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Investigation of the bullwhip effect in the LNG supply chain and evaluation of mitigation methods

Diploma Thesis

Of

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«Μελέτη του φαινομένου διαταραχής παραγγελιών (bullwhip effect) στην εφοδιαστική αλυσίδα LNG και αξιολόγηση λύσεων για την άμβλυνσή του»

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

του

ΒΑΦΕΙΑΔΗ ΙΩΑΝΝΗ

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What we call the beginning is often the end.
And to make an end is to make a beginning.
The end is where we start from.

T S Eliot

Abstract

The scope of this thesis was the development of a methodology able to examine the scale of the bullwhip effect in the LNG supply chain, estimate how an LNG Terminal influences the network, and evaluate solutions for the mitigation of the effect. For this purpose, an artificial neural network was designed that can simulate various natural gas demand scenarios and create reliable output. The data used to train the network was daily usage information from the Transmission System Operator, from whose side the optimization was pursued.

Specifically, a thorough examination of the LNG market and its prospects for the near future are presented, both at a global and national level. Furthermore, the bullwhip effect is analyzed, initially in the light of operational research and then in particular for the LNG supply chain according to existing research. Afterward, the design of the neural network follows, where its operation and parametrization are explained. The model receives as inputs the total demand of natural gas for a specific day, the demand for electricity production, the loaded capacity of the LNG Terminal of Revithoussa, the LNG imports, the pipeline feed gas imports, and other parameters related to the price of the commodity and returns an estimation for the bullwhip effect for a period of thirty days.

This model can be used as a guide for the efficient operation of the natural gas transmission system, as it is able to give a prediction about the behavior of the supply chain according to changes in the import policy or the capacity of the terminal. This way, the mitigation of the demand amplification in the LNG supply chain can be achieved and also, the results can indicate a path for the viability of the system in the upcoming increase in demand for natural gas and electricity production the next years.

Keywords: <<*bullwhip effect, demand amplification. supply chain, LNG, natural gas, operational management, artificial intelligence, neural networks, ANN, TSO, DESFA, electricity production, mitigation of the bullwhip effect*>>

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CHAPTER 1

1.1 Introduction

In a technology-driven world, search for optimization through new possibilities offered by the fast-growing field of informatics and artificial intelligence is always a critical necessity for any industry willing to adapt successfully, overcome the difficulties of a mutable environment, and embrace the future. Inevitable aftermath of this transitional era is that those who fail to keep up with the drastic changes in their sector will eventually be overwhelmed by the competition. Moreover, as Max McKeown quotes, “all failure is a failure to adapt, all success is successful adaptation.”

Supply chains are a key element of a typical business model as they determine the smoothness and cost-efficiency of an important part of the operational process. Therefore, maximizing their level of effectiveness is a significant aspect of the planning and research realized in most aspects of entrepreneurship nowadays. A few decades before though, little attention was given to the proper function of the logistics department of a company, which resulted in capital and labor force waste. Even if the problem were detected, the existing means did not permit further develop an efficient solution. With the introduction of scientific and systematic approaches to deal with business problems and the consequent development of the fields of business management and operational research, supply chain management gained tremendous appeal. However, the problems surrounding the operation of a supply chain are difficult to be distinguished and categorized, as they differentiate in each business and their causes can be described by a multifactorial complexity.

The primary objective for the viability of a company and the efficient operation of its value chain is the demand forecast. Any decision made in each stage of the total process is based on the assumption of having a specific amount of orders, despite the size and mission statement of the company. The precision of this forecast will determine the financial results of a project and ultimately its success. The impact of a poor plan on the overall business is significant. It causes cycles of excessive inventory and severe backlogs, poor product forecasts, unbalanced capacities, poor customer service, uncertain production plans, and high backlog costs, and even lost revenue, depending on the scale of over or under-estimation. Furthermore, an inaccurate prediction ignites a chain reaction, where every echelon of the supply chain overreacts to the signal of alternation in demand and amplifies the problem, widening the gap between actual demand and false data. Therefore, it is essential to strike a golden mean in order to satisfy the demand in the most efficient way possible and maximize the profit.

The main reasons for the volatility of demand vary, but with a good understanding of the market, they can usually be predicted as they relate to fixed factors. Seasonal demand depending on the product or service, national holidays, climate changes, advertisement and marketing, special offers, sales, and the overall financial system are the most common causes. Nevertheless, unforeseen circumstances can have detrimental effects on the overall planning and operation of a supply chain. The recent pandemic of Covid-19 demonstrated in the most evident way that even state-of-the-art industries, with the most advanced tools and direct access to the latest technological innovations, struggle through periods of global turbulence, because their orientation was only cost-related. An extreme change in demand disrupted the whole procedure of supply, leading to shortages of basic commodities, drugs, and medical equipment, all critical for human life. Consequently, it is necessary to prepare accordingly and have the agility to adjust to every possible scenario, whether it is a "black swan" event like COVID-19, trade war, act of war or terrorism, regulatory change, labor dispute, sudden spikes in demand, or supplier bankruptcy

The repercussions of demand fluctuations are determined of course by the size of the market. Hence, capital intensive industries entail accurate and reliable estimations, despite slight changes in demand they usually present. This study will focus on the energy sector, the backbone of every economy, and especially the LNG market. Except for its contribution to the country's GDP, it also constitutes a public good, as it is used for electricity production, heating, and transportation which are all vital aspects of today's human activity. Therefore, the necessity to study and predict the behavior of the market, in periods of acute demand irregularities, emerges as well as the need to better prepare the distribution system to respond efficiently to these changes.

The case study of the LNG industry in Greece constitutes a springboard for the thorough examination of the global market analysis. In addition, the operations of the supply chain must be examined from the upstream production, midstream transportation, and downstream processing to the final distribution system. In this way, the different echelons of the supply chain will be clearly defined to establish the theoretical framework to proceed to mathematical modeling. Different numerical methods for the representation of the supply chain and its response to demand fluctuations have already been suggested in the relating literature, although the present thesis will attempt to find a proper and solid approach with the data discussed and analyzed below concerning the LNG market

CHAPTER 2

2.1 Supply Chain in Operational Research

Supply chains comprise grids of firms that combine their capabilities and resources to deliver value to the end customer. Any network of companies that includes different people, activities, resources, entities, and information, all cooperating to create a final product or service for the customer, can be considered a supply chain. (Will Kenton, 2019.)

The supply chain represents the required steps to make the product or service available to the customer, starting from its original state. Following the development of global trade, supply chains have become ever more elaborate and complex to optimize their efficiency, reduce costs and tackle inflation which keeps pressure on prices. Consequently, apart from transforming raw materials into unique products and transporting them to retailer stores, supply chains also comprise product development, marketing, operations, distribution networks, financing, and customer service. In modern corporate management, it is considered impossible for a company to own or control complete supply chains. Information technology and innovative logistics solutions have contributed to creating a global market, where companies can source internationally. As companies grow bigger and invest in their development, they should pay closer attention and devote more resources to supply chains and logistics. A supply chain consists of suppliers, manufacturers, distributors, retailers, as well as customers, including all stages of transportation of goods, from raw materials through to customer's end. A supply chain is of course structured in such a way that customer's needs are met. The pyramid chart given below depicts the different stages of the supply chain, starting from the basis, emphasizing the significance of the customer.

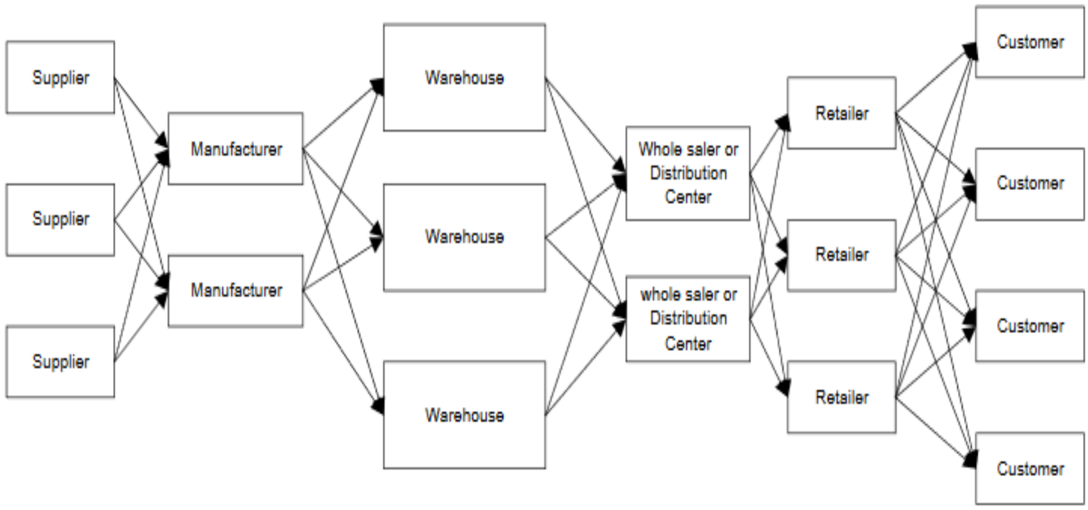


Fig.2.1.1: Supply Chain Grid Chart
(Chang, Makatsoris, 2000)

The supply chain is often compared to a river, in the sense that there is a continuous flow from the source (production) to the mouth (customer) of materials, information, products, or services. In the same context, a supply chain can be divided into upstream and downstream, although there can be a midstream stage as well.

Upstream production refers to the activities required to collect all the needed parts for the creation of the final product, while the downstream scale is associated with the processing of materials gathered in the upstream production up until the sale to the customer. Therefore, customer service is also part of the process, as it links the customer to the finished product or service. The downstream stage also includes the intermediate phases of the process, such as distribution, wholesaling and retailing, all of which are related to delivery to clients. However, the latter part can also be identified as the midstream level.

2.2 Supply Chain Management

The term "Supply Chain Management" was originally introduced by consultants in the early 1980s and from that time onwards it has gained tremendous attention as a vital part of operational research. (Perkins, Wailgum, 2017.)

Initial definitions of Supply Chain Management originally focused on the management of activities and material flows, whilst more recent theories emphasize the management of the supply chain as a holistic system with definite strategic targets. Supply chain management consists of a collection of approaches, employed to integrate into the most efficient way suppliers, manufacturers, warehouses, and stores so that merchandise or services can be produced and distributed in the adequate quantities, to the correct locations and at the right time, to minimize system-wide costs while satisfying service level requirements.

Fig.2.2.1: Operations of the supply chain management
(Openxcell, 2019)

Therefore, the main objectives of today's supply chain management focus on the improvement of coordination of materials and capacity, cycle time reduction, inventory cost reductions, optimized transportation, visibility across the supply chain, managerial analysis, and increase of customer responsiveness (Chang, Makatsoris). However, the practice of supply chain management in many occasions presents numerous dysfunctions, as supply chain members are mostly concerned with optimizing their objectives, ignoring the overall performance of the supply chain. This principle results in reduced coordination and inefficient transportation. One of the most typical examples of this logistics inherent phenomenon in the supply chains is the bullwhip effect.

2.3 The Bullwhip effect

The bullwhip effect refers to a phenomenon where the order variability increases as one moves upstream along the supply chain starting from the costumer's point. Slight fluctuations of demand in sales can progressively result in a chain reaction. Larger fluctuations in demand are observed at the wholesaler, distributor, manufacturer, and raw material supply levels. In other words, irregularities in orders in the lower part of the supply chain, tend to be more distinct higher up in the supply chain.

This differentiation is responsible for interrupting the normality of the supply chain process, given that every member involved in the supply chain over or underestimates the product demand. As a result, exaggerated fluctuations build up as the errors in the demand prediction grow in number. As

Pilevari et al [2016] highlights, bullwhip generates fluctuation in three aspects in supply chain - information, physical and financial. The common drawbacks of bullwhip effect could be bad demand forecast, insufficient or excessive inventory holding, poor customer service and uncertain production planning (Lee, Padmanabhan, & Whang, 1997). The bullwhip effect has been recognized in SCM literature as one of the chief barriers in up-scaling supply chain performance. The bullwhip effect is observed frequently in industries that serve developing markets where demand surges suddenly. Examples of such industries entail telecommunications manufacturing, grocery, automotive industry, electronics industry, computer components manufacturing, retail, furniture industry, food, and apparel. It can occur even in relatively stable markets where the demand is essentially constant and turmoil can cause great frustration and unbalance, such as in the energy market, where the research of this thesis will shed light on and specifically in the Liquefied Natural Gas (LNG) market.

The first to observe and record the so-called bullwhip effect was “Procter & Gamble” (P&G®), one of the biggest multinational companies focused on daily- use products. While examining order patterns for one of their best-selling products and more specifically baby diapers “Pampers”, P&G logistics executives noticed that demand was fluctuating slightly at the retail stores (stable demand taking in consideration that seasonal variations in births are slight), while greater variability of orders was observed in the upstream members of the supply chain. When they looked at distributors’ orders and the company’s orders of materials from their major supplier “3M”, they were astonished by the degree of variability. P&G called this phenomenon the bullwhip effect, based on the physics behind a bullwhip’s wave patterns: when the person holding the whip snaps their wrist, the relatively small movement causes the whip's wave patterns to increasingly amplify in a chain reaction. The further from the originating signal, the greater the distortion of the wave pattern. Therefore, the bullwhip effect is characterized by oscillations of orders at each level of the supply chain and amplification as one moves away from the customer.

When Hewlett-Packard® (HP) managers examined the sales of one of their printers in a grand reseller; they noticed a limited range of fluctuations. However, they were surprised by the scale of swings in the retailers’ orders and even more by their own orders to the integrated circuit division of the company.

Barilla®, the famous pasta company originated from Italy, experienced the serious impact of the bullwhip effect. In a widely recorded case, the company offered for a considerable amount of time, price discounts to customers who ordered full truckload quantities. Nevertheless, these marketing deals resulted in highly spiky and erratic orders. The orders fluctuations amplified the bullwhip effect which caused higher supply costs, enough to outstrip the benefits gained from full truckload transportation.

Another example of the bullwhip effect lies with the case of Campbell Soup, a company with relatively stable customer demand. They observed that despite the stable weekly demand, there was an annual cycle. The manufacturer faced even greater swings in demand at a factory level. After investigation, they concluded that these variations in demand were a result of retailers’ order practices and forward buying. The above is also illustrated in a chart made by Cachon and Fisher about the consumption in comparison to shipments of cases of chicken noodle soups throughout a year based on company data. (G. Cachon, M. Fisher, Production and Operations Management, 1997.)

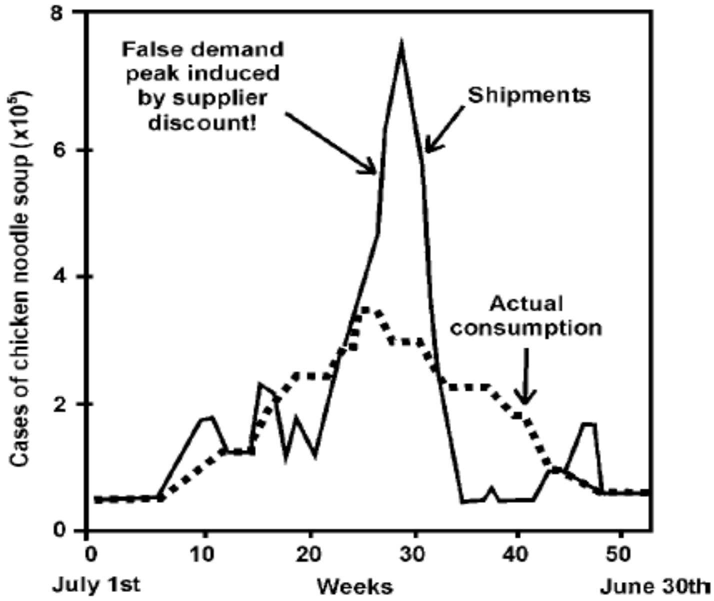


Fig.2.3.1: Shipments vs. Consumption chart in the Campbell Soup case

(Disney, Labrecht 2008)

It is noticeable that around January, where an increase in consumption is observed, product shipments are multiplied and exceed the demand by double the amount needed. The aftereffect of this seasonal pattern is ineffectiveness in both time and money for the whole supply chain.

Several recent empirical studies are worth highlighting. Cachon et al. (2007) used monthly sales and inventory data from the U.S. Census Bureau of 1992–2004 to examine the bullwhip effect in the manufacturing, wholesale and retail sectors. Hence, there was aggregation of time units, and aggregation across products. The bullwhip effect analysis was based on the material flow concept. They found that if seasonality is included in the measurement, production smoothing indeed exists in the retail industry and in some manufacturing industries, but not in the wholesale industry. With seasonally unadjusted data: 62% of manufacturers have a bullwhip ratio less than one, 86% of retailers had a bullwhip ratio less than one, while 84% of wholesalers have a bullwhip ratio larger than one. Hence, there is empirical evidence that while there was a tendency for companies to bullwhip the upstream suppliers, sometimes the desire to smooth production may be even stronger, dampening the bullwhip effect.

Bray and Mendelson (2012) reported that about two-thirds of firms bullwhip in a sample of 4689 public U.S. companies over 1974–2008. Building on the model of a generalized order-up-to policy proposed by Chen and Lee (2009), the authors decomposed the bullwhip effect by information transmission lead time. They found that demand signals with shorter time notice have greater impact on the bullwhip effect. Bray and Mendelson (2015) further investigated the bullwhip effect and production smoothing in an automotive manufacturing sample comprising 162 car models and found that 75% of the sample smooth production by at least 5 %, despite the fact that 99% of the sample exhibit the bullwhip effect. They measured production smoothing with a structural econometric production scheduling model based on the generalized order-up-to policy. The Order-Up-To (OUT) policy΄s main concept is that the system's inventory position (on-hand inventory + outstanding orders + backorders) is reviewed every period and an order is issued to bring the inventory position 'up-to' a defined level. More specifically, in a classical OUT the order quantity is generated to satisfy the demand and to recover the gap between the target stock level and the current level of available inventory (Cannella, Ciancimino, 2010). According to their structural estimation, there exist both a strong bullwhip effect (on average, production is 220% as variable as sales) and robust smoothing.

Shan et al. (2014) investigated the bullwhip effect using data from over 1200 public companies in China during the period 2002–2009. They found that more than two-thirds of the companies exhibit the bullwhip effect. Their regression analysis suggested that the bullwhip effect magnitude is positively associated with average on-hand inventory and persistence of demand shocks, and is negatively associated with degree of demand seasonality.

Osadchiy et al. (2016) investigated the systematic risk in demand for different industries and firms in the U.S. economy, including retail, wholesale, and manufacturing sectors. They used sales as a proxy for demand, and defined the systematic risk in sales as the correlation coefficient of sales change with the contemporaneous market return. They found that aggregation of orders from multiple customers and aggregation of orders over time can result in the amplification of systematic risk upstream along the supply chain.

The "Beer Distribution Game" is the best illustration of the bullwhip effect in a supply chain. The above-mentioned game was invented by Jay Forrester, professor of Management in System Dynamics at the MIT Sloan School of Management, as an exercise for the understanding of distortions in the supply chains for his students. (MIT Sloan- Management Executive Education.) Jay W. Forrester's research focused on the behavior of economic systems, including the causes of business cycles and the major depressions, a new type of dynamics-based management education, and system dynamics as a unifying theme in college education. The original Forrester paper on the bullwhip effect (1958) and the subsequent text book (1961) formed the foundation for Industrial Dynamics, or what is now termed System Dynamics, the school of thought that relates system structures to dynamic behavior in organizations. A fundamental principle of System Dynamics is that "feedback theory explains how decisions, delays, and predictions can produce either good control or dramatically unstable operation" (Forrester, 1958). Therefore, the bullwhip effect is also known as the "Forrester Effect". (Lee, Padmanabhan, Zhang, 2015.*)* Forrester also called it "demand amplification" (S.M. Disney, M.R. Lambrecht, 2008).

The beer distribution game was further developed by Sterman. Computerized versions of the game were made and several versions are now available, making it one of the most popular simulations in business schools, supply chain electives, and executive seminars. In the game, participants play the role of customers, retailers, wholesalers, and suppliers, forming a four-stage supply chain. Their main goal is to produce and distribute the demanded beer bottles. It is prohibited for participants to communicate with each other and they must make their decisions based only on downstream orders. Lack of communication and coordination amongst the supply chain members can cause great difficulties to the players, who struggle to accomplish the desired goal (Supply Chain Academy). Sterman also published a study with 20 years of data from the game, noticing that the tendency of the players to ignore the inventory-on-order (orders placed, but yet not received) was a major contributor of the amplification.

