisations effort to improve its sustainability [42]. However, there is limited published literature that identifies and compares SSC performance measurement indicators [35,43].

There are five critical KPIs that influence the capitalisation of the buyer–supplier relationship and the whole efficiency of the supply chain and include: Purchased orders, production activity, transportation, customer satisfaction, finance, and logistics costs [44]. However, these measures are designed mainly for the general performance measurement of SCs and are insufficient to describe the performance as related to SSC. There are significant factors behind the emerging focus on sustainability in SCs driving the need for sustainability-related performance measurement. This includes increased: Globalisation and outsourcing; uncertainty; resources shortages; pressures from regulatory bodies and non-governmental organisations; and consumer awareness. Various standards provide guidelines to evaluate SC performance across different sustainability dimensions. For instance, environmental assessment can be conducted using ISO 14031 [45], Eco-Management and Audit Schemes [46] for environmental assessment, International Labour Organisation [47]. Social assessment can be conducted using social Accountability International (SA8000) [48]. Assessing multiple objectives within sustainability have been highlighted in the Global Reporting Initiative guidelines [49], and the United Nations Global Compact ten principles [50]. Adopting the appropriate set of KPIs, which can be easily communicated to all stakeholders, is one of the main challenges in sustainability-related performance measurement. By extension, the continuous monitoring of KPIs at regular periods using the appropriate tools is necessary to ensure sustainability compliance and optimum operation at all stages of the SC.

4. Review of Quantitative Models

Quantitative models to evaluate sustainability and robustness within LNG supply chains can generally be classified into deterministic and stochastic methods within both forward and closed-loop supply chain management. Together they can integrate various parameters the characterise the dynamic functions of supply chains and evaluate their influence on objectives that relate to resilience and economic, environmental and social sustainability.

4.1. Deterministic Models

Deterministic models are popular as they strive to reduce randomness. They consist of objective functions and decision variables, which are classified into four main groups. Linear programming is a mathematical model where requirements are represented by direct relationships to achieve optimum outcomes. If any of the constraints or objective functions are nonlinear, nonlinear programming is introduced to solve the optimisation problem; whereas integer programming is a mathematical optimisation model used if all variables are restricted as integers. Mixed-integer linear programming (MILP) is used if only some of the unknown variables are required to be integers, and this kind of problem is considered a non-deterministic polynomial-time (NP-hard) problem. Finally, mixed-integer nonlinear programming is one of the most common optimisation techniques and includes both non-linear programming and MILP as sub-problems. The proceeding text highlights deterministic approaches in SSCM within forward and closed-loop supply chains.

4.1.1. Sustainable Forward/Open Supply Chain Management

There have been multiple published reviews that analyse quantitative models as applied to forward sustainable supply chains. The 134 papers reviewed by Brandenburg et al. [51] emphasise the dominance of mathematical programming models as compared to other tools. In terms of quantitative models, Seuring [52] examined 36 different papers that focused on forward supply chains and include equilibrium models, multi-criteria decision making, analytical hierarchy process, and LCA. Brandenburg and Rebs [53] reviewed 185 different papers published in the last 20 years and observed that SSCM models mainly focus on deterministic approaches, and the integration between environmental and economic aspects of sustainability, without focusing on social factors and stochastic modelling approaches. Most of the research utilised optimisation models for strategic decision making with a focus on environmental and economic dimensions in order to advance SSC [54].

In terms of applications, most of the forward SSC applications have been applied to biofuel supply chains. For instance, Mele et al. [55] designed a support decision-making tool for a combined sugar and production of the ethanol supply chain. In terms of multi-objective MILP, Huang and Xie [56] addressed a strategic multistage expansion of a cellulosic biofuel supply chain system with additions of corn grain biofuels. A multi-objective optimisation framework was applied to the supply chain to identify best-compromise solutions between economic competitiveness and environmental quality, whilst satisfying significant factors such as developing fuel demand, feedstock resources, and technological constraints. You et al. [57] measured the total annual cost, the life cycle GHG emissions, and the number of accrued local jobs for lignocellulosic biofuel through the multiobjective optimisation that integrated with LCA and input-output analysis, while Pérez-Fortes et al. [58] considered the properties of the biomass supply chain.

In terms of combining the concept of sustainability principles and the methodology of LCA, Andersson et al. [59] examined the feasibility to achieve an operational tool that incorporates sustainability in product development and strategic planning; while Chaabane et al. [60] developed a model for the based framework for sustainable supply chain design and LCA principles in addition to the traditional material balance constraints at each node in the supply chain to evaluate the trade-offs between economic and environmental objectives under various cost and operating strategies. The typical LCA methodology can be combined together with multi-objective optimisation in what is known as life cycle optimisation (LCO), which can be used to optimise multiple sustainability objectives within a supply chain life cycle. In some cases, applications of functional unit-based LCO approaches are further developed to provide a systematic approach to optimise the life cycle economic and environmental performance of supply chains and product systems considering both cooperative and non-cooperative stakeholders [61]. Other applications of forward SSC include the development of tools that support dynamic decision making with the consideration of supply chain's economic and environmental inputs [62]. To control decision making, Chaabane et al. [63] developed a multi-objective MILP model to determine the balance between economic and environmental considerations for sustainable supply chain design problems. The evaluation of the environmental and economic performance of an environmentally friendly product by a quantitative model of an integrated supply chain conducted by Ding et al. [64]. Moreover, Halati and He [65] developed an integrated model for the environmental and economic dimensions for a single forward supply chain product, thus enabling decisions related to environmental impacts and profit across the supply chain. Neto et al. [66] developed a framework for the design and evaluation of sustainable logistic networks to balance between profitability and environmental impacts to change the objective of the logistic networks from cost minimization only to cost and environmental impact minimization. Moreover, Ferretti et al. [67] addressed the green supply chain problem and incorporated the environmental aspects in its analytical description by developing a model to evaluate the economic and environmental effects of the industry; while Brent A. [68] used LCA to obtain quantified environmental performance resource impact indicators that associated with limited process parameters to determine where assistance is required to improve environmental performance within supply chain.

The integration of all three sustainability dimensions to identify design requirements for SSC that combine two decision-making methods, analytic network process, and zero-one goal programming in quality function deployment conducted by Büyüközkan and Berkol [69]. Furthermore, Chen and Andresen [70] developed a multi-objective programming model for the SSC of production-sourcing and supply chain network design for perishable food using a hybrid multi-objective metaheuristic to minimise the total cost and CO_2 emissions. The integration of sustainability performance with the supply chain was conducted by Boukherroub et al. [71] through the development of an optimal design using a multi-objective mathematical programming model. This model enables decision-makers to perform operations that consider alternative pathways that reflect the balance between the three dimensions of sustainability.

Deterministic Models of LNG Supply Chain

Most of the work that has been conducted in the deterministic models of the LNG supply chain focused on the economic side. Therefore, the evaluation of the relationship between supply chain strategies and the financial performance of the LNG systems studied by Zubairu and Dinwoodie [72] is important. Most deterministic model-driven research articles within LNG supply chain management have focused on the effectiveness of decision support system on shipping operations. In this case, decision support system provides the means to optimally manage LNG, liquefaction, and regasification terminals including optimal LNG delivery planning [73]. Within the LNG supply chain, inventory management is a key feature in the LNG delivery planning stages. This is because if an inventory level at a liquefaction terminal exceeds its limit, the producer has to slow down or shut down production, which is costly for the producer [73,74]. Inventory management, which is linked to shipping operations in terms of supply chain management, can generally be categorised into two types; inventory routing and supply chain infrastructure development. The LNG inventory routing problem is a unique case in what is known as the maritime inventory routing problem, which considers variable production, contractual obligations, and berth constraints at production terminals [75]. The entire LNG supply chain from the natural gas extraction to customer delivery was analysed by Andersson et al. [73]. The study proposed a mathematical programming model and briefly sketched solution methods to undertake shipping decisions that are integrated seamlessly with inventory management decisions at the liquefaction and regasification terminals. The consideration of the LNG inventory routing problem conducted by Grønhaug and Christiansen [74] and Grønhaug et al. [76] focused on multiple discharge ports during one voyage for a single vessel. This new formulation for the LNG inventory routing problem was initially studied by Grønhaug and Christiansen [74] and later proposed by Andersson et al. [77] by introducing a new path flow formulation consisting of a novel decomposition scheme supported by strong inequality constraints. The same problem was solved by Grønhaug et al. [76] for a schedule-based formulation by using a branch-price-and-cut algorithm. The computational results illustrate that the new formulation provides tighter bounds comparing to the previous schedule-based formulation. However, Goel et al. [78] developed an arc-flow formulation for the LNG inventory routing problem to optimise ship schedule decisions and proposed both construction and improvement heuristic models. Later, a constraint programming model was developed by Goel et al. [79]. For significant scale problems, the authors proposed a rolling horizon heuristic, which aggregates the original problem into sub-problems with time window restriction. For the same problem, Stålhane et al. [80] proposed a heuristic approach by constructing a set of initial solutions then improved it by applying different neighbourhood operators. The issue of creating a cost-effective ADP was addressed by Rakke et al. [81] through the development of a compact mixed-integer programming (MIP) model while considering the opportunity of selling spot cargo of LNG if the annual production exceeds the total yearly long-term contractual demand. Due to highly limited production changes, there are cases where there is excess in production.