The chaotic and unpredictable demand signal, as interpreted by the upwards stages of the supply chain, was also a field of interest for Hau Lee, a professor of Operations, Information, and Technology at the Stanford Graduate School of Business. His areas of specialization include global value chain innovations, supply chain management, global logistics, inventory modeling, and environmental and social responsibility (Stanford University). Chen and Lee (2012) argued that bullwhip primitive effect definitions have conceptualized the concept in different ways, and that the original BWE definition (Lee et al., 1997a) measured the effect based on information flow in single product and an order decision period situation. However, a number of empirical studies that came after measured the BWE based on the observed material flow, aggregated products, and aggregated time-periods.

Despite the methods used to forecast future demand that will later be elaborated, at every stage of the procedure, there are unexpected fluctuations and disruptions that can influence supplier orders, making it a nonlinear problem. As complex, a phenomenon as it might be, certain commonly accepted operational causes for its development have been identified and recorded. Some of the most important, as categorized by operational management and academic findings are: *demand signal processing, rationing, shortage gaming, order batching, price fluctuation, and information communication*. It is interesting that despite the expanded research on the field conducted the last years, the main causes of existence of the bullwhip effect have not been doubted or alternated. On the contrary, recent papers have supported the above reasons with providing evidence through empirical studies depending on the emphasis given in each study.

Information Sharing

The importance of information sharing among the channel member groups has been one of the centers of discussion in the bullwhip effect relating literature. Information-sharing is often proposed as a remedy for coordination of flows in the supply chain and for reducing the negative impact of the bullwhip effect (Sahin and Robinson, 2002, 2005), as they observed a 48% reduction in operational costs due to information sharing and coordination in make-to-stock supply chains. Cachon and Fisher (2000), Xuet al. (2001), Huang et al. (2003), Sawaya (2003), Lee et al. (2000),Patnayakuni et al.(2006) also claim that information sharing and coordination both reduce the bullwhip effect and improve the overall supply chain performance. These benefits include enhanced inventory management capabilities that may boost operational efficiency and reduce costs in some areas. The enhanced service level and fill rate capabilities from an effective inventory policy can also result in higher revenues in many cases (Dai et al., 2017). This is why modern industrial tools for supply chain management, promote information sharing, such as Dell's Integrated supplier-logistics information systems and Cisco's Virtual Manufacturing Model, which share information with channel members in order to enable reduced system-wide inventory costs through better coordination. Croson and Donohue (Interfaces, 2002.) together with Sterman (Management Science, 1989.), concluded that during decision making, interested parties consistently under-weight the supply chain. In other words, people are not certain for what is available upwards or downwards the supply chain. The bullwhip effect exists in supply chains with low levels of trust, where only a little information is being shared between the involved parties. Lack of communication between each link of the supply chain makes it difficult for processes to run smoothly and efficiently. Managers, as mentioned before, often perceive a product demand quite differently within different links of the supply chain and therefore order different quantities. Besides, a lack of coordination may occur, either because of conflicting interests between different members of the supply chain or because of delays and distortions in the information flow between stages. Conflicting objectives can arise when each stage is owned by a different individual who is meant to seek the highest possible profit. Therefore, each stage tries to maximize its gains, resulting in actions that diminish total supply chain profits. This competition blocks information sharing which ultimately leads to demand fluctuation. Generally though, the reasons for inefficient communication vary and sometimes relate to trust issues or perceived risk factor considerations concerning the usefulness of the information to best coordinate the supply chain. (Oijah, Sahin, et al., 2019) For instance, there may be situations when a specific type of information is shared only for a particular tactical purpose, such as for freight consolidation in the supply chain (Shockley and Fetter, 2015).

Demand signal processing

Companies often rely on past demand information to estimate the current demand of a product. This method, convenient and relatively accurate as it may be, it cannot take into account any sudden and unexpected fluctuations that may occur in demand over a period. This results to a critical delay that in turn creates a mismatch between real orders and false assumptions that aggregate over time and intensify the phenomenon. In general, the forecasting methods used by a company to

Order Batching

In a supply chain, most companies batch or accumulate demands before issuing an order. There are plenty of reasons for companies to do so. Order batching occurs mainly due to economies of scale (e.g., reducing order transaction costs, obtaining volume discounts and achieving full truck shipments), but may also result from a periodic inventory review process. It is common for a supplier not to be able to handle frequent order processing due to time delays and high cost that derives from labor intensity and transportation fees. Likewise, many companies place an order after they consult their PMS (Property Management System) software, something that does not happen on a daily basis. Consequently, instead of ordering frequently, companies usually order on a weekly, biweekly or even monthly basis. Companies that choose periodic ordering usually observe a higher variability in demand than the actual one. This occurs when there is for example a sudden rise in demand at some stage followed by no demand afterward. In that way, periodic ordering increases variability and therefore contributes to the bullwhip effect.

Price Fluctuation

Companies often buy items in advance of requisitions. Estimates indicate that 80% of the transactions between manufacturers and distributors in the grocery industry in 1991 were carried out through a “forward buy”, which added up to 75-100 billion dollars (P. Sellers, 1992.). This usually happens due to price fluctuations created by special promoting actions, such as price discounts, quantity discounts, and coupons. However, this leads to companies buying quantities that do not reflect their immediate needs to stock up for the future, taking advantage of lower prices. If the cost of holding inventory is less than the price difference, buying in advance may indeed be a rational decision. Nonetheless, when companies buy superfluous stock and expect depletion of their inventory at a specific rate, the constant variation of the consumption will force them to change multiple times their business planning. Liquidity crises, unexpected price formation, lack of flexibility in market alternations prompt managerial problems that inevitable lead to extensive delays, further increasing the bullwhip effect. This applies of course to the side of the customer at the end point of the supply chain. External cost shocks, such as promotional discounts, will induce forward buying behavior, which again causes the bullwhip effect (Blinder 1986)

Order fulfillment has strategic components that play a key role in the function of supply chain management, even if it is traditionally viewed as a more of a logistics function. Order fulfillment performance is a composite measure of the inventory availability, processing timeliness of orders, inventory acceptance, and the speed and accuracy of order delivery (Davis-Sramek et al. 2010; Griffis et al. 2012; Gao et al., 2012). Croxton (2003) argues that order fulfillment is a cross-functional practice that requires some degree of coordination and control. Shortage gaming and rationing gaming are terms attributed to the behavior related to the inventory control of a company

Rationing Gaming

When product demand exceeds supply, manufacturers often set limitations to their products to satisfy their customers in the highest possible degree. For instance, the manufacturer allocates its products in proportion to the amount ordered by the different retailers. Retailers often anticipate potential shortages and therefore exaggerate their real needs when they place an order. If demand drops later, this will lead to reduced orders or even cancellations. This overreaction by customers is called rationing and shortage gaming and it results in misleading information on the product real demand. In a supply chain consisting of a manufacturer, multiple wholesalers, and multiple retailers, if the manufacturer appears to be in short of supply, wholesalers will play the rationing game to get a large share of the supply. Considering the possibility of not getting enough from the manufacturer, retailers also participate in the rationing game. The aftermath is that demand and its variance are amplified as one moves up the supply chain.

Shortage Gaming

More specifically, shortage gaming occurs when customers place multiple orders for the same product from different suppliers and then cancel all orders except one or when they place a larger order than needed. Customers tend to do this if they know inventory will be in short supply. This kind of order creates a false demand picture for the product provider, making them increase output. The problem appears often in businesses where shortages are expected. In reality, there are a plethora of examples to this rationing and shortage gaming. One of the most common in the bibliography is the shortage of DRAM chips in the 1980s. In the computer industry, orders for these chips grew fast, not because of an increase in customer demand, but because of anticipation. Customers placed duplicate orders from multiple suppliers, bought from the first that could deliver and then canceled all other orders. In many companies, especially those in the retail industry, a common practice to cope with this problem is to ask the customer for payment in advance.

Behavioral Causes

In bigger companies with more elaborate supply chains that control every stage of the process, this is considered a minor issue, as there is higher expertise and an extended use of automations as a safety valve. It is important to understand though, that behind every decision there is an employee responsible, since integrated digitalization has not been accomplished yet. The decision logic of the individuals in the supply chain is characterized by a tendency to over-respond to increases or decreases in demand from customers. People’s perceptions and mistrust are key elements of the misconceptions created throughout the supply chain. Also, uncertainty for future demand creates anxiety and often forces people to make irrational and hurried decisions, ignoring the detailed forecasts carried out with the use of statistical science. Time lags due to increased workload or procrastination, in the transmission of both order information and materials alongside the supply chain can also exacerbate the effect.

Delivery Delay

Delivery delay, also called “lead time”, refers to the period between the placement of an order and the delivery of the product. If a company does not maintain sufficient inventory, it needs to account for the time it takes its suppliers to produce and/or deliver goods. When the wholesaler receives an order from the retailer, they prepare the merchandise and deliver it. Processing the order and delivering it to the customer takes considerable time. While the order is being transported, the retailer continues to sell; as stock disappears, the retailer orders even more from the wholesaler. The wholesaler, in turn, experiences a decrease in inventory and places additional orders with the manufacturer. The greater the delivery delay, the more prone the supply chain is to the bullwhip effect because orders increase across it, as everyone expects delivery. If all participants in the supply chain do not account for the orders and continue to order in the same pace as inventory is being depleted, when the ordered items start arriving, the participants will end up overshooting their desired inventory levels and decrease future orders

It is also believed that smoothing/ amplification behavior may vary among different nations and cultures. Mollick (2004) described evidence of production smoothing in the Japanese automotive industry, where the production smoothing is more common due to the prevalence of Heijunka (leveling) and Just-In-Time manufacturing strategies. Shan, Yang, and Zhang (2014) studied the bullwhip effect in China, finding that bullwhip was gradually being reduced.

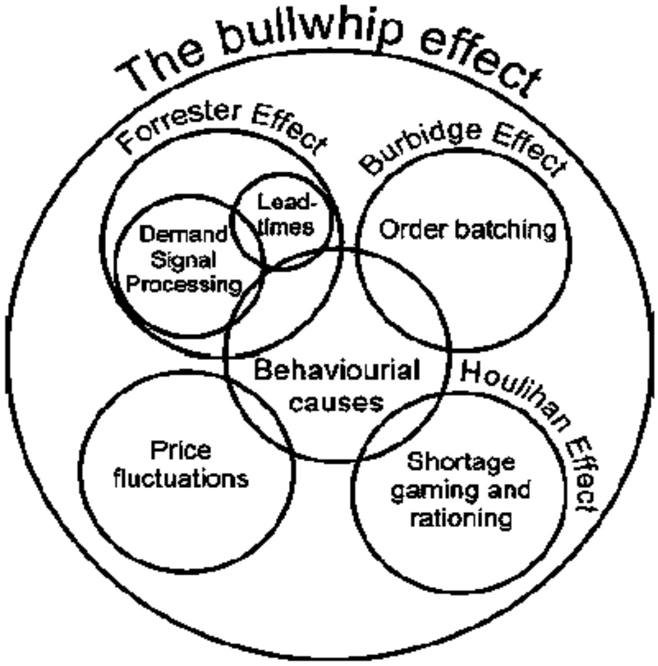


Fig.2.3.2: Categorization of the causes of bullwhip effect based on researchers who identified them
(Disney, Labrecht 2008)

In addition to the causes proposed by Lee et al. (1997a, 1997b), multiplier effect, also known as the "investment accelerator effect" in macroeconomics, is a cause of the bullwhip effect often overlooked by researchers. It refers to the phenomenon that a small change in demand for consumer goods creates a dramatic change in demand for capital equipment used to produce those goods (Anderson et al., 2000; Wang and Disney, 2016). Different from finished goods whose residence time in inventory is rather short, capital equipment is typically replaced on a depreciation basis, whose residence time is the defined lifetime of the equipment (Anderson and Fine, 1999; Anderson et al., 2000). For example, supposing that a firm is operating at full capacity with 10 machines, and replaces its machine at the rate of 10% per year (i.e., the average machine lifetime is ten years). In this case, the quantity of machines ordered is generally stable (i.e., one machine per year). However, if the company expects a sustained 5% increase in demand, they will purchase machines to expand their production capacity by 5%. Thus, the machine order quantity increases to two in that year (100% increase, as it is impossible to purchase half a machine to meet the exact change in demand), and the change in product demand (5%) is amplified twenty times (100%) in the upstream echelon, causing the BWE. However, it should be noted that this example is oversimplified. In practice, the constant capital output ratio (e.g., one machine produces one product per day) may not necessarily hold constant; varying depreciation policies can affect the replacement demand; for new equipment, replacement demand may not exist in the short run; and obsolescence also influences the order quantity (Bishop et al., 1984). Bishop et al. (1984) described how the multiplier effect (they called "the acceleration principle") and purchasing agents' behavior cause volatility in demand for turbo machinery equipment used in oil and gas production. Anderson et al. (2000) demonstrated that the multiplier effect is an important source of the bullwhip effect in the machine tool supply chain.

The Bullwhip effect is directly correlated to the forecast of demand which is considered quite a challenge itself. Companies often predict demand, based on insufficient information while accounting for complex factors that enable the required quantity to be delivered. The selection of a method consists of a plethora of factors such as the context of the forecast, the relevance and availability of data, the degree of desirable accuracy, the time of the forecast, the cost- advantage of the forecast to the enterprise, and finally the time available for the analysis. Chen et al. (2000), Chen, Ryan, and Simchi-Levi (2000), Zhang (2004) all conclude that that the poor choice of forecasting method can increase the bullwhip effect magnitude. Most companies schedule their duties as far as production planning, inventory control and material requirements are concerned, based on forecasts they do according to previous orders from the company's direct customers. When an order is placed, this information itself is perceived as a signal about future product demand. Based on this signal, the upstream manager of the supply chain readjusts their demand forecast often with a safety factor in mind. As one moves upstream the chain, this safety margin created by each link may accumulate to create great variability. As Gavetti and Rivkin (2005) point out "Dangers arise when strategists draw an analogy on the basis of superficial similarity, not deep causal traits", that is, there is reliance on what is termed 'surface similarity'. But as Forrester noted in an interview: "The trouble with systems thinking, is it allows you to misjudge a system. You have this high-order, non- linear, dynamic system in front of you as a diagram on the page. You presume you can understand its behavior by looking at it, and there's simply nobody who can do that" (Fisher, 2005). This reinforces Richardson's (1991) argument that simple visual inspection of causal loop diagrams to determine system stability is insufficient and deeper understanding of the underlying control mechanisms is required. The most common forecasting techniques, as described in the bibliography, are analyzed below.

Qualitative Methods

- **Complete Enumeration Method**

This method can be used for products of a limited outreach to the public, as it takes into account all the potential consumers of the product or service. Afterwards, the final demand is calculated by the total sum of the individual demands.

$$D_p = \sum_{i=1}^{N} Q_i$$

- **Sample Survey Method**

In cases where the demand is bigger, so an accurate and reliable evaluation of the potential consumers cannot be done, the sample survey method is preferred instead. In this method, a representative sample is picked with the use of scientific data analysis that takes part in a survey conducted by the company through interviews or questionnaires. The demand is given by the below formula:

$$D_p = \frac{N_R}{N_s}(N \cdot A_D)$$

where N_S stands for the number of people participating in the survey, while N_R is the number of potential buyers based on their responses and A_D the mean anticipated consumption.

- **End-Use Method**

In products whose use differs greatly depending on the type of the consumer, research is conducted to determine preferences, consumer habits, desired quantities and future plans of the buyer. It applies mostly in industrial products, which in contrast to consumer goods are finite in number making it possible to conduct an analytical research. In these cases there is direct and continuous contact between buyers and producers in order to determine the real demand as opposed to the other methods.

- **Market Experiment Method**

This method refers to an analysis performed to identify the level of sensitivity and the behavior of the demand towards changes in product prices or total amount spent by the customers. The experiments are performed in real market conditions and in areas with similar parameters such as corresponding population, average income, educational level, age, consumer habits, gender etc.

- **Panel Consensus**

The technique is based on the logical assumption that a panel of experts will come up with a better prediction than this of a single employee. Among the experts, communication and exchange of views are encouraged to achieve the best possible result. This team of experts can be composed either by company executives (Jury / Executive Opinion Method) or a mixture of internal and external experts

(Survey of Experts' Opinions). The forecast of demand is formulated by the collective result of the average opinions of all experts.

- **Historical Analysis**

This is a comparative analysis of the market which considers the entry and growth of a product in the consumers' environment, based on patterns of similar products or services. It is used mainly for new products that have not yet been released and there are no detailed information on the demand.

- **Delphi Method**

A group of experts express their opinion on future demand by answering to a set of questions. This group often includes people who come from both inside and outside the business. Each member specializes in a specific aspect of the problem, but has not a holistic understanding of the problem as in panel consensus. It is a way of combining a broad knowledge base, using the expertise of experienced professionals. By maintaining anonymity, the Delphi method attempts to neutralize subjective polarization and the influence of participants by factors such as prestige, persuasion, and the dynamism of certain experts (Hallo effect). The results are fed back to the experts, who then update their predictions and the process is repeated until a convergence is reached. At the end of each round, a statistical summary of the various crises, their scope and the causes of the difference between them is made.

Quantitative Methods

- **Naïve Forecasting**

Naïve forecasting is mainly used as a reference with which other methods are compared, in order to be assessed. It makes use of the latest value of the variable to calculate future demand, ignoring demand patterns from previous data or adjusting data to establish a certain forecast model. Because a naïve forecast is optimal when data follow a random walk it is also called a random walk forecast. (Monash Business School). Therefore:

$$y_{t+1} = y_t$$

- **Time series Analysis**

A part of the quantitative methods of demand forecast entails a time variable analysis in which the forecast is conducted only with the use of the demand-time chart, often neglecting the influence of external factors that lead to this change in demand. However, after extensive research in the field of time series analysis, experts have concluded that the principal reasons that provoke these changes and can be determined without further technical analysis can be summarized in the below mathematical symbol:

$$D_t = f(t, I_t, b_t, e_t)$$

- t : $time$
- I_t : $Seasonal\ trend$

- b_t : $Market\ trend$
- e_t : $randomness$

Some of the most commonly used time series forecasting methods that are going to be presented more extensively below are:

- Moving Average (MA)
- Autoregression (AR)
- Autoregressive Moving Average (ARMA)
- Random Walk
- Autoregressive Integrated Moving Average (ARIMA)
- Seasonal Autoregressive Integrated Moving-Average (SARIMA)
- Vector Autoregression (VAR)
- Simple/ Double/ Triple Exponential Smoothing

- **Moving Average**

Moving average is an extensively used indicator in technical analysis that uses the average of a series of values in a defined time period to calculate future demand. In this way, random short- term fluctuations in demand or pricing are filtered out. It belongs to quantitative forecasting methods and it is a trend-following or lagging indicator, given the fact that it is based on sales history. The moving average can be calculated by different formulas, but the most widely used ones are the simple moving average, which is the arithmetic mean of a set of values and the exponential moving average, which emphasizes more on recent history. (Investopedia)

Simple Moving Average can be easily calculated:

$$y_{t+1} = \frac{y_t + y_{t-1} + \cdots + y_{t-m+1}}{m}$$

with m being the actual number of distinct values

or found as: $\widehat{D_t} = \frac{1}{T} \sum_{\tau=t-N}^{t-1} y_\tau$

The number of periods N for which the moving average is calculated, also determines the degree of smoothing of the value, under random fluctuations. These fluctuations seem to be influencing the demand less for an increasing number N. It is important for the precision of the forecast to pick a number of periods that is neither big nor too small, thus it is a common practice to choose the number of periods that present the lowest MSE value (mean squared error).

In some cases, a weighted moving average is used. In this way, the effect of the older periods is usually given reduced gravity, while the process of defining these weights is performed intuitively, based on past experience and level of expertise of the individual. In general, a delay in trend monitoring and a phase difference in circular demand are observed in the moving average hence not allowing the use of analytical data on circularity or seasonality.

- **Autoregression**

In the autoregression model of forecasting (AR), demand is calculated using a linear sum of past values of the variable to feed the equation with constant information about the demand. The demand is in other words regressed over itself to predict the future. This method is preferred when there is an uncertainty about the future behavioral patterns of the demand and there are no sufficient data that can lead to a reliable prediction. The model gives a better forecast over time, as the information provided gets more detailed.

$$\widehat{D_t} = c + \varphi_1 y_{t-1} + \varphi_2 y_{t-2} + \cdots + \varphi_p y_{t-p} + \varepsilon_t$$

Where ε_t is the error factor or white noise. It is usually chosen as a random variable following the normal distribution with a specific variance (Var[ε_t]) and mean (E[ε_t]) and changes the scale of the time series, not the patterns which are determined by the parameters ϕ_i.