An optimal ADP for rich LNG to minimise the vessel fleet size by considering the availability of berth, liquefaction inventory, planned maintenance, and bunkering requirements was designed by Al-Haidous et al. [82]. Moreover, Mutlu et al. [83] developed a model to minimise the sum of the operational costs, penalty costs that are associated with contractual deliveries, and operational cost for clearing excess production by spot sales with the consideration of the production, inventory, and delivery routing decisions at the lowest possible cost for LNG. The extensive computations reveal that heuristic approaches generate significantly lower-cost solutions compared to commercial optimisers. The same problem was solved by Andersson et al. [84] using a branch-and-cut algorithm by introducing several types of valid inequalities, which reduces the linear programming gap in the MIP formulation. The computational results illustrate that although the problem is very complex, valid inequalities are effective in simplifying the model to achieve faster results. Table 1 summarises selected papers that apply deterministic models to LNG supply chains, in terms of: (1) application stage; (2) objective function; and (3) application methods.

Table 1. Summary of deterministic models within LNG supply chain management.

Author	Stage	Objectives	Models
Andersson et al. [73]	Shipping Operations	Minimise voyage operating cost, and over and under deliveries cost	Single objective MIP Optimisation method
Grønhaug & Christiansen [74]	Shipping Operations	Maximise revenue of selling LNG	Single objective MIP Optimisation method
Goel et al. [78]	Shipping Operations	Minimise lost production, stockout, and unmet demand	Single objective MIP–Rolling horizon heuristic
Stålhane et al. [80]	Shipping Operations	Minimise cost	Single objective MIP–Rolling horizon heuristic
Rakke et al. [81]	Shipping Operations	Minimise transportation and penalty costs	Single objective MIP–Rolling horizon heuristic
Al-Haidous et al. [82]	Shipping Operations	Minimise the number of vessels that satisfy all customers	Single objective MILP Optimisation method
Mutlu et al. [83]	Shipping Operations	Minimise cost	Single objective MIP–vessel routing heuristic
Andersson et al. [84]	Shipping Operations	Minimise cost	Single objective MIP–branch and cut algorithm

4.1.2. Sustainable Closed-Loop Supply Chain Management

Sustainable closed-loop supply chain management (CLSC) is defined by Fleischmann et al. [85] as "*the logistics activities all the way from used products no longer required by the user to products again usable in a market*." There are various applications for which CLSC have been applied, as detailed in this section. For instance, Chaabane et al. [60] considered the importance of SSC through the development of a MILP model based on an SSC framework using LCA principles. Moreover, Eskandarpour et al. [86] developed a multi-objective MILP model for post-sales network strategic and tactical decisions considering economic and environmental dimensions. Devika et al. [87] examined the three pillars of sustainability in a network design problem in order to use quantitative modelling to bridge social impacts together with environmental and economic objectives.

Within CLSC, various reverse logistics networks are required to develop sustainable products or ensure material recovery improving the sustainability performance. The independent design of reverse and forward networks is the most appropriate approach for the bi-directional network's design. A deterministic model using MILP for integrated reverse logistics into the existing forward supply chain, which extended to robust, sustainable bi-directional logistics, was developed by De Rosa et al. [88]. A CLSC model that considers environmental sustainability using an LP model that aims to increase transportation efficiency and to minimise total supply chain costs was proposed by Faccio et al. [89]. Mota et al. [90] proposed a generic mathematical programming model for CLSC integrating sustainability dimensions designed. Furthermore, Taleizadeh et al. [91] evaluated social and environmental indicators linked to the global reporting initiative and developed a sustainable CLSC comprehensive programming model. Moreover, Sahebjamnia et al. [92] proposed a sustainable CLSC model to optimise total cost, minimise environmental impact, and quantify social effects such as job opportunities and work damages. To reduce the computational time and improve the quality solutions, a hybrid meta-heuristic algorithm was used to solve this particular problem.

4.2. Stochastic Models

Stochastic models incorporate uncertainties into performance evaluation through analytical methods. While deterministic models require given parameter values as inputs, stochastic models consider the respective probability distributions of input parameters. Analytical methods that incorporate uncertainties into the deterministic model include stochastic linear programming, stochastic MILP, and Markov chain modelling approaches. Furthermore, Juan et al. [93] introduced a new class of optimisation algorithm called "simheuristics", which integrate simulation into the metaheuristic-driven framework to solve the complex stochastic combinatorial optimisation problem. The proceeding text highlights stochastic approaches in SSCM within forward supply chains.

4.2.1. Sustainable Forward/Open Supply Chain Management

For biofuel supply chains, Awudu and Zhang [94] conducted a review of uncertainties and sustainability concepts that allude to the evolution of biofuel supply chains, decision-making levels, and uncertainties, which can be applied to raw material supply, transportation and logistics, production and manufacturing, demand and price, tax, governmental, and regulatory policies. A framework to support decision making to address the economic and environmental dimensions of sustainability in bioenergy driven systems was developed by Mirkouei et al. [95]. The economic analysis supports a vector machine technique through the incorporation of uncertainties into the stochastic optimisation model to predict the pattern of uncertainty. The objective of the stochastic model is to minimise the total annual cost of the mixed supply chain network by using a genetic algorithm. The analysis of environmental impact utilises LCA to evaluate a cost-effective supply chain network considering the potential for global warming. To meet sustainable bioethanol demand, Gao and You [96] developed a hybrid generation bioethanol supply chain method, which was exposed to several uncertainties related to price, demand, and biomass yield. A stochastic mixed-integer linear fractional programming model was developed by Gao and You [96] to tackle many uncertainties for both feedstock supply and product demand uncertainties. A stochastic MILP to maximise economic benefits under environmental and social constraints to propose an optimal hybrid generation bioethanol supply chain design was developed by Gonela et al. [97]. Furthermore, Fattahi and Govindan [98] proposed a cost-efficient multi-stage stochastic program to consider GHG emissions and social implications within the biofuel supply chain. The model was evaluated by a rolling horizon procedure that depends on a tree scenario to represent different parameters required for stochastic analysis.

Stochastic models in logistics and supply chain applications have also been developed. For instance, Lee et al. [99] developed an uncertain sustainable logistics network by formulating the problem as two-stage stochastic programming to expand deterministic models. The second stage resembles the allocation of product flows through the conventional network based upon the configuration and the realised uncertain scenario. Furthermore, it was assumed that the demand for forward products and the supply of returned products from customers are stochastic parameters with known distribution.

Stochastic Models for LNG Supply Chains

In terms of factoring in uncertainty in large scale LNG projects, Cardin et al. [100] introduced an innovative flexibility analysis to improve the expected value of large-scale, capital-intensive projects considering market uncertainty. The combined effects of uncertainty include those related to economies of scale, learning, and geographic distribution. The procedure considers uncertainty in the design stage encouraging the addition of flexibility in the early design stages and project evaluation in terms of uncertainty fostering positive long-term economic performance. A stochastic MILP was applied to LNG supply chains to support the strategic planning processes with a focus on economics (i.e., infrastructure, vessels chartering and purchases and sales of LNG) [101]. The vulnerability in the LNG supply chain was addressed by Berle et al. [102] through a vulnerability assessment approach and developed a stochastic model to measures disruption risks and tested the effect of mitigating measures using heuristics-based planning and the Monte Carlo simulation tool. The preliminary formulation of the scheduling problem was issued by Halvorsen-Weare et al. [103] to ensure that all cargoes are serviced by one vessel with the minimum cost, without consideration for the berth capacity and inventory level constraints.

Uncertainties related to sailing times due to changing weather conditions and LNG production rates can be introduced to create a robust route and schedule for the vessel fleet. In terms of stability and robustness within energy supply chains, Urciuoli et al. [104] factored in resilience against exogenous security threats and concluded that oil and gas supply chains have in place the right combination of disruption plans. Shuen et al. [105] highlighted a comprehensive portfolio strategy that addresses the oil and gas resource scarcity strategy developed by the European Union. In terms of consumption, Badea et al. [106] developed a method for building an energy security motivated composite indicator that considers the risk-averse level of the decision-maker ranging from continuously risk-prone to risk-averse. There are four indicators for the security of gas supply, which include gas supply disruptions, the gas price volatility, transportation and distribution, and a growing reliance on imports over longer distances [106]. Based on these indicators, a composite gas supply security index is estimated as an overall indication of gas vulnerability.

Impact analysis from natural gas price fluctuations and infrastructure requirements during the natural gas supply system development was conducted by Zhang et al. [107]. Li et al. [108] addressed optimal design and operation of the natural gas production network by developing a two-stage stochastic pooling problem optimisation formulation considering flow quality characteristics. Later, Li and Barton [109] proposed two-stage stochastic programming for the optimal design and operation of energy systems and used the nonconvex generalised benders decomposition for the optimisation. This method was used to solve the infrastructure development of the natural gas supply system, which could improve the solving efficiency [109]. Based on existing studies, most of the research considered multiple uncertainties in pipeline-based natural gas supply chains and developed efficient forward solving algorithms. However, the construction time planning for infrastructure growth and development, in addition to the demand increase, was not considered. Furthermore, to determine the diversity of LNG delivery and additional uncertainties related to LNG price and demand, there is a need for further development in the research related to the integrated optimisation of infrastructure and inventory routing within the LNG supply chain. Table 2 summarises selected papers that apply stochastic models to LNG supply chains, in terms of: (1) Application stage; (2) objective function; and (3) application methods.