It is often found as an AR(p) model (autoregressive model of order p)

An autoregressive model with ϕ_1=1 and c≠0 is also known as the *random walk method*.

- **Autoregressive Moving Average**

The general ARMA (p,q) model has *p* autoregressive terms, as in the AR (*p*) process in the previous equation, and in addition contains *q* moving average terms that compose a weighted average of the *q* previous values of the error term ε_t. It is not very commonly used, in comparison to the general autoregression method (AR). The ARMA (*p*, *q*) model thus contains *p* autoregressive parameters ϕ_p and *q* moving average parameters ϑ_q that affect the time series according to the below formula:

$$x_{t+1} - \mu = \sum_{p=1}^{P} \varphi_p x_{t-p+1} - \mu + \varepsilon_{t+1} - \sum_{q=1}^{Q} \theta_q \varepsilon_{t-q+1}$$

Where μ is the mean of the series and ε_t a random process component (Shahin et. al., 1993)

- **Autoregressive Integrated Moving Average**

Autoregressive integrated moving average (ARIMA), a generalization of the ARMA model with the addition of differencing. In statistics differencing constitutes a transformation applied to time-series functions to make them stationary, so that their properties are time- independent. In this way, seasonality and trend are eliminated giving the series a steadier mean. The ARIMA model applies advanced econometric modeling techniques to forecast time-series data by first back-fitting to historical data and then forecasting the future. (Giantz, Morton, 2011)

It is symbolized ARIMA (p,d,q), with *p* standing for the lag order of the autoregressive model, *d* for the degree of differencing and *q* for the lag order of the moving average model, is given by the equation:

$$\left(1-\sum_{i=1}^{p}\varphi_i L^i\right)(1-L)^d x_t=\left(1+\sum_{i=1}^{q}\theta_i L^i\right)\varepsilon_t$$

With L being the lag operator, which returns the previous element of the variable:

$$L^k X_t = X_{t-k}$$

- **Seasonal Autoregressive Moving Average**

When the element of seasonality is considerable in the phenomenon under study, it is essential to be able to insert this information in the forecast in order to have the desired results. The SARIMA model fulfills this purpose by adding seasonal parameters (P, D, Q) to the ARIMA method. The general form of SARIMA (p, d, q)(P, D, Q) is given by: (Chang, Gao et. al., 2012)

$$(1-\sum_{i=1}^{p}\Phi_i L^{is})(1-\sum_{i=1}^{p}\varphi_i L^i)\cdot(1-L^s)^D\cdot(1-L)^d\cdot x_t=\left(1+\sum_{i=1}^{q}\Theta_i L^{is}\right)\left(1+\sum_{i=1}^{q}\theta_i L^i\right)\cdot e_t$$

Where s is the period of the time series, for example s = 12 for a monthly overview.

- **Structural Vector Autoregression**

Structural Vector Autoregression, a general form of the Vector Autoregression model [VAR(p)], is used in the case where causal influences can occur either instantaneously or with considerable time lags. It is a linear combination of the past values of variables. As a model it is very popular in econometric theory, in which numerous attempts have been made for its estimation, see, for example, Swanson and Granger (1997), Demiralp and Hoover (2003) and Moneta and Spirtes (2006).

The formula of the model SVAR (p) is shown below (Lane, Luotto et. al., 2019)

$$B_0 x(t)=c_0+\sum_{i=1}^{p}B_i x_{(t-i)}+\varepsilon_t$$

Where p is the number of time delays, k is the number of the observed values, c_0 is a (k × 1) vector of constants, B_i is a (k × k) matrix (for every i = 0, ..., p) and ε_t is a k × 1 vector of the known Gaussian error terms. The main diagonal terms of the B_0 (k x k) matrix are scaled to 1.

For a better understanding it would be useful to show a double variable SVAR (1) example:

$$\begin{bmatrix}1 & B_{0;1,2}\\ B_{0;2,1} & 1\end{bmatrix}\begin{bmatrix}x_{t;1}\\ x_{t;2}\end{bmatrix}=\begin{bmatrix}c_{0;1}\\ c_{0;2}\end{bmatrix}+\begin{bmatrix}B_{1;1,1} & B_{1;1,2}\\ B_{1;2,1} & B_{1;2,2}\end{bmatrix}\begin{bmatrix}x_{t-1\,;1}\\ x_{t-1\,;2}\end{bmatrix}+\begin{bmatrix}\varepsilon_{t;1}\\ \varepsilon_{t;2}\end{bmatrix}$$

A difficult task for the realization of demand forecasting with this time-series method is the definition of the equation parameters, a problem for which numerous techniques have been proposed, such as the one of multivariate least squares.

- **Exponential Moving Average**

Also called Brown's Simple Exponential Smoothing, where the weights assigned to the periods are being reduced exponentially. It is given by the below formula:

$$y_t = \left[Y_t \cdot \left(\frac{s}{1+d}\right)\right] + y_{t-1} \cdot (1 - \frac{s}{1+d})$$

or: $$y_t = a \cdot Y_t + (1-a) \cdot Y_{t-1}$$

Where: y_t = Exponential moving average today

y_{t-1} = Exponential moving average yesterday

Y_t = Value today

a = smoothing factor, calculated as $\frac{s}{d+1}$ usually between 0.01 and 0.3

d = number of days

- **Double exponential Smoothing**

Experience has shown that simple exponential smoothing presents significant prognostic errors in cases of one-sided changing demand. The basic concept is that demand is overestimated when the trend is positive and devalued when it is negative. To address this disadvantage, the projected demand price $\widehat{D_{t+1}}$ can be divided into two parts, the first of which (a_t) refers to the smoothened values of demand fluctuations, while the second (b_t)to the influence of market factors (trend). This technique is also called the Holt method and is described by the equations:

$$a_t = a \cdot y_t + (1-a)(a_{t-1} + b_{t-1})$$

$$b_t = \beta \cdot (\alpha_t - a_{t-1}) + (1-\beta) \cdot b_{t-1}$$

While the demand:

$$\widehat{D_{t+1}} = a_t + b_t \quad ,for \quad t < t_e$$

$$\widehat{D_{t_e+k}} = a_{t_e} + b_{t_e} \cdot k \quad ,for \quad k \geq 1$$

- t_e : the period of the last recorded value of demand Dt_e
- k : the number of periods of the forecast after t_e

In this way it is possible to evaluate the demand $\widehat{D_{t_e+k}}$ based on the last real value of demand in the moment t_e.

The choice of the two constants α, β ∈ $[0,1]$ defines the rate of convergence of the smoothened curve of demand to the real trend. To achieve error minimization it is useful to test a variety of combinations in the range of values of the two constants.

- **Triple exponential Smoothing with trend**

If the actual demand data shows systematic fluctuations, then this may be a sign of seasonality. The model is based on a seasonality index (It), which results from dividing actual demand at some point by the average value of demand for that period. The most commonly used method that reckons the element of seasonality is essentially an adaptation of the Holt model, and it is called the Winters' method. It is preferred as a method when there is seasonality and trend based demand behavior.

For a period of variations equal to l, this adjustment lies in the adoption of another constant to describe the problem, the "γ" smoothing parameter:

$$a_t = a \cdot \frac{D_t}{I_{t-1}} + (1-a)(a_{t-1} + b_{t-1})\,, \quad 0 \leq a \leq 1$$

$$b_t = \beta \cdot (a_t - a_{t-1}) + (1-\beta) \cdot b_{t-1}, \quad 0 \leq \beta \leq 1$$

$$I_t = I_0 \quad when \quad t > 1$$

$$I_t = \gamma \cdot \frac{D_t}{a_t} + (1-\gamma) \cdot I_{t-1} \quad , t \geq 1 \; and \; 0 \leq \gamma \leq 1$$

$$\widehat{D_{t+1}} = (a_t + b_t) \cdot I_{t-1} \quad , for \quad t \leq t_e$$

$$\widehat{D_{t_e+k}} = (a_{t_e} + b_{t_e} \cdot k) \cdot I_{t_e-1+k} \quad , for \quad k \geq 1$$

The initialization of the constants a_t, b_t, I_t influences as well the errors of the method, at least for the first periods.

- **Linear Regression/ Time Series trend- based forecasting**

Trend based forecasting is based on a regression model that uses time as an independent variable and calculates the demand as a function of time. It is quantitative forecasting, based on solid data from the past which are usually presented in a time chart. It is considered the basic method of time series forecasting. It is applicable not only to the field of time, but also to other variables that affect the demand and can provide sufficient data for the forecast. In this context, it is known as linear regression model which is widely used in many aspects of business and finance.

Its mathematical representation is shown below:

$$\boxed{y_i = at_i + b + \varepsilon_\iota}$$

$$a = \frac{\sum_{i=1}^{N} y_i \cdot \sum_{i=1}^{N} t_i^2 - \sum_{i=1}^{N} t_i \cdot \sum_{i=1}^{N} t_i y_i}{N \cdot \sum_{i=1}^{N} t_i^2 - (\sum_{i=1}^{N} t_i)^2}$$

$$b = \frac{N \cdot \sum_{i=1}^{N} t_i y_i - \sum_{i=1}^{N} t_i \cdot \sum_{i=1}^{N} y_i}{N \cdot \sum_{i=1}^{N} t_i^2 - (\sum_{i=1}^{N} t_i)^2}$$

$$\sum_{i=1}^{N} \varepsilon_i^2 = \sum_{i=1}^{N} (y_i - a \cdot t_i - b)^2$$

As the ε_i factor shows the random error which is the Euclidean distance of the real value of the demand y_i from the theoretical line y = at + b.

A useful indicator in the above method is the coefficient of determination, a measure of how closely the trend line corresponds to existent historical data:

Let $\hat{y_i}$ be the calculated value from the above algorithm.

$$R^2 = 1 - \frac{SSE}{SST} = \frac{SSR}{SST}$$

since SST = SSR + SSE

Where: $SSE = \sum_{i=1}^{N}(y_i - \hat{y_i})^2$ (error sum of squares)

$$SST = \sum_{i=1}^{N} y_i^2 - \left(\frac{\sum_{i=1}^{N} y_i}{N}\right)^2 = \sum_{i=1}^{N}(y_i^2 - \bar{y}^2)$$ (Total sum of squares)

and the regression sum of squares: $SSR = \sum_{i=1}^{N}(\hat{y_i} - \bar{y})^2$

The total sum of squares (SST) measures the variance of observations when the information about the time variable is not used, but only the average value of Y. The SSR expresses the variance removed from the problem when utilizing the information for the time variable, while the SSE expresses the residual variance after the regression. The coefficient of determination R^2 expresses the percentage of the total variability of y_i in the regression model chosen. It takes values in the codomain [0, 1] and is equal to 1 when all points (x_i, y_i) lie on the line of regression. On the other hand, when the slope α of the line of minimum squares is zero, R^2 also equals to zero. In practice, the closer the value of the determination factor to the unit is, the better the estimate of the minimum squares.

- **Regression Analysis**

In the above paragraph, an analysis was made of the projected demand according to a time-varying analysis. Below it will be analyzed how demand (D) can be changed based on a specific factor (x), for example, the change in demand for heating oil based on the outside temperature. This analysis leads to significant assumption errors when the demand for a product is multifactor, hence giving satisfactory results when the demand depends on few elements or even on more but with a dominant factor that undoubtedly influences the demand. In each regression model, two types of variables can be distinguished: the independent (independent, predictor, casual, input, explanatory variables) and the dependent or response variables. To examine whether there is a relationship between the two variables and its extent, the correlation coefficient is often used. Between two variables (Y and X), the correlation coefficient is defined as:

$$\rho = \frac{\sum_{i=1}^{N}(X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X - \bar{X})^2(Y - \bar{Y})^2}}$$

or:

$$\rho = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$$

With σ being the covariance of the variable.

The correlation coefficient takes values in the domain [-1,1]. Value equal to 1 (positive correlation) signifies an absolute correlation between the two variables, with an increase in the independent variable implying an increase in the dependent. The opposite is true for correlation coefficients of -1 where a drop in one variable implies an increase in the other. Zero value, indicates no correlation. While the correlation coefficient examines whether there is a relationship between two variables, regression as analyzed above establishes the appropriate relationship between them.

- **Neural Networks**

Artificial neural networks (ANNs) provide a way to make intelligent decisions while leveraging on today's processing power. The advantage of using neural networks in demand forecasting is that it maps the dependence of each variable involved accurately without having to worry about the details of the programming algorithm as long as the learning ability of the artificial neural network is ensured by the solid mathematical model established in the beginning.

The idea of neural networks has been inspired from the function of the brain. The brain consists of a large number (approximately 10^11) of highly connected elements (approximately 10^4 connections per element) called neurons. These neurons are connected in the sense that they pass electric signals amongst themselves on receiving input from the sensory organs and thus coming to various "output nodes" where the decision is taken. This can be modeled graphically as shown with the use of nodes, inputs and outputs:

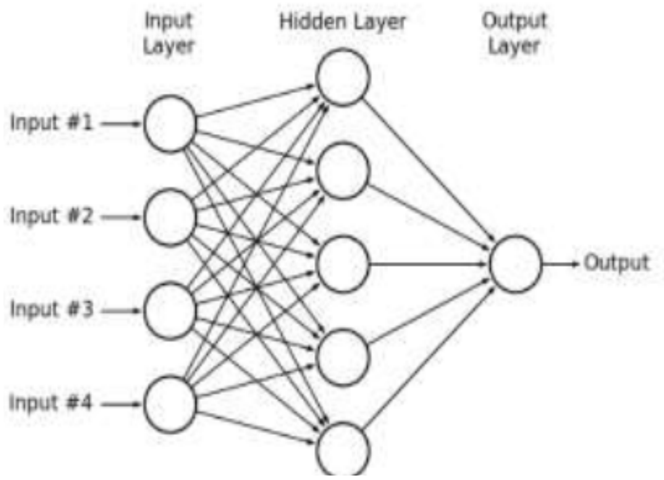


Fig. 2.3.3: Layer structure of neural networks

Likewise, a neural network consists of a set of nodes/ neurons which receive signals that affect the weights and the activation function. The basic mathematical model of this operation is the below:

$$y = f(\sum_{k=1}^{N} w_k u_k + B)$$

Where u_k is the k^{th} input, w_k its weight that contains the information about the importance of the input, B the bias which is also a weight that functions as a safety net for the calculations in case certain parameters of the problem have been omitted, and f the activation function that is usually sigmoid i.e. $f(x) = \frac{1}{1+e^{-\lambda x}}$

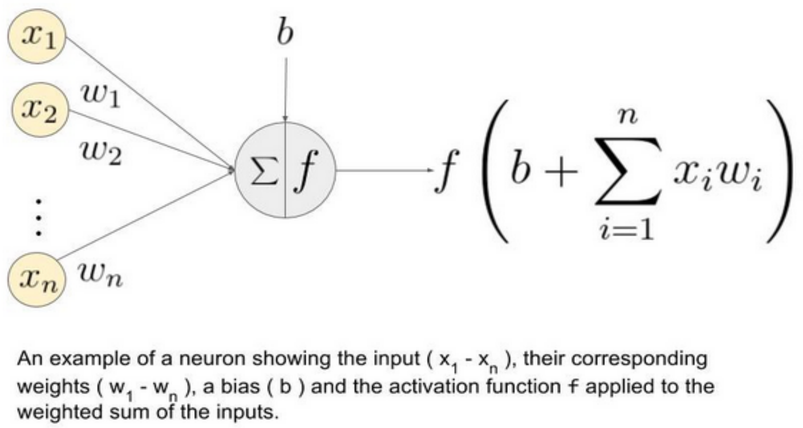


Fig. 2.3.4: Representation of the neural network function
(Babs, Temi, 2019)

The optimum solution is found after the procedure of 'learning' has finished, where the method is tested with real data provided by the user so that the appropriate weights are assigned to the input values. The output with the smallest error is the one that prevails based on the conditions set by the problem.

Measuring the bullwhip effect

Measuring the bullwhip effect is considered a difficult and complex task. Aggregating sales from across the supply chain can be challenging, as it is a dynamic phenomenon, and the reference base is constantly fed with new data which do not always present the same behavior. Production smoothing research usually focuses on quarterly or even annual statistical reports, where products and sales are often described only as quantitative elements. As a result, deseasonalization techniques are required to separate seasonality and inflation influences to the effect. (Bray and Mendelson 2015; Chen and Lee, 2012; Duan et al.,2015; Wang and Disney, 2016; Wang et al., 2016). Besides, information sharing is not always fully transparent, depending on the domain of interest of the industry, and there may be a need for jumping to conclusions. It is a common fact also, for downstream stages of the supply chain to overlook increases or reductions of logistics costs, as they are obliged to keep up with the market competition and offer the best customer service possible, a tactic unrelated to the bullwhip effect.

Consequently, a metric of performance of the supply chain is required to understand the real impact of the bullwhip effect. By definition, volatility can be measured by the coefficient of variation, variance, and standard deviation. In the relative literature, the most common measure, proposed by Fransoo, Jan C., Wouters, Marc JF., (Measuring the bullwhip effect in the supply chain, 2000.) is called "Variance Ratio" and it occurs from the basic concept of the bullwhip effect, viz., the relation between the real demand and the orders placed in a position of the supply chain, given by the below formula:

$$Bullwhip = \frac{\sigma^2{}_{orders}}{\sigma^2_{demand}} = \frac{Var(Orders)}{Var(Demand)}$$

If this metric equal to one, it means that demand is satisfied most efficiently by the orders placed throughout the supply chain and there is no variance amplification. A ratio greater than one indicates the presence of the bullwhip effect underlining this amplification, while a ratio smaller than one implies a smooth order pattern compared to the variation of demand.

A modified version of this metric (Cannella et al., 2013; Disney et al., 2006) which involves the mean value as well is shown below and it is characterized by its ability to monitor the scale of the variance amplification phenomenon.

$$Bullwhip = \frac{\frac{Var[orders]}{E[orders]}}{\frac{Var[demand]}{E[demand]}} = \frac{\frac{\sigma^2_{y_{orders}}}{\overline{y}_{orders}}}{\frac{\sigma^2_{y_{demand}}}{\overline{y}_{demand}}}$$

The same metric with the inventory stock instead of the orders quantity can be found (Disney & Towill, 2003) and it is called inventory variance ratio:

$$InvVAR = \frac{\frac{Var[inventory]}{E[invntory]}}{\frac{Var[demand]}{E[demand]}} = \frac{\frac{\sigma^2_{y_{inventory}}}{\overline{y}_{inventory}}}{\frac{\sigma^2_{y_{demand}}}{\overline{y}_{demand}}}$$

It is of major importance to have a measure of net stock level in comparison to demand variation, so there is also the below indicative ratio:

$$Bullwhip = \frac{\sigma^2{}_{net\ stock}}{\sigma^2_{demand}} = \frac{Var(Net\ Stock)}{Var(Demand)}$$

In the work of (Ouyang & Daganzo, 2006; Ouyang & Li, 2010), the bullwhip metric is the ratio of the root mean square errors of order and demand, instead of conventional Variance, because the modified metric makes the transfer function of ordering policy easier to derive via spectral analysis, facilitating the supply chain modeling process of the study.

$$Bullwhip = \frac{RSMD(orders)}{RSMD(demand)} = \frac{\sqrt{\sum_{t=0}^{T}\left(\widehat{y}_{t_{orders}} - y_{t_{orders}}\right)^2}}{\sqrt{\sum_{t=0}^{T}\left(\widehat{y}_{t_{demand}} - y_{t_{demand}}\right)^2}}$$

Where $\widehat{y_t}$ is the value of the predicted quantity of the forecast, while y_t is the real value as observed at a specific time t. RMSD stands for root mean square deviation.

Bullwhip slope metric is another indicator of the magnitude of the effect (Cannella & Ciancimino, 2010; Dejonckheere et al., 2004), but it requires the previous calculation of the variance/ mean ratio of orders and demand (B_i in the equation).

$$SL = \frac{\{N\}\sum_{i=1}^{\{N\}} p_i \cdot B_i - \sum_{i=1}^{\{N\}} p_i \sum_{i=1}^{\{N\}} B_i}{\{N\}\sum_{i=1}^{N} p_{i^2} - \left(\sum_{i=1}^{N} p_i\right)^2}$$

It measures the geometric propagation of bullwhip in a multi-echelon system, where $\{N\}$ is the total number of echelons and p^i is the position of the i^{th} echelon. A large value informs a fast propagation of the bullwhip effect through the supply chain and a low value means a smoothed propagation.