Table 2. Summary of stochastic models within LNG supply chain management.

Reference	Stage	Objectives	Models
Werner et al. [101]	Shipping Operation	Create a model to support LNG strategic planning.	Stochastic MILP
Berle et al. [102]	Shipping Operation	Address a vulnerability in a maritime transportation system.	Monte Carlo simulation
Halvorsen-Weare et al. [103]	Shipping Operation	Consider uncertainty to create robust routes and schedules for the vessel fleet.	Single objective MIP Optimisation method
Urciuoli et al. [104]	Delivery and Consumption	Build resilience energy supply chains against exogenous security threats.	Data collection
Li and Barton [109]	Overall supply chain	Integrate the design and operation of energy systems with the consideration of uncertainties.	MINLP

From the review of the two approaches discussed above, it is evident that most published work on LNG supply chains have considered deterministic approaches mainly for shipping operations and have neglected other stages of LNG supply chains. Moreover, sustainability and resilience principals related to LNG supply chains should be further developed and integrated to establish a more holistic approach to their design and operations.

4.2.2. Sustainable Closed-Loop Supply Chain Management

For CLSC, various reverse logistics networks are required to ensure that discarded products, or elements within them are re-utilised to ensure material recovery and enhance their sustainability performance. There is a limited work related to CLSC and the management of uncertainties. For instance, Ravi et al. [110] considered a multi-criteria decision-making problem, which was later enhanced by Dubey et al. [111] by introducing uncertainty analysis within sustainable supply chains. The study developed multi-objective MILP model to handle high uncertainties related to demand and supply. Moreover, Chen and Fan [112] developed a model to support strategic planning of bioenergy supply chain systems and optimal feedstock resource allocation in an uncertain decision environment and the model shows that biowaste-based ethanol can be a viable part of sustainable energy solution for the future.

5. Sustainable Supply Chains and Resilience

Risk can influence performance by either lowering the projected profits or by generating a loss. Therefore, it is crucial to understand the importance of preventing and eliminating risks to prevent such losses. In terms of supply chains, risks can lead to supply chain disruptions and vulnerability exposures, which are more likely to occur as supply chains increase in complexity, exposed to market unpredictability, and enhance outsourcing and single point sourcing [113]. External risks to supply chains can also include terrorist attacks, floods, earthquakes. As a result, networks are increasingly more vulnerable to events that may have previously caused only minor local disruptions. Although efficiency improvements are essential in a severely competitive marketplace, the challenge is to ensure that vulnerabilities are contained and managed, thus removing and mitigating risks [113]. Corresponding impacts to the supply chain can include cost, timely delivery, and impact on an image when delivering a product or service to a customer [114]. The five main stages of supply chain risk management (SCRM) are illustrated in Figure 4 [115].

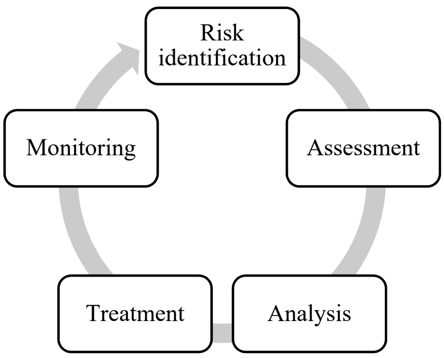

Figure 4. Main stages of supply chain risk management (SCRM) [116].

The fundamental phase in the risk management practice is risk identification in order to advance decision making during periods of uncertainty. Subsequently, risk assessment and analysis are necessary to inform suitable management actions for the identified risk, which would then require treatment and continuous monitoring. Undertaking of risk management within sustainability assessment was conducted by Giannakis and Papadopoulos [116], where business-related risks were assessed in terms of their impact on sustainability dimensions. Sustainability impacts an organisations stance within future scenarios that involve the natural environment, societies, and business viability [114]. Therefore, the level of future uncertainty should be considered in sustainability strategies, and the risks that decisions may impose on natural and social environments. Sustainability risks within supply chains were investigated by Valinejad and Rahmani [117] who developed a comprehensive framework that classifies risks into five main categories; environmental, social, economic, technical, and institutional, and applies them to four main supply chain areas that include suppliers, organisation, customers, and the environment. Furthermore, Xu et al. [118] developed a framework to evaluate risks to supply chains by measuring supply chain-wide operational, social, and environmental risks to form an aggregate metric. There are multiple factors, which contribute towards supply chain design from a resilience perspective. A resilient supply chain must be adaptable where at any particular point, it may need to absorb disturbances and operational realities that are different to steady state modes [119]. A 'robust' process may enhance reliability, although do not necessarily imply adaptability and resilience. In addition to resilience and robustness, agility defined as "react," "respond," "adapt," or "re-configure" can promote performance improvements [119]. Adopting and integrating these strategic paths will have a significant impact on improving resilience driven performance. Three types of competencies to facilitate supply chain resilience include communication, cooperation, and integration demonstrated by Dyer and Singh [120]. In application of these competencies, Wieland and Wallenburg [121] conclude that there is a positive impact from communicative and cooperative relationships on resilience.