Due to data availability, some empiricists use alternatives such as production quantity, sales and shipments which are easier to observe in comparison to orders and demand (Blinder & Maccini, 1991). Under non stationary demand it is necessary to perform difference operations on the time series. That is, to measure bullwhip by the variance of order changes instead of the variance of orders itself (West, 1986). Alternatively, one may compare the difference between order variances and demand variances which has been proved to be finite (Gaalman & Disney, 2012).

The above metrics reflect the qualitative perspective of the bullwhip effect in a supply chain, as the economic impact cannot be put in exact numbers. The relation between demand amplification and business profitability is not one-dimensional given that the costs of the effect may include workforce hiring/firing, machine setup, or idle time.

2.4 The Bullwhip Effect and Macroeconomics

In an advanced technological environment where globalization is more evident than ever before, it is clear that worldwide economic changes directly affect businesses. Market psychology has an immediate effect on business turnover and consequently on orders and inventory levels. Interest in inventory behavior tends to follow cycles such as in economy, as Blinder and Maccini (1991) have suggested. An empirical study by Pesch and Hoberg (2016) indicates that 70% of the firms in the study, under financial pressure, reduce their inventory as a measure to deal with liquidity problems. It goes without saying that during a global financial shock, when companies from around the world will start following this strategy, the bullwhip effect will be significantly amplified. The above hypothesis has been confirmed as far as the manufacturing sector is concerned by a study following the financial crisis of 2008 after the Lehman Brothers collapse (Inventory management and the bullwhip effect during the 2007–2009 recession: evidence from the manufacturing sector, 2010.).

Further proof will definitely be given by the current situation of the coronavirus pandemic and the studies that will follow examining the causes of collapse witnessed by several industries. It has already been characterized as the biggest shock to supply chains so far (Business Insider). Never before had a market so much dependent on global trade, faced a similar situation where whole countries put a halt in their production. Unfortunately, the results of this stress test were far from encouraging, though impossible to be quantified considering the shortages of basic commodities, or other indispensable products for the confrontation of the crisis, such as drugs, test kits, masks, and antiseptics. Even the effort to 'flatten the curve' by delaying the spread of the virus was an attempt to reduce the spikes in demand which in that case is the number of patients the health system can support. It is anticipated to witness dramatic changes in the structure of the supply chains at a global scale the following years, as there will be an effort for compactification of the different compounds of logistics systems especially when they depend on the cooperation of different companies in different countries.

A 2012 World Economic Forum survey of supply chain professionals ranked incidents related to external variables, most likely to provoke severe and systemic disruptions on supply chain networks. A pandemic was listed as the environmental factor least likely to provoke such disruptions. It is obvious then that supply chains must be secured from external threats and be built on more stable ground, while being prepared for dealing with extreme situations.

In conclusion, despite the evolution in the supply chain sector and the corresponding research, there is still enough space for improvement. This progress moreover, creates new challenges and the need for adaptation in the new technological environment. The bullwhip effect is one of the most important factors that should be taken into consideration especially in capital intensive markets where optimization is a primary target and there is also a plethora of involved parties with different interests that amplify the negative consequences of the effect. Such a market is undoubtedly the energy sector, and specifically the LNG market, which this paper will shed light on.

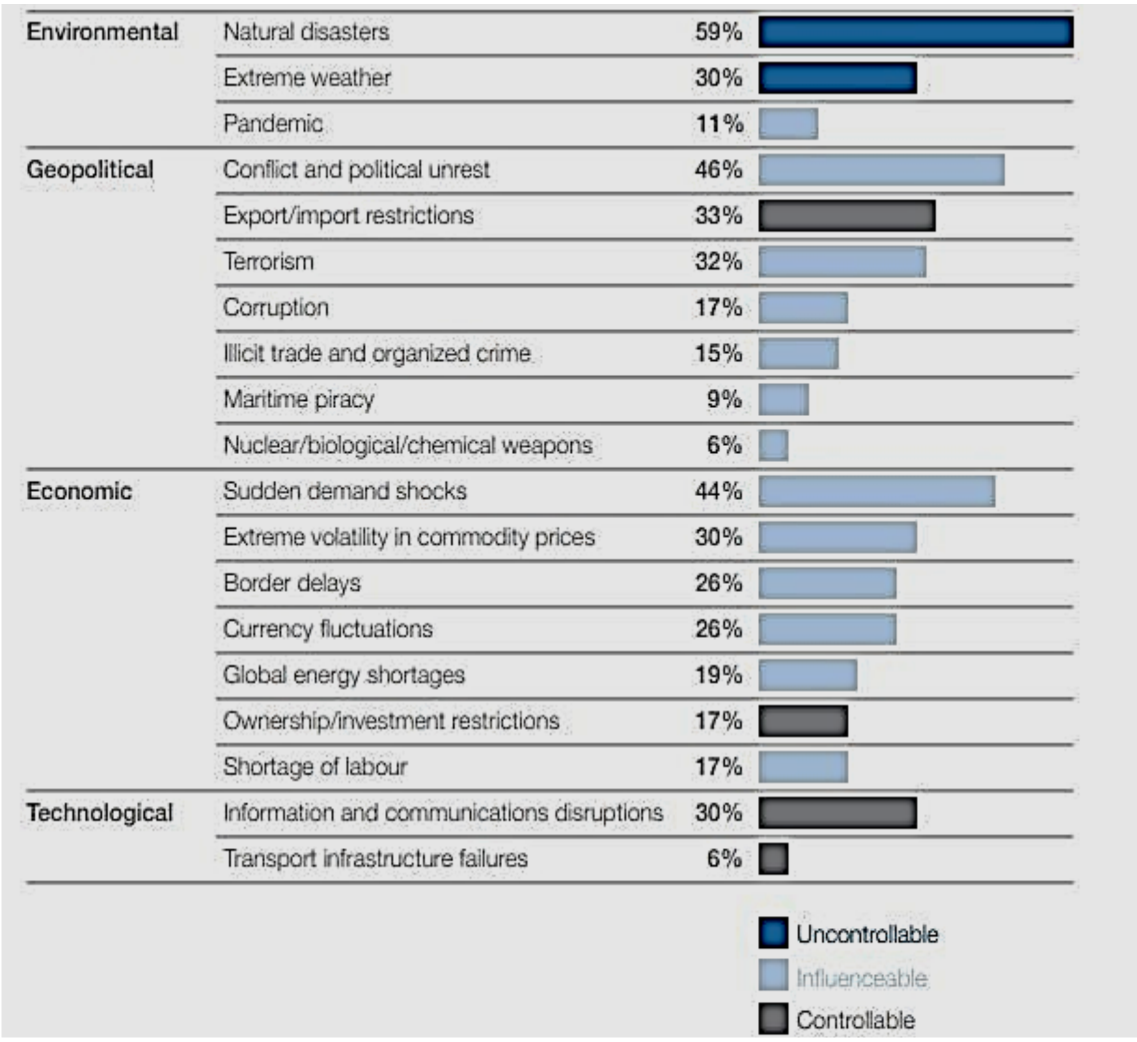


Fig. 2.4.1: Statistical analysis on possible threats to supply chains
(World Economic Forum, 2011)

CHAPTER 3

3.1 An update on the LNG Market

The LNG (Liquefied Natural Gas) is considered the energy source of the future by many, an argument that this paper will attempt to develop in the following chapter. The constant increase in demand in the developing economies for energy production purposes, in combination with the low carbon dioxide emissions and particulate release after its combustion, render LNG the successor of petroleum products. Along with the improvement of living standards in a continuously growing population, energy demand is not expected to cease rising. On the contrary, energy demand, according to estimations of Global Energy Institute, will grow about 26% from 2019 to 2040. (IEA, *World Energy Outlook 2019*.). The below charts are indicative of this augmentation in demand, showing the global use of LNG firstly by regions throughout the years 1989 to 2014 and secondly by the market's total performance until 2018. An important statistic for the market is that since 2000, a yearly average growth rate of 6,4 % has been reported.

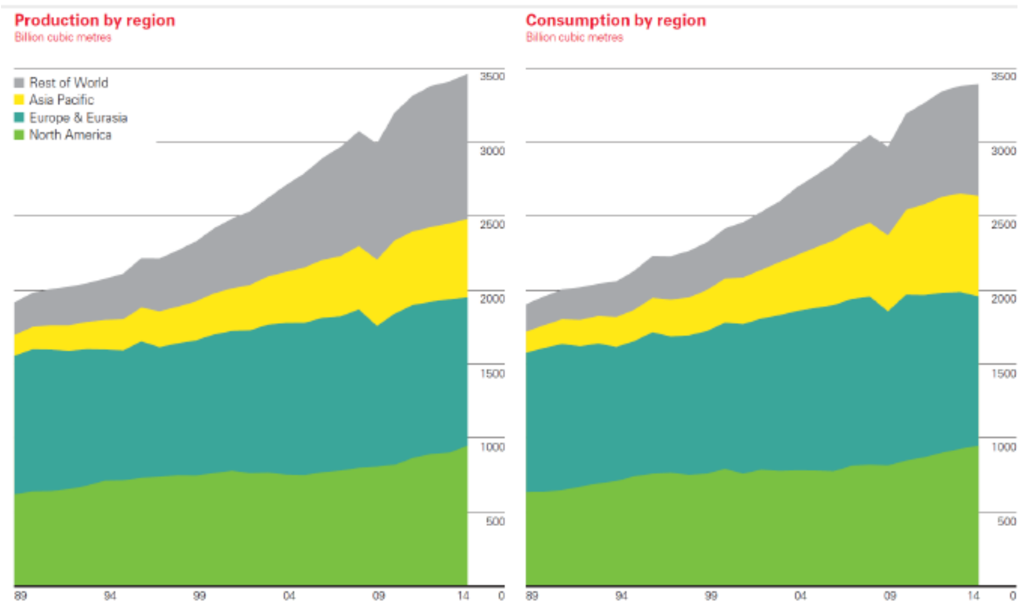
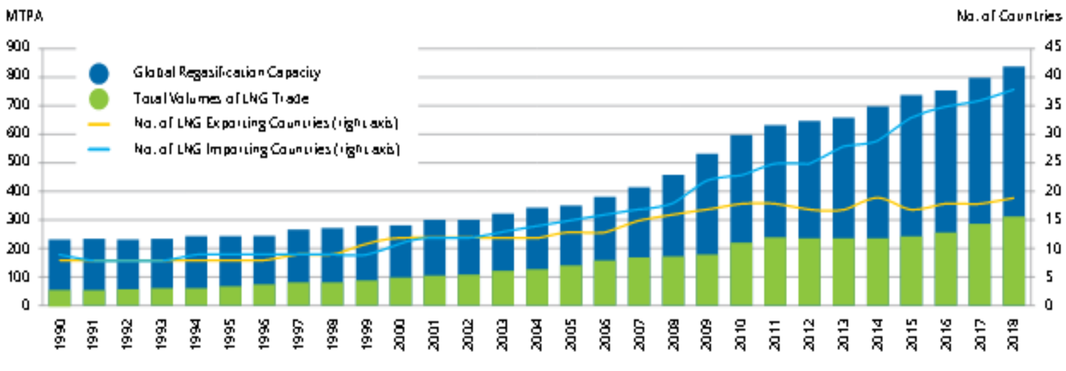


Fig.3.1.1: LNG Production & Consumption by Region

(IGU)



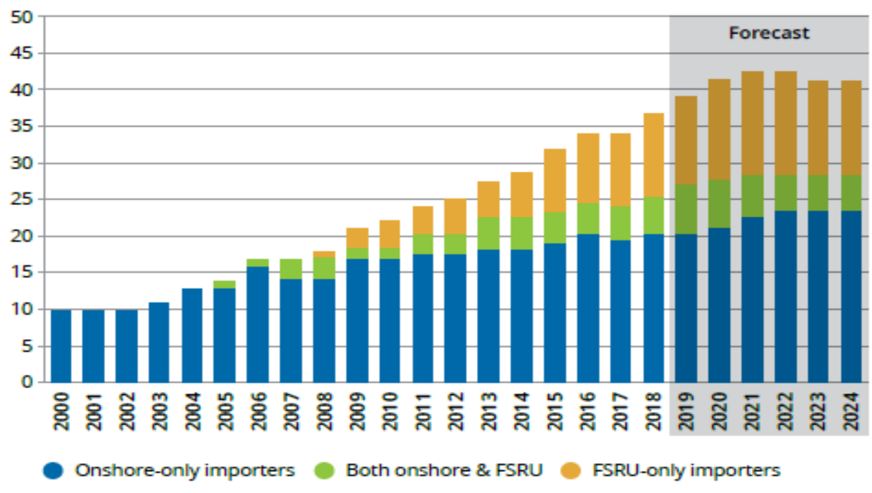
Source: IHS Markit, IEA, IGU

Fig.3.1.2: International Trade and Regasification Capacity of LNG

Despite recent initiatives aiming to replace fossil fuels with renewable energy sources, mainly from developed countries, for instance in the Paris Agreement for a climate-neutral Europe by 2050 (*Leading the way to a climate-neutral EU by 2050*, 2019), IEA claims that hydrocarbons will remain the backbone of global energy production, as their use is expected to grow by 15% until 2040, while natural gas will grow at a rate of 43%. (*WEO2018*).

Given the above statistical data, the energy market is currently making significant investments in the LNG sector. Projects such as the Sabine Pass liquefaction terminal in Texas (27 million tonnes per annum -mtpa), Gorgon project in Australia (15,6 mtpa) and LNG Canada by Shell (14 mtpa), underline the importance of natural gas as an energy source in the following years.

A new field of interest for the industry, which will further boost the market, lies with the floating LNG units (FLNG). There are two different types of FLNG the floating, production storage and offloading units (FPSO) and the floating, storage and regasification units (FSRU). Although there are few applications today, the concept's potential is worth mentioning. Its greatest advantage is the fact that it can offer faster processes in a more downsized scale, which can be the ideal solution for smaller or developing markets. In addition to that, it could be used to avoid national regulations applicable to onshore facilities and the resultant paperwork which is a considerable delaying factor. Further down, a chart including IGU's forecast concerning the expansion of FSRU importers is attached. According to this data, by 2022, only 54% of the currently operating importers (in 2018) will not have invested in FSRUs and relating technology.



Note: The above graph only includes importing markets that had existing or under-construction LNG import capacity as of end-2018. Owing to short construction timelines for regasification terminals, additional projects that have not yet been sanctioned may still come online in the forecast period. The decrease in number of markets with receiving terminals is due to the expiration of FSRU charters, although new FSRU charters may be signed during this period.
Sources: IHS Markit, Company Announcements

Fig.3.1.3: FSRU Development over the next years based on IGU's data on LNG importers

Fig.3.1.4: World's largest FSRU in operation in the Turkish port of Dörtyol, Hatay

The above-mentioned market expansion has not left the shipping industry indifferent. Except for the floating units, the close nature of these markets and the need for reliable, safe and environmentally friendly transportation of the liquefied gas drives the industry to technological innovations as far as conventional vessels are concerned. New propulsion systems are being implemented, increasing efficiency and forcing ship-owners to make a shift towards greener solutions. The latest developments in DFDE, TFDE, XDF and ME-GI technology strengthen the tendency to replace the traditional steam turbine engines in LNG Carriers. The below figures, based on data by Flex LNG Ltd. And IGU (2019 report) on existing global LNG carrier fleet and new built vessels or orders, is a proof of that change.

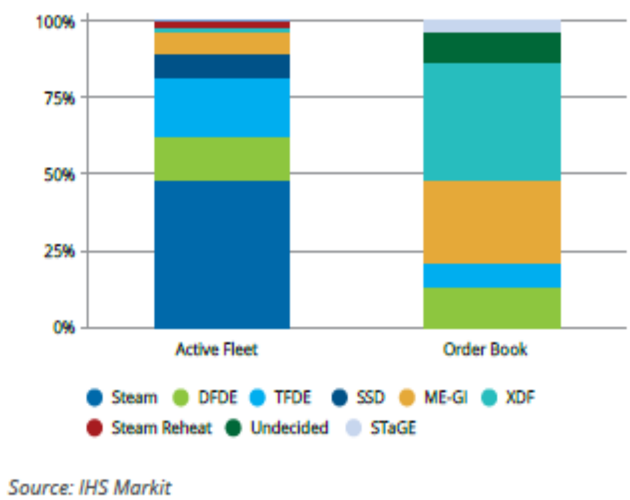


Fig.3.1.5: Existing and on Order LNG Fleet by Propulsion Type end-2018

The basic characteristics and advantages of each engine system are briefly analyzed below for the sake of completeness of the present paper and for a better understanding of the supply chain that will be later expounded.

Steam Engine

- The norm for nearly 40 years which can be translated to high levels of expertise by the crew and better technical assistance
- Propulsion system capable of burning gas
- Efficiency at a rate of 30%, which can be optimized through reheating processes and reach 36%

Double/ Triple Fuel Diesel Electric Propulsion

- Multiple generators burning gas, provide electricity to propulsion motors
- System efficiency at 41%
- Capability of supplying with cheaper fuel HFO/ MDO
- Lower boil-off rate, a basic request for the product's charterers

ME-GI/ XDF Two-Stroke Propulsion

- Direct gas injection into medium speed direct drive chains
- Two-stroke engines moving two different propellers
- High Pressure (Diesel Cycle)/ Low Pressure (Otto Cycle) gas concept
- Re-liquefaction units are necessary to recover excess boil-off, as it cannot be burnt because of slower consumption and consequently slower speeds.
- System efficiency up to 50%

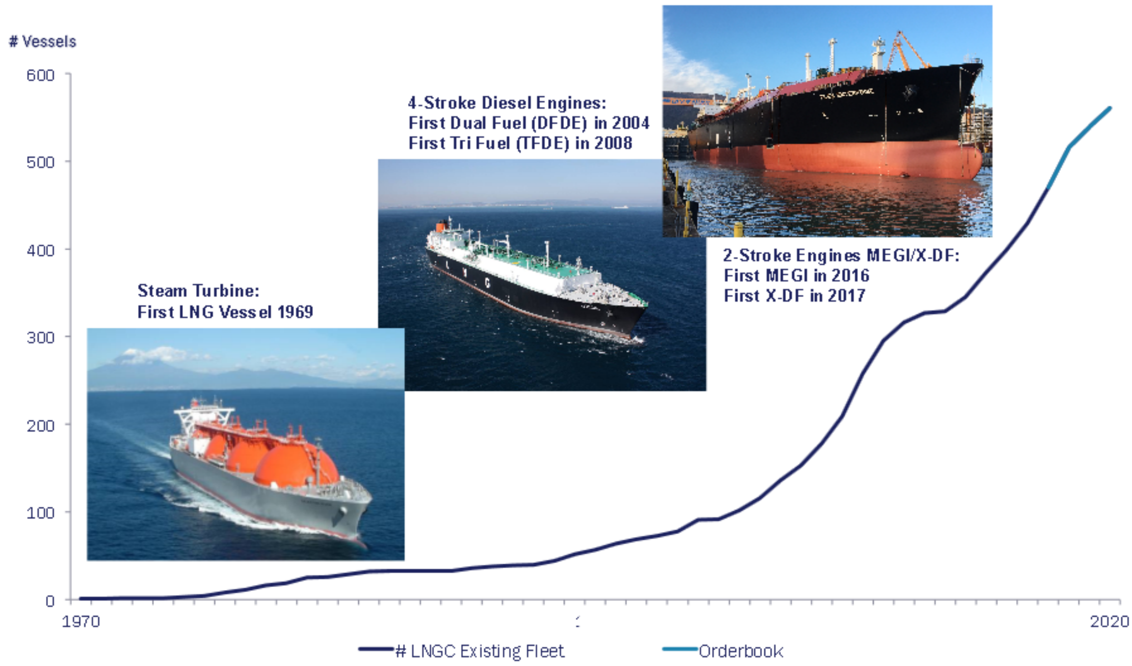


Fig.3.1.6: LNG Carriers Fleet increase from 1970 until 2020 based on existing and ordered vessels
(Maran Gas Inc., 2019)

The above chart is indicative of the increase in the fleet size for LNG transportation during the last decades. Apart from the already predicted increase in demand for LNG carriers, multiple fuel combustion technology is attractive to investors in the shipping sector, due to the new regulations concerning environmental limitations. More specifically, the International Maritime Organization (IMO), enforced from the 1st of January 2020, a regulation preventing commercial ships to release fuel emissions with a sulfur substance of more than 0,5% [IMO-MARPOL- Annex VI- Regulation 14]. Therefore, the property of natural gas to burn without releasing SOx particles (100% reduction compared with HFO -Makeen Energy, 2019) could be a reliable alternative to fuel oil. Together with the increase in demand for LNG, the latest technological advancements have boosted the orders and construction of vessels, achieving a more efficient supply chain.