Considering sustainability and resilience at the operational level is of increasing importance within supply chains in order to weather rapid-changing and competitive markets. A novel dynamic network to dynamically evaluate the performance of supply chains from both sustainability and resilience perspectives was developed by Ramezankhani et al. [122]. The proposed hybrid method consists of a quality function deployment to systematically select the best sustainability and resilience factors that influence the performance of supply chain. The consideration of emission control areas was addressed by Zavitsas et al. [123] to connect between environmental and network resilience performance for maritime supply chains through both operational and emissions cost metrics.The objective is to control environmental and resilience legislation, and supply chain operators who constantly seek to minimise operational costs and also minimise their exposure to costly supply chain disruptions (i.e., fuel pricing instances and regulatory strategies). In terms of performance indicators, both flexibility and redundancy were discussed by Hohenstein et al. [124] who proposed three KPIs to quantify supply chain resilience (SCR) that reflect customer service, market share, and financial performance. In 57 different articles, Karl et al. [125] constituted resilience into 13 elements, which were classified into pre, during, and post-disruption and organised in terms of performance indicators related to the producer, supplier, and customer. Furthermore, delivery lead time, order lead time, and stock level are operational parameters that can be related to resilience supply chains, and as such are relevant to SCR. Figure 5 illustrates the published articles that discuss the operational factors of supply chain resilience, as opposed to strategic factors, which have longer term implications and cannot be modified regularly.

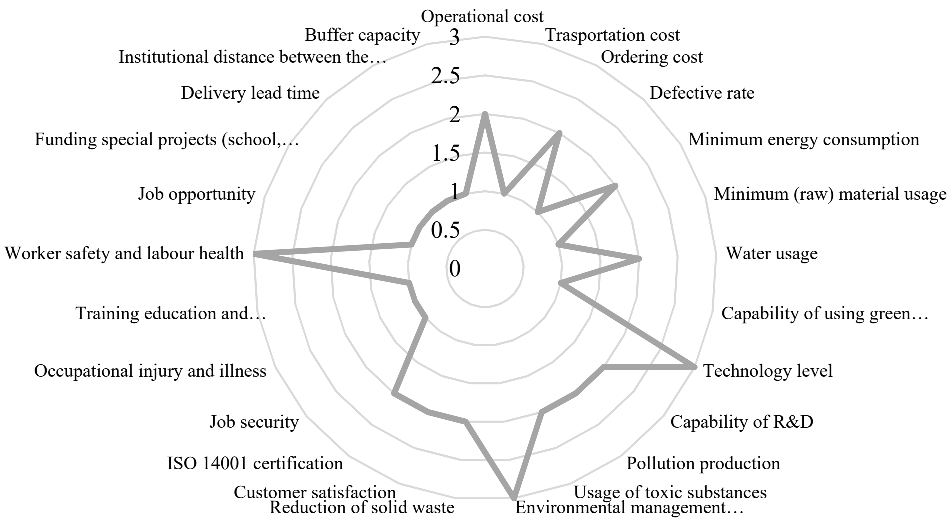

Figure 5. Number of publications of supply chain resilience factors [122].

6. Future Perspectives in LNG Supply Chain Management

Due to the influence of different stakeholders, companies have been encouraged to integrate sustainability conscious practices into their business throughout the entire supply chain. This will help the shift from local optimisation at the firm level towards the whole supply chain, including product management flows from the initial sourcing of raw material to the consumer in both forward and reverse directions. This review demonstrates the opportunity to enhance existing LNG supply chain modelling further and account for all dimensions of sustainable development and resilience. This includes evaluating environmental performance by measuring life cycle emissions and compliance with regulations; whilst social sustainability can be measured through demand satisfaction and social conformity. Profitability and market competitiveness can provide reasonable indicators for economic sustainability.