Given all the above information, it is presumable that profitable progress for the market lies ahead. Projections for future demand for LNG have also been forecasted by the International Energy Institute in 2019's world energy outlook and are presented below.

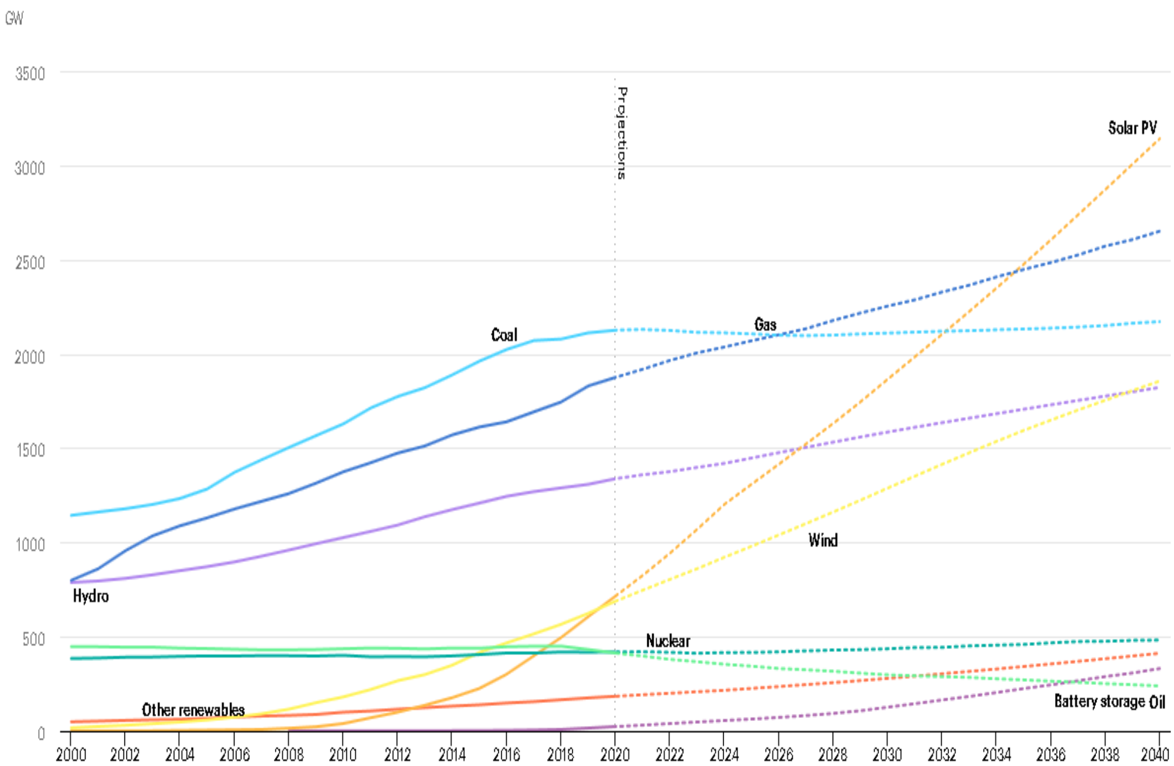


Fig.3.1.7: Power Generation Capacity by Source for the period 2000-2040 in the stated policies scenario
(IEA 2019)

It is clear that these projections are depicting a prosperous future for the market, which has yet to expand. However, despite this optimistic image of the LNG sector, it will be necessary to have the ability to predict and respond fast and in a flexible way to even the slightest changes in demand over the following years and prepare the supply chain accordingly. Besides, as it as mentioned before, there could be incidents impossible to predict, such as wars, natural disasters, financial crises, or pandemics that would affect the global economy and consequently the energy demand. Therefore, with the appropriate strategic planning, the negative results of the bullwhip effect could be mitigated in order to avoid huge capital losses considering the size of the market and the relevant consequences for the industry.

A greater understanding of the supply chain is necessary though, prior to studying the bullwhip effect in the LNG market and its resulting reaction. The stages of the supply chain will be developed thereafter and their connection with the extraction of the natural gas.

3.2 The upstream LNG Supply Chain

The supply chain of the LNG is inextricably corelated with the supply chain of the NG as it will be elaborated subsequently. The different echelons of the natural gas supply chain consist of exploration, mining, and production, processing, liquefaction, storage, transportation, regasification, and distribution.

The commodity of LNG starts being produced at the stage of liquefaction, so this is considered the beginning of the upstream production process of LNG, but for purposes of completeness of the thesis and for a better understanding of the reader, there will be a brief presentation of the processes beforehand that enable the liquefaction of the natural gas.

The below diagram depicts the analytic flow chart of the supply chain

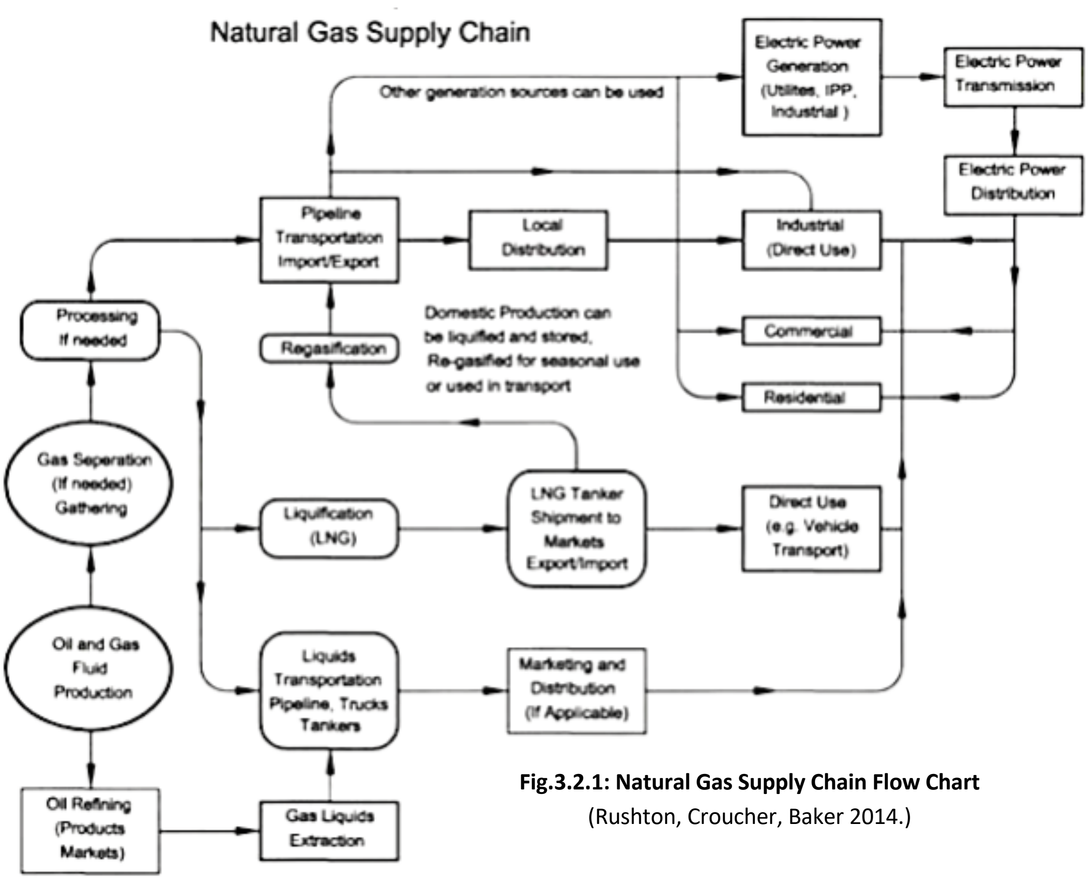


Fig.3.2.1: Natural Gas Supply Chain Flow Chart
(Rushton, Croucher, Baker 2014.)

In order to satisfy the constantly increasing necessity for power generation, the energy sector is always in search of new natural oil and gas deposits. By taking advantage of the technological progress and the innovative solutions offered through further research, previously discarded projects concerning the mining of remote territories are reassessed, as financial viability may have been achieved. Therefore, unconventional onshore resources and deep-water offshore facilities are gaining ground. Offshore developments, in particular, are shifting from easily accessed areas such as the Middle East, the North Sea, South East Asia, North America and Australia to deep waters in Africa, Brazil, the Gulf of Mexico and the Arctic.

Oil major companies use highly advanced multi-dimension seismic acquisition and processing technologies such as ocean bottom nodes and full-waveform inversion modeling as well as interpretive and interactive seismic modeling and imaging algorithms. These technologies improve their understanding of complex subsurface conditions throughout the life of their assets from the exploration stage to ongoing reservoir management.

Offshore developments require a prolonged period usually from 5 to 15 years (Chevron) from the exploration until the start of production. A typical development process consists of four sequential stages:

- *Exploration*: it involves the discovery of oil or gas prospects through geophysical and geological study and exploration.
- *Development*: it assesses the recoverability of reserves by drilling certain appraisal wells and analyzing the data obtained. At this time, the operator will determine a development plan, setting development milestones. After having conducted multiple feasibility studies, concept studies and 'Front-End Engineering and Design' (FEED) to produce quality process and engineering documentation of sufficient depth that define clearly the project requirements, the operator then considers proceeding with the final investment decision (FID). These requirements entail engineering, procurement, fabrication, and construction of facilities while performing cost estimation for the project.

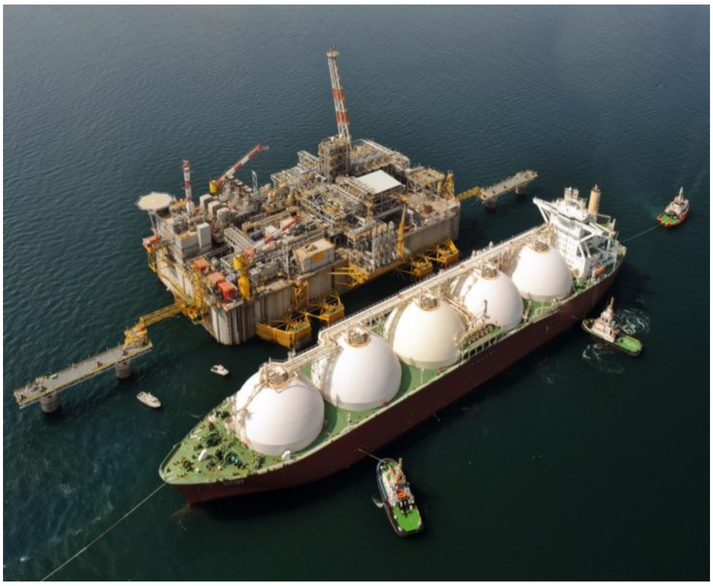


Fig.3.2.2: NG production field in Qatar
(Qatargas Operating Company Ltd.)

- *Execution,* following the approval of FID, is the 3rd stage of the project and it is the implementation of the Engineering, Procurement, Construction, and Installation plan (EPCI).
- The *Life of field* is the final step after the completion of construction and the start-up of the production line. The main fields of concern for the people in charge of the unit operation in this stage are the ongoing asset operations and integrity management. It could be described as the follow-up stage of the project and it has the longest duration.

Under the lifecycle mentioned above, offshore oil and gas fields are developed through aspects including reservoir geology, drilling, well completion, environmental assessments, facility design, installation, and operations

Continuing, as far as the gas treatment is concerned, the majority of the procedures take place in the LNG plant, commonly known as "LNG Train". It is roughly divided into five stations, each performing a different process. More specifically, these processes are mentioned and explained below:

- Pre-treatment process: after the delivery of the gas from the field, undesired substances are being removed, with the help of gravity. Afterward, the gas is separated in a slug catcher into oil and water.
- Acid gas removal: natural gas taken from a gas field contains non- methane environmental pollutants like hydrogen sulfide (H_2S) and carbon dioxide (CO_2). These impure substances are absorbed and removed from natural gas with an amine absorber acid gas removal (AGR). Also, a sulfur removal unit (SRU) is used to extract sulfur from hydrogen sulfides in the removed pollutant.
- Dehydration: an adsorbent is used to remove water from the natural gas so that ice cannot be formed during the subsequent liquefaction process.

<u>Upstream Production Process (Liquefaction)</u>

The previous actions all lead to the fulfillment of requirements needed for the production of LNG; first the finding of the natural resource, then its acquisition, the transportation to process units and finally the refinement of the product.

In the upstream production of the LNG, the liquefaction takes place, a process where the refined gas turns into liquid to facilitate the transportation and storage of large volumes of the hydrocarbon so that it can be delivered to the end customer.

- Compression: Traces of harmful mercury are removed before liquefaction. Then, the purified methane goes to the compressor trains to be transformed into a liquid.
- Natural gas is cooled to –162°C, completing the phase of liquefaction, using the propane condensers for cryogenic refrigeration. Natural gas's volume shrinks up to 600 times. (U.S. Energy Information administration)
- Heavy Oil Separation: The heavy compounds are removed while being in the reservoir. These gases, called Natural Gas Liquids (NGL) or condensates, such as ethane, propane, benzene, butane, and pentane are of major importance to the LNG plant and its efficiency. Apart from their wide application in the petrochemical industry, they are also used in the refrigeration process.

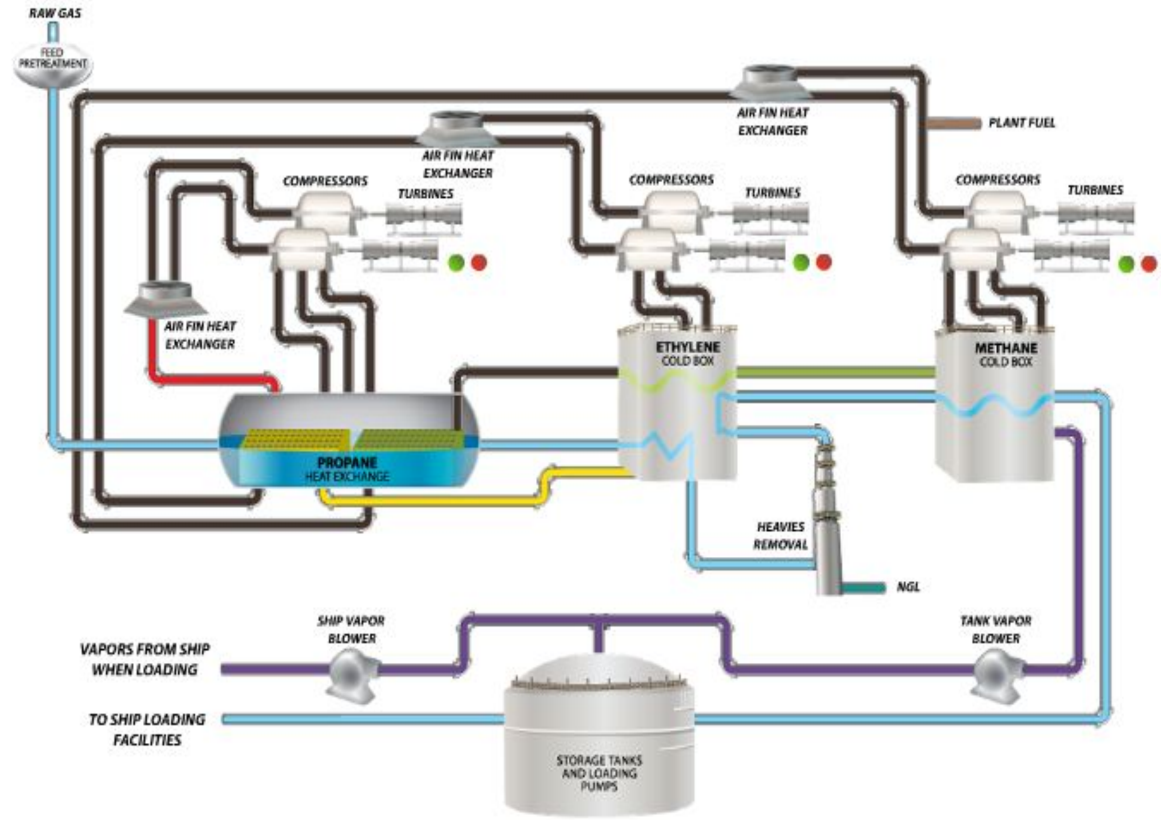


Fig.3.2.3: LNG Train Configuration
(2b1st consulting)

As gas is cooled and liquefied at an extremely low temperature during the process, a significant amount of energy is consumed (almost 10% of the energy contained in the natural gas is needed for its refrigeration- Gate Terminal). Reduced consumption of this sort of energy is very important, so various ingenious processes have been proposed and commercialized. The C3-MR method is currently the most widely used in the industry. In this method, propane and other mixed substances (nitrogen, methane, ethane, and propane) are used as the coolant for the cryogenic process. All of these methods require robust refrigeration compressors. Gas turbines are used for power plants with increased production capabilities. Therefore, elaborate engineering based on experience, high level of technical knowledge and expertise is required to design, produce and assemble the compressors and gas turbines and achieve the best possible degree of efficiency for the plant.

LNG Storage & Loading Facilities

Modern LNG storage tanks are typically constructed with a pre-stressed concrete outer wall and high-nickel steel (9% alloy) inner tank, with sufficient insulation between the walls. Large tanks are cylindrical in design with a low aspect ratio (height to width) and domed steel or concrete roof. Storage pressure in these tanks is less than 10KPa, as it would be hazardous to store the liquid gas in higher pressure. Consequently, LNG must be kept below liquefaction temperature under atmospheric pressure. In some cases, more expensive underground tanks are preferred for storage, taking advantage of the colder environment. Heat leakage is inevitable in an LNG tank, notwithstanding the efficiency of the insulation. This results in the vaporization of the liquid gas. This boil-off gas acts as a coolant to keep the LNG in such a low temperature, in a cryogenic reaction. The boil-off gas is usually compressed and exported as natural gas or re-liquefied and returned to storage tanks. The tanks are fitted with vertical pumps and connected via extensively insulated pipelines from LNG Train leading to export marine loading arms or onshore transportation networks.

Product Loading Facility (PLF) is usually constructed in a certain distance away from the main LNG plant site in a dredged pocket with sufficient depth for the LNG and Condensate vessels to moor and load. There is a connection through a platform starting from the landside which also includes all piping systems. Vessels are piloted in and out of the port facility by licensed Marine Pilots to reassure safe and efficient operation. These technically qualified and highly experienced mariners act as both the Pilot Loading Master (PLM), organizing vessel loading operations and as ship-shore interface assistant.

Fig.3.2.4: Yamal gas project in Siberia
(Yamallng.ru)

3.3 The midstream LNG Supply Chain

LNG Transportation

LNG, as it was mentioned before, can be transported either by sea as a liquid or by land in expanded pipeline systems in a gaseous state. When transported by sea, the most efficient way is onboard specially designed LNG vessels. Tank construction systems currently in use can be predominantly separated into two types:

- *Membrane Types* – LNG containment systems of the Membrane design generally fall into two categories that were originally designed by the two separate companies, GAZ Transport (GTT®) and Technigaz®. The membrane may be Invar – FeNi36 (Gaz Transport) or stainless steel (Technigaz). The membranes in a usual design are 0.7mm thick, while each layer of insulation is about 200mm. The tanks are not self-supporting as in the Moss design; they are constructed in the inner (double) hull of the vessel, in a similar design to oil tankers. Nitrogen is purged through the insulation layers, while a gas detection system is installed for obvious reasons.
- Moss Rosenberg Types – The Moss® LNG tank enables high accuracy of predicted stresses and fatigue life of all parts of the tank structure, eliminating the need for a complete secondary barrier. The tanks are generally made from aluminum and supported around the equatorial ring by a Structural Transition Joint (STJ), which also acts as a thermal break between steel and aluminum. The tanks are then insulated with polyurethane foam, covered with nitrogen on the outside. A partial barrier in the form of a drip tray beneath the sphere is fitted. In addition, a gas sampling system is fitted to detect any signs of leakage. Corrosion prevention of the tanks and the holds is achieved through a weatherproof cover.

3.4 The downstream LNG Supply Chain

LNG Terminals and distribution networks

An LNG terminal is a reception facility for unloading cargo from the LNG carriers. These purpose-built ports are specially designed for import and export of LNG, hence the variety of facilities for unloading, regasification, tanking and metering of LNG, which are provided at these terminals. The LNG terminal is an indispensable compartment of the supply chain, given that the regasification of the liquid takes place in there, after the discharge of the cargo by the vessels, making the distribution of the gas to the end-user feasible. The main activities of an LNG terminal can be divided into four main categories. (Raunek K., 2019.)

- Receiving LNG from Ships

Specially designed pipes are wont to transfer LNG from the ships to the storage tanks on the terminal. The LNG remains at an extremely low temperature (-162 ^{o}C) throughout this procedure. The tanker is moored at the unloading quay, hence the LNG is offloaded by these pipes (arms) located at the jetty.

- Storage or Tanking of LNG

The LNG passes through pipelines that join the arms to the tanks and is then stored inside the tanks at a liquid form. Following an equivalent practice as in an LNG train, the storage tanks operate through a cryogenic reaction with the utilization of NGLs. Sufficient insulation and boil-off prevention are achieved with the use of double walled storage tanks. The outer walls of the tanks are constructed by pre-stressed ferroconcrete or steel to achieve the best possible insulation, in an attempt to reduce refrigerating costs.

Despite this elaborate insulation, minor evaporation still occurs due to unsubstantial heat leakage. Compressor and re-condensing system are used to collect the boil-off gas and send it back to the tank. This recycling system prevents LNG wastage from the system.

Re-liquefier constitutes a collector system wherein LNG from the tanks and boil off from the compressors is collected before passing through the regasification process. High pressure pumps are utilized to send the LNG from the re-liquefier to the regasification system. Re-condenser also contributes in keeping the boil off gas in the liquid state.

The advantages gained from storing LNG are numerous. The most important though, is that it covers the necessity of maintaining a reliable distribution network during the coldest days of the year, when demand for gas utilities concerning residential customer base grows considerably. In the United States, more than 80% of storage capacity is located in the eastern part of the country, where there are extensive needs for heating due to the scale of population and the climate. (U.S. Department of Energy)

- Regasification Process / Vaporizer system

Regasification describes the process of converting LNG from the liquid state to the gaseous state. To perform this operation, heat exchangers are mostly utilized. LNG, after the above-mentioned process, is pressurized to an extent of 70-100 bars. Generally, sea water is preferred for the regasification process alongside high pressure pumps for transferring the LNG. This happens because the regasification process requires a significant increase of the liquid's temperature. Therefore, the LNG gas is passed through a heat exchanger that uses sea water. Another method found within the industry is using turbine flue gases from the energy recovery systems to re-gasify the liquid. LNG is thus converted into the gaseous state by being heated at a temperature greater than 0 degree Celsius.

There are also LNG terminals supporting underwater burners that heat the LNG to convert it to gas. These types of burners use natural gas as a fuel and are generally used during peak demand period. Such vaporizers are called submerged combustion vaporizers.

- Transmission

After the regasification process is completed, the gas undergoes metering, odorizing and qualitative analysis before it is fed to the transmission system. Given the fact that natural gas is odorless and inflammable, it must be odorized to facilitate the detection of a possible leakage. This is mostly done by injecting a chemical substance called tetrahydrothiophene in the LNG before distributing it to the network.

Finally, the end user of the value chain:

- Consumption of natural gas

  Either for domestic or industrial use, including

  - Heating - Combustion in boilers
  - Energy Production- Gas turbines
  - Transportation- cars, trucks, trains, vessels

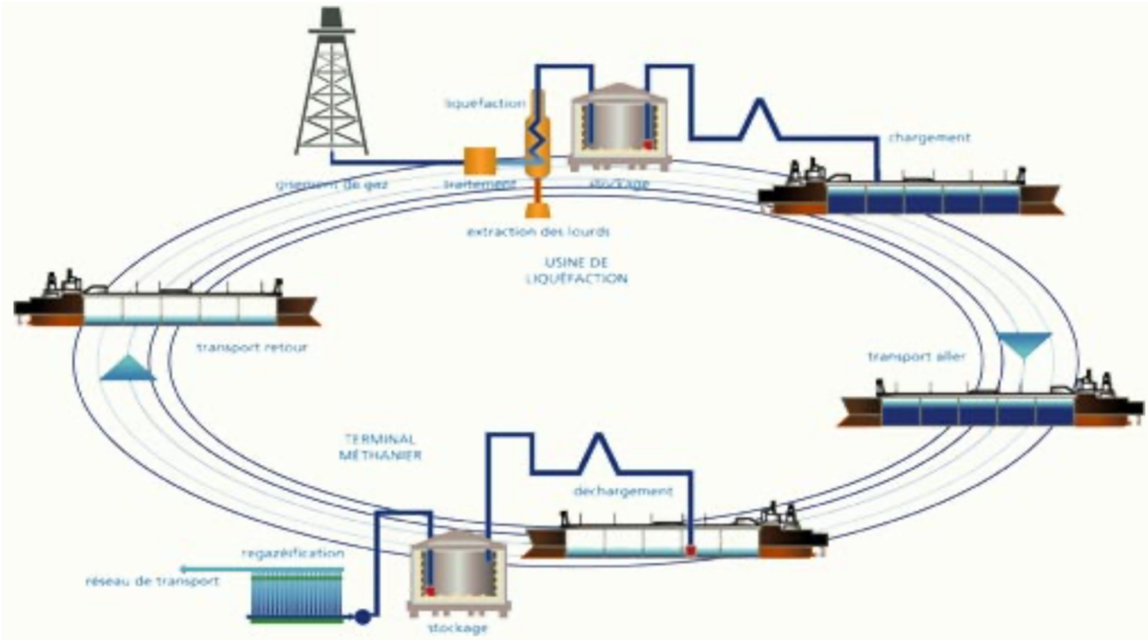


Fig.3.4.1: LNG Supply Chain

(rabaska.net/lng)

3.5 LNG Supply Chain Development on an International scale

After the analysis of the different supply chain echelons and their operations, an examination of the present situation as far as the LNG trade routes and distribution networks will be performed. (U.S. Department of Energy, Office of Fossil Energy, 2005.)

International trade in LNG is concentrated mostly on three geographic regions:

- *The Asia/ Pacific Basin*, involving trade in Southeast Asia, India, Russia, and Alaska.
- *The Atlantic Basin*, concerning trade, carried out in Europe, Northern/ Western Africa, and the U.S. Eastern and Gulf coasts.
- *The Middle East/ Arabic Basin*, involving trade in the Persian Gulf

Exports

The Pacific basin is considered the leading exporting route. In 2019 it contributed to global LNG exports with a percentage of 38,4%, according to IGU. As far as countries are concerned, Qatar holds an important share of the market, with a quarter of the pie. It constitutes the biggest LNG exporting country. This is due to the large scale LNG Plants constructed in the Gulf. In a more detailed analysis of natural gas exports at a national level:

Qatar

The BP Statistical Review of World Energy 2019, claims that the emirate's natural gas exports reached 175.5 billion standard cubic meters (bcm in ISO 12213-2 [2006], T=15°C, p = 101,325 KPa) in 2018. Qatargas®, headquartered in Doha, is the world's largest LNG producing corporation. The company produces nearly 18,5 billion standard cubic feet per day (bscfd) of unprocessed gas from 208 wells and then distributes it to 14 LNG trains onshore. The gas, along with the consequential condensates, is then transferred through subsea pipelines to the shore. Under the jurisdiction of Qatargas are also the North Field Bravo and RasGas Alfa, offshore complexes contributing 2,8 bscfd of dry gas. North Gas Field, the largest single gas reservoir in the world is operated by the state company Qatar Petroleum. The field was discovered in 1971and it is estimated to have a total gas mining potential of more than 9000 bscf. Qatar also plans to increase its LNG export capacity by 43% by developing its North Field Expansion project, adding approximately 32mtpa of liquefied gas to the market from 2024. (NS Energy, 2019.)

Australia

Australia follows Qatar with natural gas exports of 91,8 bcm. The country operates one of the world's most complex LNG projects, the Ichthys LNG. Its construction included the development of the Ichthys gas-condensate field offshore Western Australia. Estimations report that the offshore field contains more than 12800 bscf of gas and 500 million barrels of condensate at a depth of 4,5 km beneath the sea level (Total®). Moreover, Australia is home to the world's most sizable FLNG facility. Specifically, the Prelude FLNG project is located in the Browse Basin offshore Western Australia and can produce 5.3 million tons of liquid hydrocarbons and condensates a year, including 3,6 mtpa of LNG.

Malaysia

Malaysia is considered the third biggest player in the gas sector, with LNG exports of 33bcm in 2018. PETRONAS LNG Complex is located in Malaysia, a complete LNG production complex and one of the world's largest LNG production facilities in a single location. With nine production trains, the PETRONAS LNG Complex has a production capacity of 29.3 mtpa. PETRONAS Floating LNG (PFLNG) is another major facility that enables the processing of LNG to be carried out offshore. The PFLNG Satu is currently operating at the Kanowit gas field, while PFLNG Dua, the second floating LNG facility, is expected to be able to produce 1,5 mtpa (ABB®). The country also operates Beryl Gas Field and by 2021Pegaga gas field.

United States

The US ranks fourth in top LNG exporting countries with an exporting capacity of 28.4bcm. They contributed to 6,7% of the world's LNG exports in 2018. (IGU) As of May 2019, the country has more than 110 LNG facilities in operation, carrying out a range of services. Certain worth mentioning LNG export facilities in the US are the Sabine Pass LNG Terminal in Louisiana (3.5bcfd), Cove Point LNG Terminal in Maryland (0.82bcfd), Corpus Christi Project in Texas (0.71bcfd), and Cameron LNG project in Louisiana (0.71bcfd). The LNG export capacity of the US is set to increase as it was mentioned before through at least eight LNG export terminals, which have been approved and are currently under construction. By 2021, six LNG projects are slated to become fully operational, while two new projects, the Golden Pass LNG export project in Texas and Calcasieu Pass LNG project in Louisiana are scheduled to begin operations by 2025.

Russia

Russia ranks fifth among the leading LNG exporting countries with a market share of 6% and an export capacity of 24.9 bcm in 2018. The majority of Russia's production is mined and processed in the Sakhalin II and Yamal LNG Project. The latter commenced operating activity at the end of 2017 and processes gas produced from the South Tambey Field. Furthermore, its design capacity reaches 9.6mtpa, with the use of two liquefaction trains. In 2018 the plant produced 11.41 million tons of LNG. The renewed potential of the country's LNG market unveiled with the beginning of full-scale production of the Cryogas-Vysotsk LNG project in Leningrad Region, in April 2019. It has an initial design capacity of 0,66 mtpa and distributes the commodity to the Baltic Region, Scandinavia, and northern European countries, apart from serving the domestic demand. Russia's LNG export capacity will increase further by the addition of the Arctic LNG 2 project in the Gydan peninsula with a total investment of $21billion (Bloomberg, 2019.). The project is expected to be completed between 2023 and 2025, expanding the country's exporting capability by 19.8 mtpa, rendering Novatek®, the administrator company, Russia' s biggest LNG producer as it will surpass Gazprom®.

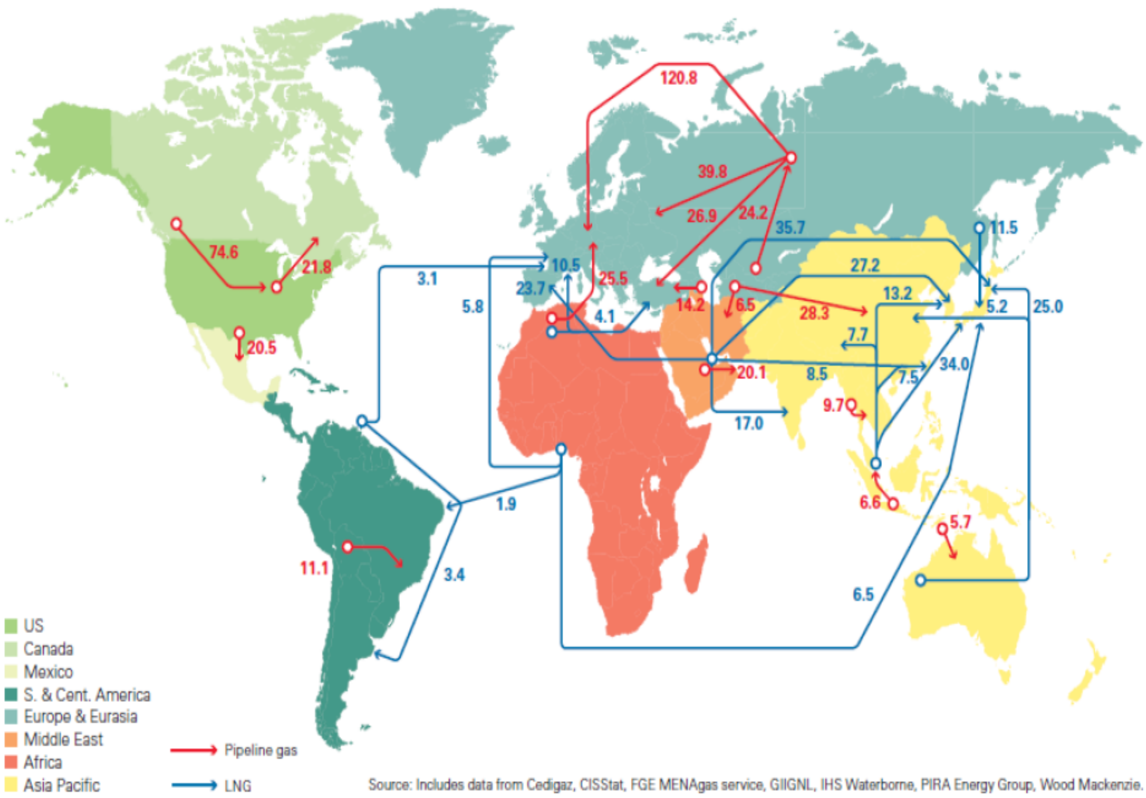


Fig.3.5.1: Natural Gas major trade routes by mtpa
(University of Strathclyde)

Imports

The demand of a commodity being traded in an international scale is directly correlated to the level of imports in the different countries. Therefore it is useful to analyze the existing situation in the importing quantities of LNG and determine the regasification and storage capacity of the receiving terminals. In this way a study concerning the demand fluctuations can be performed to investigate the results of the bullwhip effect in the LNG sector.

Market's Overview

The Asia/ Pacific basin remained the primary importing region for 2018, given that LNG's major demand comes from Asian markets. Its share of global imports dropped to 48%, thus being the biggest share by a grand margin in comparison to other trading routes. However, a declining pattern for its market dominance has been observed over the last 5 years due to the expansion of European imports.

Product's demand is driven by Japan, the largest LNG importer, representing over 26%of total imports with 83,1 MT, while South Korea follows with 44,5 MT according to IGU. The recent increase in Asian imports is on account of the development of LNG-relating infrastructure in China.

India's economic growth also reflected on the increase in demand for LNG, supporting its power generation sector and industrial development, rendering the country the fourth largest importer. Pakistan and Bangladesh are also upcoming importers, as their demand rises promisingly.

Based on the above statistical data, Asia strengthened its position as a reliable trade partner through 2019 and is likely to continue likewise for the coming decades.

European imports reached 50 MT in 2018, being increased by 7,3%. Environmental restrictions, limiting the use of coal for energy production, along with reduced domestic production, and higher charter rates for LNG carriers in opposition to the east markets were the main reason for this growth. The latter comes to show the relation between demand, price formation and the resulting differentiation of trading, basic characteristics of a free capitalistic market, despite the limitations imposed by the stable nature of the energy market.

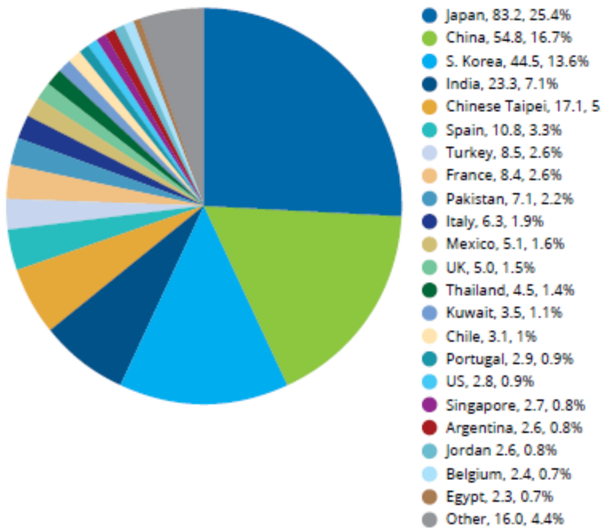


Fig.3.5.2: LNG Imports and Market Share by Country
(IGU 2019)

The American continent and Australia remain self-supported, as their LNG producing capacity exceeds by far their domestic demand.

A pie chart is presented below, showing the LNG imports and market share, for countries that imported more than 2 MT, using the statistical analysis provided by IGU.

Receiving Terminals

Global LNG regasification capacity reached a high of 824 mtpa as of February 2019, thanks to new terminals and expansion projects added in 2018. More specifically 5 new LNG onshore import terminals were added, while 2 new LNG offshore terminals started operating activity. The global market's largest levels of regasification capacity are located in the Asia and Asia Pacific regions. The introduction of FSRUs has granted access to the LNG market for smaller countries as well, especially in the Middle-East, South-East Asia, and Latin America. The regasification capacity by market is similar to the above figures regarding LNG imports, but there are certain differentiations concerning countries with active LNG production, such as the USA. China on the other hand, despite being the second largest importer, is still behind South Korea in total regasification capacity. However, it is expected to grow significantly in the following years. In the attached figure, a pie chart is presented, showing regional regasification capacity along with their annual utilization.

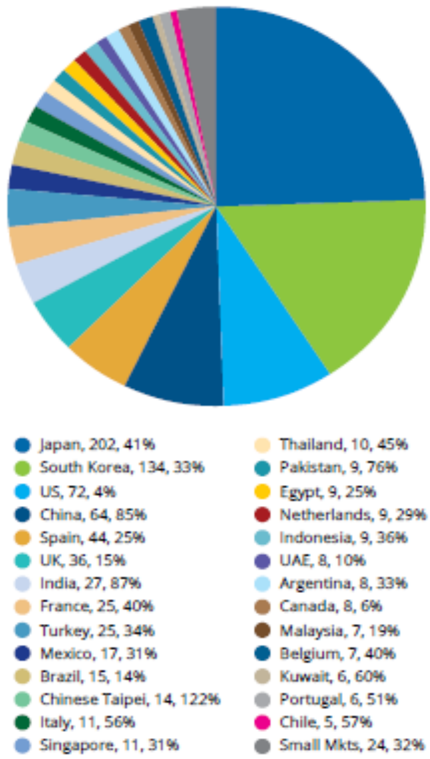


Fig.3.5.3: LNG regasification by market in mtpa and Regasification Utilization, 2018

(IGU 2019)

According to estimations, regasification utilization levels across the global LNG market reached 39% in 2018. The spread between the liquefaction capacity and the regasification utilization is due to the necessity to satisfy seasonal demand peak. This mismatch in the specific supply chain echelon of the LNG sector can be translated into a bullwhip effect problem. Therefore, it constitutes an area of study for the present paper in an attempt to perform a more efficient planning of the operational chain that could eventually lead to an important cost reduction even from the initial investment of the regasification terminal.

3.6 LNG Supply Chain Development on a National scale

The establishment of natural gas trade in the Greek energy complex is one of the most significant energy projects of the country in recent decades. In Greece, natural gas transmission is realized with the operation of the National Natural Gas Transmission System that transports gas from the Greek-Bulgarian border, where Bulgatransgaz Ltd® is the upstream Transmission System Operator (in the natural gas market, a TSO is responsible for receiving gas from producing facilities, transporting it via a pipeline through an area and delivering it to gas distribution companies) and the Greek-Turkish border, where the upstream Transmission System Operator is BOTAS Petroleum Pipeline Co®, to consumers in continental Greece.

The network consists of the following compartments:

- The central gas distribution pipeline and the branched network
- The border metering stations near Serres at Sidirokastro, and near Evros River at Kipoi. At the second station, Trans Adriatic Pipeline (TAP) was connected and is expected to begin commercial operation amidst 2020. The TAP project was developed to transfer natural gas from Azerbaijan to Greece, Albania, Italy, and from there to points beyond in Western Europe
- The compression station at Nea Mesimvria in Thessaloniki
- The Metering and Regulating Stations throughout the system
- The dispatching and control centers at Magoula, outside Athens and at Nea Mesimvria
- The operation and maintenance Centers
- The Remote Control and Communication System

The central distribution pipeline, which has a total length of 512 km and supports a design pressure of 70 bar, extends from the Greek-Bulgarian borders at Promachonas south to Attica region. The branched pipelines with a total length of 953.2 km extend from the central distribution pipeline and provide natural gas to the regions of Eastern Macedonia, Thrace, Thessaloniki, Platy, Volos, Trikala, Oinofyta, Antikyra, Aliveri, Korinthos, Megalopoli, Thisvi, and Attica.