In terms of the environment, measuring carbon dioxide (CO_2) emissions throughout the supply chain provides a reasonable indication to the environmental performance of the LNG supply chain. The following represents CO_2 emissions during the LNG supply chain [126]:

- Fuel consumption of driving turbines and motors represents less than 0.2 g CO_2/MJ HHV;
- Combustion of waste gases in flares represent between 0.1–0.5 g CO_2/MJ HHV;
- Gas losses from venting connected with pre-treatments, maintenance processes and losses from equipment and pipes represent between 1–13 g CO_2/MJ HHV;
- During LNG transportation, CO_2 emissions represent between 1.04–2.11 g of CO_2/MJ HHV.

To reduce CO_2 emissions throughout the LNG life cycle, numerous initiatives have been implemented at various stages of the LNG supply chain. For instance, jetty boil-off gas (JBOG) recovery can occur during the loading of LNG vessels to reduce flaring. This kind of modification can recover the equivalent of about 600,000 tonnes of LNG per annum whilst reducing CO_2 emissions to about 1.6 million tonnes per annum. Moreover, LNG is transported in double-hulled vessels that are specially designed and insulated to minimise the amount of boil-off LNG and enable safe and reliable transport of LNG from liquefaction terminals to the regasification terminals. The tankage and boil-off gas (BOG) management systems are always designed to maintain the cargo tank pressure below the maximum allowable relief valves settings or to utilise or dispose of the LNG BOG safely whilst at the port, manoeuvring, or standing. Other steps can be considered, such as sharing infrastructure assets and using side products and services (such as cold utilisation) to reduce cumulative environmental impacts in regasification terminals and gas markets [127].

Continued environmental enhancement throughout the LNG supply chain will contribute towards LNG evolving into the fuel of choice as governments strive towards cleaner energy portfolios. Numerous methodologies such as LCA have been developed for the quantification, assessment, and minimisation of emissions. It can be used to systematically quantify and assess environmental impacts during the life cycle of LNG supply chains identifying environmental 'hot spots', which may occur at different locations within the supply chain. In parallel to LCA, LCC can quantify the cumulative cost of LNG throughout it is life cycle. In oil and chemical industries, LCC analysis tends to focus on the prediction of the total system due component failures, maintenance, and spurious trips of emergency shutdown systems [128]. Figure 6, adapted from Kawauchi and Rausand [128], illustrates the main six basic processes required to conduct an LCC analysis, which can be adapted to LNG supply chains. The premise is an iterative process in which the baseline system is improved throughout the LCC analysis. Each process is aggregated into sub-activities beginning with the process "Problems definition," and the other five processes are iteratively carried out clockwise.

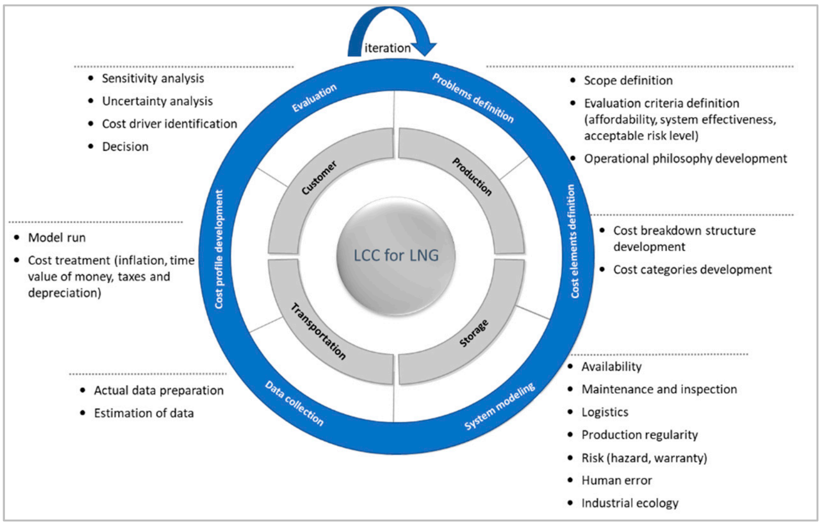

Figure 6. Six basic processes for life cycle costing (LCC) procedure, adapted from [128].

The problem definition and constituting scope of work is the first step of an LCC analysis leading to an evaluation of total system cost. This includes defining operational requirements and maintenance strategies, which should ideally be developed prior to the LCC assessment. Process 2 specifies that all cost elements should be identified as they are considered the direct inputs into LCC analysis conducted in Process 3. Within identifying process cost elements, appropriate existing models can be utilised, or new models can be developed. Process 4 emphasises on the importance of input data accuracy and reliability as it is crucial to improve the certainty of the LCC prediction. Process 5 illustrates that affordability analysis is a key feature in the LCC analysis considering long-term financial planning where a life span cost profile is developed. Finally, in the evaluation stage, the optimum configuration amongst the various alternatives is selected, meeting the criteria defined in the first part of the LCC analysis. A sensitivity analysis considering uncertainties in the input data is useful in identifying the high-cost contributors such that alternative methods may be effectively found according to the result of the sensitivity analysis.