The transmission system also operates as a supplying factor for the regional trade through the operation of the receiving terminal of Revithoussa that supports a regasification capacity of 4,8 mtpa. It was constructed in 2000 by the state-owned company DESFA (formerly DEPA) and in 2018 a large expansion project was completed, extending its storage capacity. The station constitutes, according to the International Gas Union, the 36th largest terminal globally, in terms of regasification capacity. It was designed to perform the following procedures:

a) LNG transportation from the docked vessels
b) Storage of the liquefied gas in tanks equipped with a system of boil-off exploitation
c) Pumping and Regasification of the LNG
d) Supply of the national natural gas distribution network

During operation, the station receives the liquefied gas from the LNG carriers with a maximum unloading rate of 7250 m^3/h and then stores it at one of the three storage tanks with total capacity, as of December 2018, of 225 thousand cubic meters. The sustained maximum send-out rate (SMSR) of the installation is 1250 m^3/h, while the peak send-out rate reaches 1650 m^3/h. In addition, a thermoelectric station of 13MW has been constructed to upgrade the overall efficiency of the unit.

The station's regasification potential currently reaches 7 bcm per year, five of which could be used as exporting commodity with the use of the existing onshore connection with Bulgaria, according to studies performed by DESFA. This prospect can render Greece the strategic energy hub of the Balkan Region and ultimately of Southeastern Europe, revealing the remarkable geopolitical importance of the natural gas as a national energy asset.

Fig.3.6.1: Greece's Natural Gas Transmission System

(DESFA)

Historical Data on Natural Gas Demand

Annual gas consumption in Greece reached its peak for the first time in the year 2011. From 2011 up to 2014, gas consumption was in a gradual decline due to two main reasons identified by the operator:

a) The prolonged recession of the country that naturally affects the energy sector
b) The direct impact of the changes in the electricity sector on natural gas consumption.

The aforementioned situation has been reverted from 2015 onwards and in the early months of 2019, a peak demand was also noticed.

The following graph presents the gas consumption percentages in Greece from 2007 to 2018 per category of consumption, while the table below presents the historical data of peak demand for the period 2008-2019.

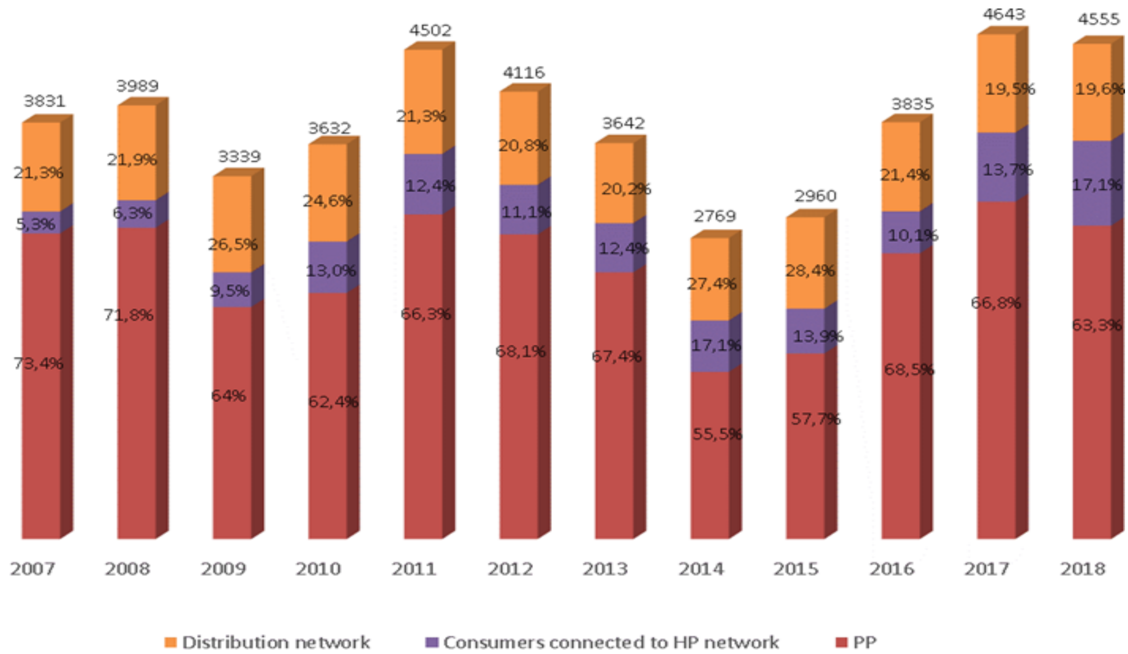


Fig.3.6.2: Natural Gas Consumption percentages 2007-2018 [in 10^6 Nm^3]
(Development Study DESFA)

Table 1: Peak of the system 2008 – 2019

Year	Peak Demand (Nm3/d/yr)	Date
2008	15.068.599	29/1/2008
2009	16.248.899	14/12/2009
2010	16.916.119	17/12/2010
2011	18.291.876	10/3/2011
2012	21.850.369	9/2/2012
2013	18.621.922	8/1/2013
2014	16.778.873	5/2/2014
2015	18.116.335	21/12/2015
2016	19.596.897	14/12/2016
2017	23.580.220	12/1/2017
2018	22.054.551	13/12/2018
2019*	**25.652.291**	8/1/2019

**up to 31/5/2019, peak observed on 8/1/2019*

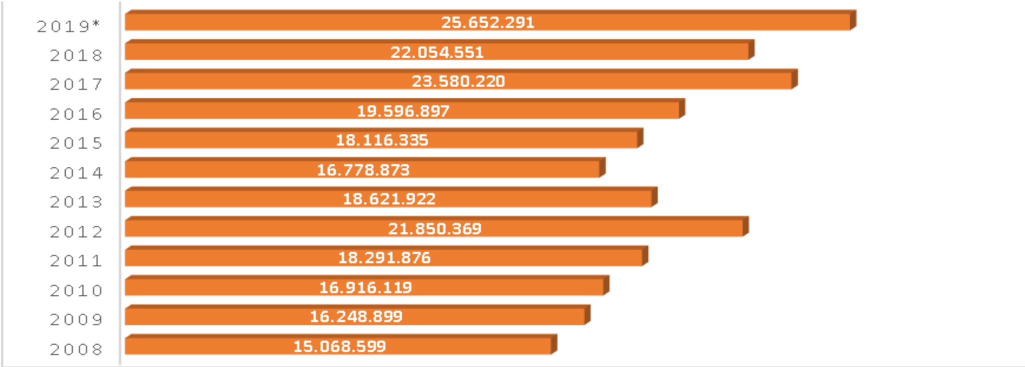


Fig.3.6.3: Peak demand of the system 2008–2019 [Nm³/day/yr]
(Development Study DESFA)

It should be highlighted that in January 2019 natural gas consumption was at the highest level up to now. Despite the fact that consumers of natural gas connected to distribution networks are constantly increasing, the depicted peak is mainly attributed to the gas consumption for power production.
The situation in January 2019 resembles much the situation in January 2017 (where another notable peak of gas consumption took place). The system load was at about the same level (due to the unexpected low temperatures in Greece in January of that year). Further to that, this situation coincided in both years with increased energy exports. In 201,7 commercial trades were affected due to an energy deficit in a European level, emerged after the renewed plan for energy policy in France and its emancipation from nuclear plants, imposed by the newly-elected president Emmanuel Macron. In the year 2019, a significant amount of exports was realized from trading companies to neighboring countries. Such exports at low purchase prices have been banned from the Regulatory Authority for Energy (RAE) through respective regulation of the Forward Contracts Code, so the exports to neighboring countries have been significantly decreased from March 2019 onwards.
The following graph depicts the national natural gas supply and the contribution of gas transferred via pipelines and the LNG imported from 1998 to 2018.

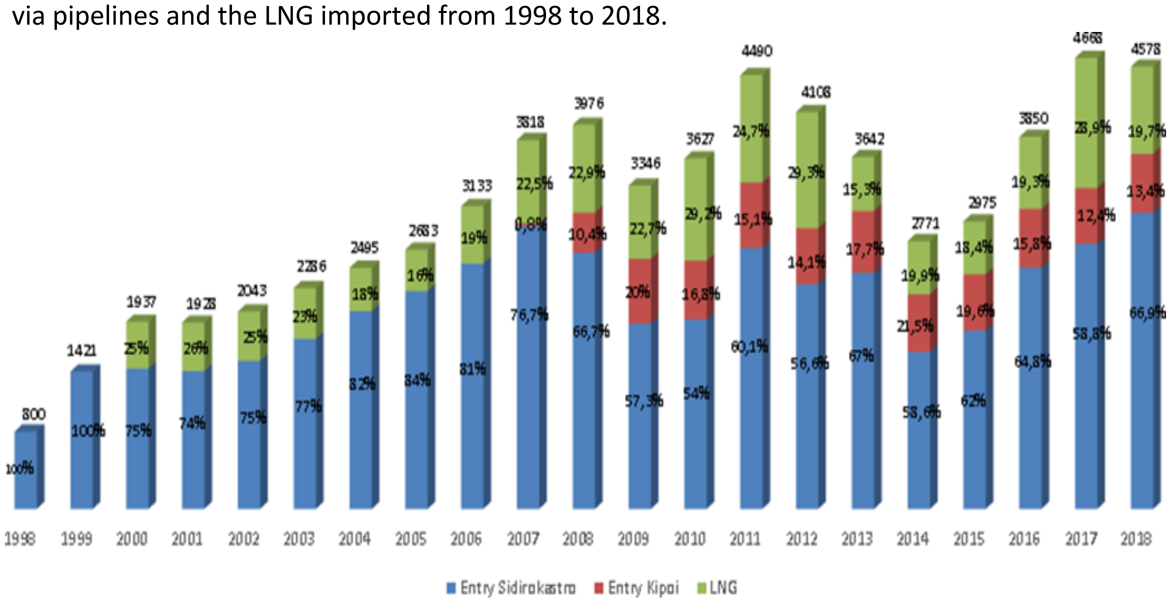


Fig.3.6.4: Procurement of natural gas in Greece [10^6 Nm³/yr]

For 2018, the percent contribution of natural gas imports per Entry Point was as follows: Entry Point Sidirokastro 66,9%, Entry Point Kipi 13,4% and LNG 19,7%.

On the contrary, the natural gas supply for the first five months of 2019, at a gaseous and at a liquid state depicted below, follows a different pattern.

The increased imports through the LNG terminal are an outcome of the decreased LNG prices observed in the early months of 2019 combined with the high demand for natural gas quantities. The upgrade of the send-out rate of the Revithoussa terminal which took place in December 2018 had also an effect on the utilization rate of the terminal.

Apart from the operation of the Revithoussa terminal, an FSRU is under development in Alexandroupoli with the expectancy to become a reliable alternative for faster and more flexible supply of natural gas for the neighboring countries. The floating terminal will consist of four regasification units, each with a regasification capacity of 400 m3/ h. The total nominal regasification capacity of the unit will be approximately 5,5 bcm per year (Gas Trade).

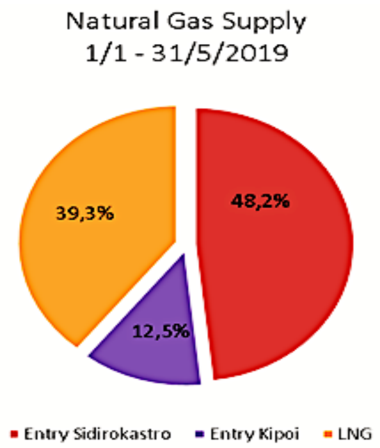


Fig.3.6.5: Procurement of Natural Gas for 2019
(DESFA)

CHAPTER 4

4.1 The bullwhip effect across the LNG supply chain- Review

The bullwhip effect across the LNG supply chain has not been extensively studied in the relative literature, despite its important economic impact. This is mainly because, as it was mentioned before, the production process as well as the trade of the commodity are conducted by huge corporations with specialized departments for the optimization of the supply chain practices that usually control the whole procedure from the upstream production to the final distribution. However, there have been certain efforts to decode the operation of the supply chain of the industry and identify the existing inefficiencies and their causes. The actual term 'bullwhip effect' or 'demand amplification' in reference to the natural gas value chain has been the main subject of study of the below papers that will be presented in short as for their approach to the topic and their different perspectives, in order to give a spherical view of the problem before proceeding to the realization of the computational part of the thesis. The liquid natural gas market, as a more specialized subsector of the gas industry has not been distinguished in these studies, although their findings will be exceptionally useful for the understanding of the supply chain operation and how the bullwhip effect applies to it.

Recent studies focusing on the oil and gas industry have mentioned the existence of the bullwhip effect, mostly in the upper parts the supply chain (*Jacoby, 2012*). In this study, the economic inefficiency related to the bullwhip effect in the oil and gas industry is found in four types of malfunction:

- Higher prices of the commodity which results in
- Excess inventory during "the peak demand"
- Excessive capacity investments near the peak with low or negative return of investment
- Loss of orders due to inability to meet total demand (inadequate capacity and longer lead time).

Smaller companies of the industry, tend to have a higher bullwhip effect ratio comparing with the oil super majors. With the development of the market and the introduction to more flexible business models that will enable the modularization of the production process, which is considered a requirement for the next day of the industry (Deloitte, 2016), smaller companies will start to appear, facing the above problems. According to the study, vertical integration, multinational reach, economic scale of the companies and market dominance are the main contributors to the mitigation of the bullwhip effect.

Jacoby makes his remarks about the complexity of the gas supply chain management and points out two generic strategies most applicable to companies from this supply chain: rationalization and synchronization. Substantial savings in logistics costs (rationalization) could be achieved by reducing or even avoiding the Bullwhip effect (through synchronization).

In another study "*Bullwhip effect in the oil and gas supply chain: A multiple-case study*", after a thorough examination of the supply chain echelons of the oil and gas industries and an extensive review of the bullwhip effect in operational management, the authors identified the causes applicable to extraction process-related industries and after studying a variety of companies operating at different stages of the value chain, they concluded to the below findings:

- Higher proportion of long-term contracts with fixed delivery quantities used in refined products sales, increases certainty about future demand, thus lowering order variability
- In demand forecasting for refined products, the use of additional information that explains the demand fluctuations reduces crude oil order variability
- Limited storage capacity reduces crude oil order variability. The natural gas industry is not mentioned here. However, the similar operation studied in this particular stage of the supply chain with the distribution system to pipelines or the seaborne transportation of the oil resembles the trade of natural gas and LNG
- Variability in orders for drilling services can increase as the E&P company intentionally aggregates its drilling activities either to maximize profit or due to seasonality disturbing the whole supply chain
- Substantial Bullwhip effect is unlikely to exist in orders of consumable items used in O&G well drilling

A study that investigates the quantitative existence of the bullwhip effect in the natural gas supply chain of Croatia is "*Towards exploring bullwhip effects in natural gas supply chain" (2019)*. Firstly, it is pointed out that the demand for natural gas is formed according to the price fluctuations of the product, despite the stable need for energy. The final consumption at the end of the year may be consistent with the forecast, but the intermediate deviations are crucial for the performance of the supply chain. The price of the final product generally consists of two parts: the price of natural gas as a commodity at the well (the "wellhead" price) and the "basis" price. The basis is the location differential part of the price which includes the cost of transportation via pipeline, the processing, storage, refrigeration, transportation by sea, regasification, the tariff of the suppliers and brokers, and the risk/liquidity premium (depending on the state of the market, customers' credit and other factors). It is clear that the logistics costs have a major contribution to the final pricing, so managing this cost can substantially improve the competitiveness of the whole supply chain or of each individual organization linked to it.

It is interesting that according to the authors of the paper, initial talks to natural gas supply chain members in Croatia showed that there was lack of adequate knowledge about the bullwhip effect as well as absence of actions to prevent or mitigate it.

After an analytical presentation of the bullwhip effect and the natural gas supply chain, the study emphasizes on the market of Croatia, naming the major players and identifying the physical and economic relations between them. The below chart is an illustration of their findings.

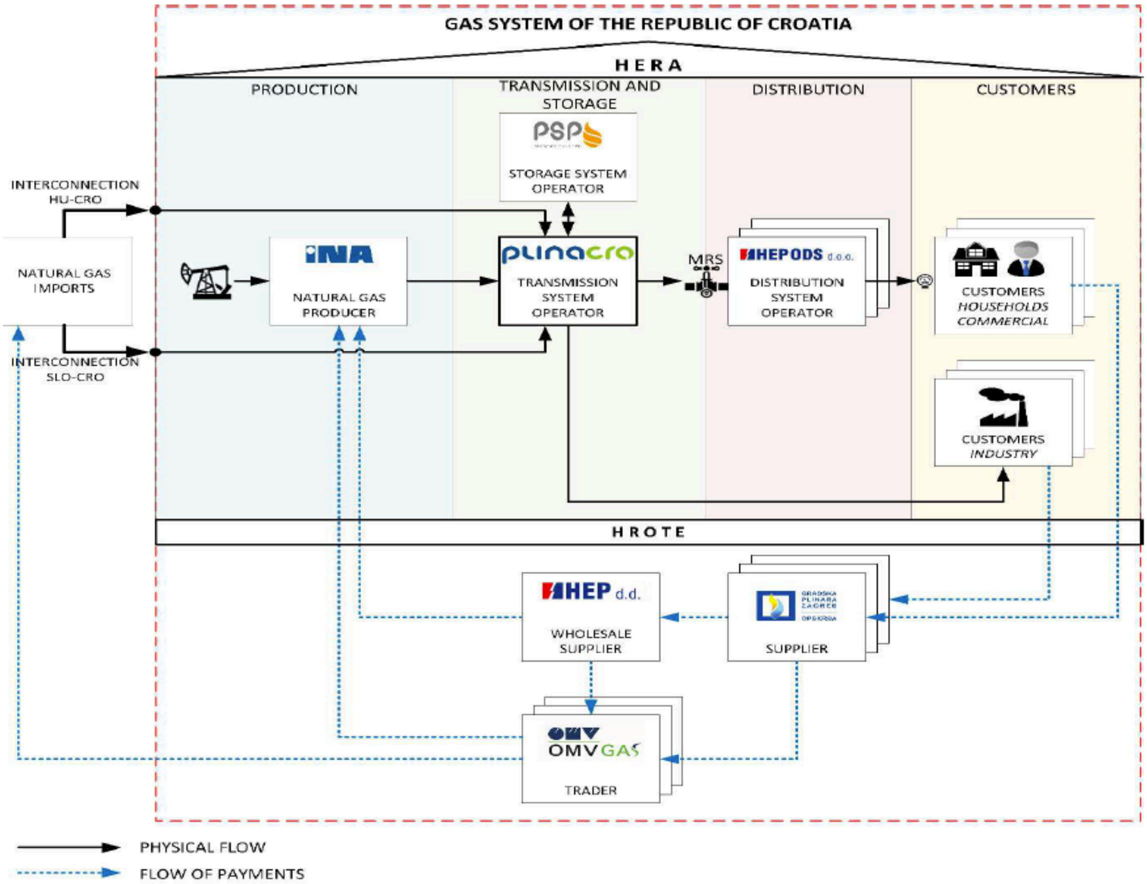


Fig. 4.1.1: Key players and flow chart of the Natural Gas supply chain of Croatia
(Dujak, Šebalj, 2019)

The bullwhip effect was calculated with the typical bullwhip effect ratio:

$$BE_{ratio} = \frac{Var[Orders]}{Var[Demand]}$$

Using the data from 2017, their initial suggestion that the bullwhip effect cannot be observed in a yearly basis, but is present in shorter periods, was confirmed to a certain degree. The monthly orders may differ from the consumption, but they seem to have a stable and smooth behavior despite the spikes in demand, which can be considered a good planning of the supply chain operation if the total demand is met.

The operating processes conducted as part of the above supply chain model and as a form of the business model followed by the natural gas industry sheds light on the problems that might occur and disturb the supply chain, creating the bullwhip effect. This is also linked with the consumption of LNG, which is influenced by the natural gas distribution and for this reason, the decision making concerning the supply of LNG is strongly depended on the forecast of natural gas consumption. Suppliers play the role of retailers towards final consumers (countries, households, or industrial units), as they sell large quantities of gas to them and measure their consumption through metering stations. Based on historical consumption data and other variables (e.g. weather forecast, seasonality character, other industry or regional specifics) they are making their own predictions and send them as daily nominations for the following day on hourly level to the "balanced group manager" – one of the suppliers who represent a group of corporations that are buying and withdrawing gas from the same transmission system operator. Balanced group manager collects all nominations from the members of his balance group and sends the total nomination to the transmission system operator, via a trading platform. The TSO then regulates the supply of gas in direct communication with the receiving party. The quantity distributed to the system from the stored capacities of LNG will be decided by the main gas distributor according to these estimations and the technical and economic strategy followed by the company.