Meanwhile, methods for the simultaneous optimisation of economic and environmental performance within a product life cycle have also been developed. The prospects of integration between these two methods into an LCO and embedded within the LNG supply chain should be further developed; the objective of which is to simultaneously optimise through a multi-objective optimisation economic and environmental performances of supply chains, such as the LNG supply chain. Coupled to this is the need to integrate risk and uncertainty assessment into the LCO.

Most of the work related to LNG supply chains have focused on economic objectives, whilst neglecting the compounded objectives of achieving multiple objectives within sustainable supply chain management. Evidently, there is a need to address shortcomings in LNG supply chain analysis to account for sustainability. As such, the main contribution of this review is to bridge this gap by highlighting the tools and concepts that form the basis of sustainable supply chain management and relate them to LNG supply chains. This includes a review of deterministic models that can process an array of variables to compute economic and environmental dimensions. Furthermore, considering stochasticity, it is necessary to move ample LNG reserves in a manner that is sustainable and resilient to potential risks and uncertainties. In this regard, multi-criteria mathematical models that include shipping fleet scheduling, routing, and delivery considering sustainability and risk within the LNG supply chains requires further development. Such models should incorporate parameters specific to LNG supply chains such as flexibility in delivery times, inventory management, berth availability, fuel consumption, and carbon emissions, thereby ensuring that the supply chains deliver cargo at minimal cost and environmental impact, whilst overcoming uncertainties and adhering to contract schedules. Economic functions of the supply chain could also be represented by the sum of cost components, including operations, environmental impacts, and disruption risks. In terms of advancing supply chain decision making, scenario planning can include production and shipping disruption risks, and associated inventory problems and time delays; random versus optimised delivery fleet speed which affects fuel consumption, and consequently CO_2 emissions; and finally, a consideration for multi-discharge delivery contracts. In relation to the above, Table 3 illustrates the parameters that can be considered in the design of sustainable and resilient LNG supply chains.

Table 3. Parameters that form the basis of sustainability and resilience in LNG supply chains.

Stage	Stage Inputs	Stage Outputs	Sustainability/Resilience	KPI's
Offshore operation	• Maintenance requirement • Feed gas plan	Gas to onshore operation for liquefaction	Sustainability	• Number of days of unplanned shutdowns • Production losses
Onshore operation & storage	• Maintenance requirement • Feed gas plan • Maximum capacity of trains	LNG production	Sustainability	• Number of days of unplanned shutdowns • Production losses
Shipping operation	• Number of vessels • Number of berths • Inventory level • Vessel speed • Bunker requirement	Deliver the cargo to the customer	Sustainability Resilience	• Vessels utilisation • Berths utilisation • Manage the inventory to avoid tank top • Speed optimisation to reduce emissions • Bunker in terms of type and price
Delivery and consumption	• Inventory level • Receive Cargo	Demand needs	Resilience	• Satisfy demand needs • On-time delivery

7. Conclusions

The volume of maritime transportation has been growing, and continued growth is expected in the coming years due to the increased availability and accelerating demand for natural gas. Expansion of the LNG sector draws multiple decision-making challenges, from strategic through tactical to operational. The main contribution of this study is to review quantitative models that have been used to assess sustainability within supply chains and evaluate their applicability in managing LNG supply chains. Sustainable LNG supply chains is a field that requires further research and improvement to ensure that supply chains deliver cargo at minimal cost and environmental impact, on schedule, and to ensure that supply chains can overcome vulnerabilities. In this regard, it is necessary to weather potential disruptions to the supply chain and protect the entire energy supply chain and infrastructure rather than a consideration for the availability of resources alone. This review highlights the importance of the particular techniques in guiding the decision-making process across the different levels of supply chains. Furthermore, there is an emphasis towards integrating sustainability and resilience dimensions within deterministic and stochastic methods to enhance the design and operation within LNG supply chains. This is important as there is rapid growth in maritime transportation in markets that seek to enforce more sustainable delivery plans. There are compounded challenges to enhance profitability whilst improving on environmental standing. From a modelling perspective, there is need to develop computational methods that are able to process large quantities of variables that depict complex systems and produce the necessary solutions that will aid policymakers to identify and evaluate trade-offs during decision making. The LNG supply chain is especially complex due to the large number of variables that form the annual delivery plan between the customer and supplier. It involves the delivery of cargo in a safe, efficient, and reliable manner, consideration for any variations in production impacting inventory management, evaluation of multi-discharge operations during a single voyage, multi-routing problem, and ship-to-ship operation schedules. Considering these variables in a highly dynamic market is necessary to capture how they influence economic and environmental objectives.

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