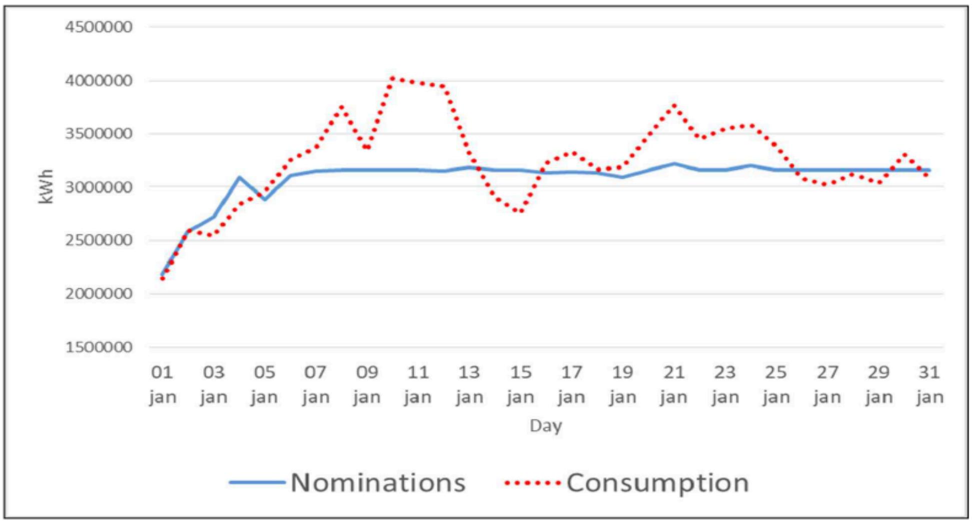


Fig. 4.1.2: Orders and actual consumption in the natural gas market of Croatia for January 2017
(Dujak, Šebalj, 2019)

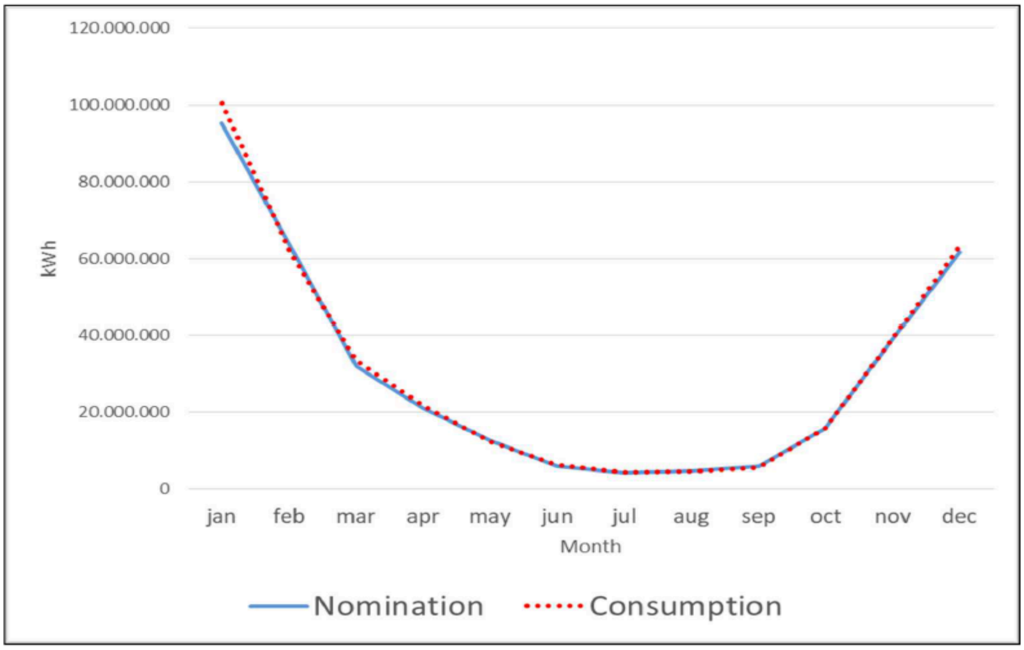


Fig. 4.1.3: Orders and actual consumption in the natural gas market of Croatia for Year 2017
(Dujak, Šebalj, 2019)

A complete examination of the natural gas supply chain and the demand amplification issue has been made in the "*Modeling for the Evaluation of Public Policy Alternatives in the Supply Chain of Natural Gas in Colombia*" (Becerra et. al., 2019).

Based on the assumption that the supply chain is consisted of a series of distinct operating activities which can be studied independently and then determine the links between them, the modeling of the supply chain has been constructed to include all these parameters and examine the problem at a multifactor level. The methodology of the study was to create a computational model to investigate the viability of potential improvement projects to the total capacity of the natural gas market in Colombia. The scenarios under consideration involved energy policies such as the import of liquified natural gas, or the extraction from new sources. It was stated that by combining the policies in the supply chain, better supply performance is achieved through:

a) the improvement in the reserve margin
b) the increase in capacity generation
c) the reduction of wellhead and consumer prices.

The below diagram from the paper, depicts the natural gas model and the links between the different stations of the production and distribution process.

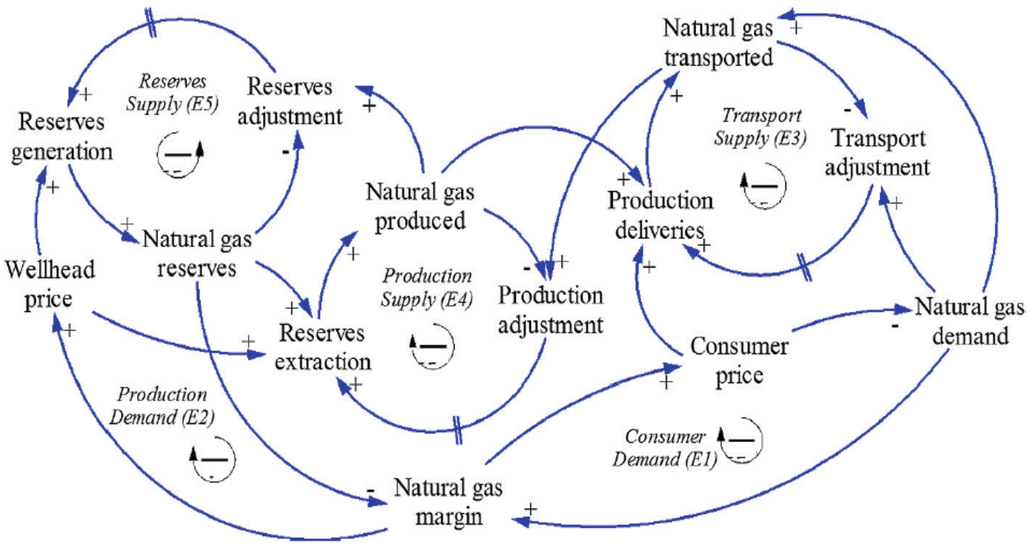


Fig. 4.1.4: Casual loop diagram for the natural gas supply chain model in Colombia
(Fernandez, et. al., 2019)

Based on the Forrester diagram, which depicts the stocks and flows of the system shown below, and the design of the supply chain model, four interconnected level variables are considered as part of the study, which represent changes in the state of natural gas from generation of reserves to delivery to the final consumer and in which the demand of the previous link (actor), corresponds to the requirements of the following link

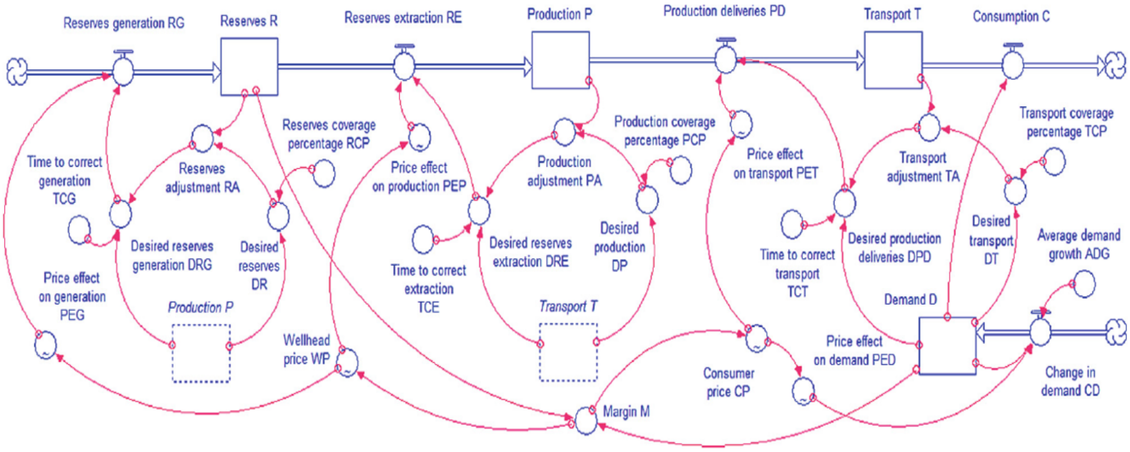


Fig. 4.1.5: Stocks and Flows for the natural gas supply chain model
(Fernandez, et. al., 2019)

The mathematical modeling of the above system, was based more on the sufficiency of data and their correct analysis, rather than the complicated solidly defined framework found in other studies in different industries. The basic quantities used to simulate the supply chain were [in Giga Cubic Feet]: flow of generation of reserves, reserves of natural gas, flow of production deliveries, production of natural gas, transportation of natural gas, demand, changes in demand, desired values to be supplied in the gas supply chain, level of demand of the next echelon, lead time to make the adjustment to the demand, wellhead and consumer price. The measure of performance used to compare the results was similar to the bullwhip effect ratio, customized to better observe the extraction process, with the amount of natural gas reserves taking the place of orders (Margin = Demand / Reserves).

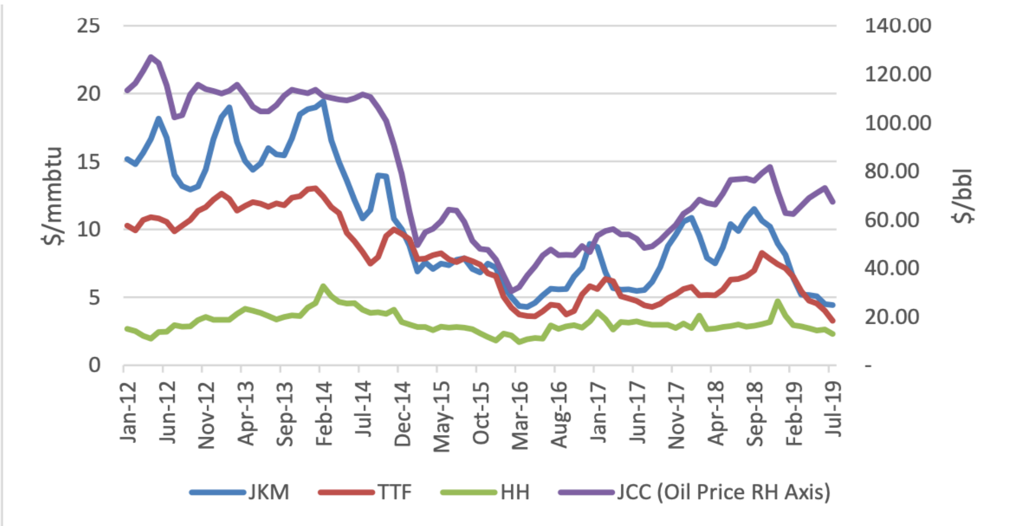
The optimization of the LNG supply chain was the topic of the "LNG supply chain analysis and optimization of Turkey's natural gas need with LNG import" (Güzel, 2011). The analysis of the LNG market in Turkey and the echelons of the supply chain, as well as the potential of natural gas as an energy source occupied the biggest part of the study. A cost benefit analysis of the natural gas transportation was conducted, highlighting the economic advantages of the LNG as a mean of gas transportation for countries distanced from production facilities. Nevertheless, the issue of LNG oversupply and undersupply was remarked and hence the optimization factor of the supply chain in the study is the storage capacity of LNG to investigate the possibility of adding a new LNG Terminal to the country. The framework used to model the supply chain was SCOR (Supply Chain Operational Reference), "a process reference model developed and endorsed by the Supply Chain Council as the cross-industry, standard diagnostic tool for supply chain management" (apics.org), which provides standardization of planning, operations, processes and resources. The author concluded that based on the demand forecasting (linear and quadratic trend forecasting) and the supply chain modeling, the construction of a new LNG terminal with a storage capacity of 500.000 cubic meters and regasification capacity of 15 bcm is strongly suggested.

It is evident that the common characteristic of these two optimization efforts of the previous papers concern the increase in capacity of the imported LNG with the addition of an LNG Terminal, because as it was mentioned in the advantages of LNG it is an easy, economic, and safe solution for the expansion of the natural gas market.

4.2 Causes of the bullwhip effect in the LNG supply chain

The reasons for the existence of the bullwhip effect in the supply chain of the LNG are related of course to the general causes of the phenomenon, as initially identified by Forrester and other researchers mentioned in the corresponding chapter above. However, certain inherent attributes of the production and distribution of the LNG distinguish the market from other previously mentioned industries, where the bullwhip effect has been widely studied and analyzed.

First of all, the high volatility of oil and gas derivatives prices favors practices such as forward buying and rationing and shortage gaming. The total need for energy production or heating may not change throughout the year, but the buyers always try to take advantage of this price inconsistency by differentiating the orders. Smoothing volatility in demand and prices would result in steadier and more profitable capital expansion, which means a higher return on assets. Steadier prices would translate to higher operating profits and lower operating costs, as companies would go through fewer waves of layoffs and subsequent rehiring. The below chart, showing the change in prices throughout the years 2012-2019 is indicative of the price instability observed in the gas and LNG market, responsible for



Source: Fulwood/OIES, Argus, Platts.

Fig. 4.2.1: International Gas and LNG Prices 2012-2019

The legal framework on the other hand is strictly regulated, as the trade usually concerns different countries or huge corporations, so the contracts signed by the interested parties are a basic part of the process. This change causes further lead times which amplify the bullwhip effect in the way described in the previous chapters.

The LNG projects, due to their scale, are developed as integrated chain of facilities and companies. Unlike any other type of shipping sector, in many cases after the signing of the LNG import or export agreements, the port and terminal facilities are built and LNG vessels are ordered. Although it does not apply to all projects, the liquefaction process and shipping costs represent roughly about half of the total cost of production to end user delivery (Alavi, 2003). A typical illustration of cost of delivery in an LNG supply chain is given in the figure. Another rough estimation often mentioned is that delivered cost of LNG consists of roughly one-third upstream production and transportation, one-third liquefaction, and one-third storage and regasification (The Economist).

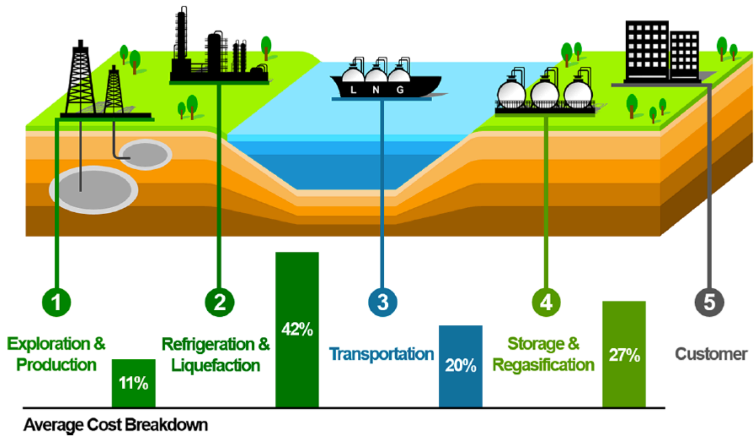


Fig. 4.2.2: LNG supply chain cost distribution
(Lee, Park, Moon, 2017)

In addition, the plans for pipeline transportation of the regasified natural gas are made on a monthly basis. Before a shipping period starts, shippers need to provide the pipeline company with accurate nominations for all the volumes they plan to move in that month. Just as the vessel must be matched to the cargo size, it must also be matched to the receiving jetty and the accompanying storage. Unlike oil, which is stored at more or less atmospheric conditions above ground, importers of LNG will need to store it at cryogenic temperatures, or regasify it and inject it into either underground storage, e.g. salt caverns, or the regional pipeline network. This entails substantial infrastructure as well as solid supply and demand balancing. It is more viable with regular and predictable LNG shipments combined with storage to meet the needs of a relatively stable demand outlook, conditions which may be lacking in many potential markets and given the price fluctuations this planning might be impossible to achieve. An important period for the testing of the proper function of the supply chain and its flexibility on sudden demand changes is the demand peak, which is usually considered a random event, as it can be influenced by numerous parameters. In the natural gas market, it is usually a specific date, when the highest demand of the year is observed by the distribution company and the TSO. The annual reports of natural gas distribution companies usually have a specific reference to that day, as it can determine the maximum capacity they can handle. To reassure the smooth operation of the process during demand peak, companies usually invest significant resources to be ready to meet the demand.

Regarding the infrastructure of the investment, the capital required to support and sustain the LNG storage and reception facilities, considering also the restrictions mentioned above, may cause a plethora of problems for the supply chain. More precisely, it has been observed that:

- Excessive capacity investments are made near the peak in order to meet the rising demand. However, the outcome is frequently a low or negative return of investment on them.

- Hardware manufacturers acquire and hold excess inventory during the demand peak, a policy that can lead to slow or even no depletion when the circumstances for the market change.
- Unpredictable events, such as recessions, natural disasters etc. can be detrimental to this market habit.
- On the contrary, certain component and parts suppliers lose orders, not able to receive at the demand peak, due to inadequate capacity and long lead times caused by large backlogs.

Another problem the LNG supply chain comes up against is the energy loss during liquefaction, transportation, regasification, and storage. The changes in temperature of the natural gas as part of the production process, except for their increased requirements of energy to perform these chemical reactions as described earlier, involve the heat transfer from the environment that causes the evaporation of LNG. As mentioned above there are several solutions in the industry to handle the boil-off gas, but the inability to determine all the parameters that affect the outcome of this evaporation, leads to loss of product. This uncertainty has negative results on the planning of cargo transportation, as the delivered volume of LNG may differ from the pre-agreed quantity. To avoid this possibility, the transported quantity is usually greater than the required as a safe margin, having an impact on both cost of transportation and logistics planning. The same can happen to the storage facilities, despite the state-of-the-art thermal insulation provided by the tanks. The demand amplification in these intermediate stages of the supply chain play their role in the increase of the overall bullwhip effect.

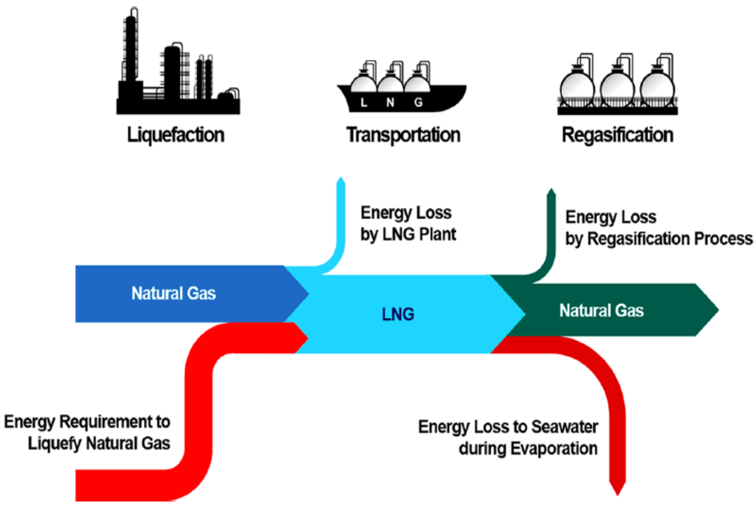


Fig. 4.2.3: Conceptual energy flow diagram of the LNG value chain
(Lee, Park, Moon, 2017)

4.3 The significance of the demand amplification in the LNG sector

It is essential to achieve the most effective supply chain management possible to every project of the energy sector. The technologically advanced infrastructure and the complex administrative framework to support such a business venture are only a part of these capital-intensive investments, entailing billions of dollars. For this reason, high standards of performance are required to satisfy the board and shareholders of the companies involved in these projects. The same time, reducing costs upstream the supply chain enables controlling the prices downstream, increasing the competitiveness of the commodity. Therefore, the existence of the bullwhip effect can cause loss of capital that translates to millions of dollars. Indicatively, the below figure presents an investment budget for a big scale LNG project.

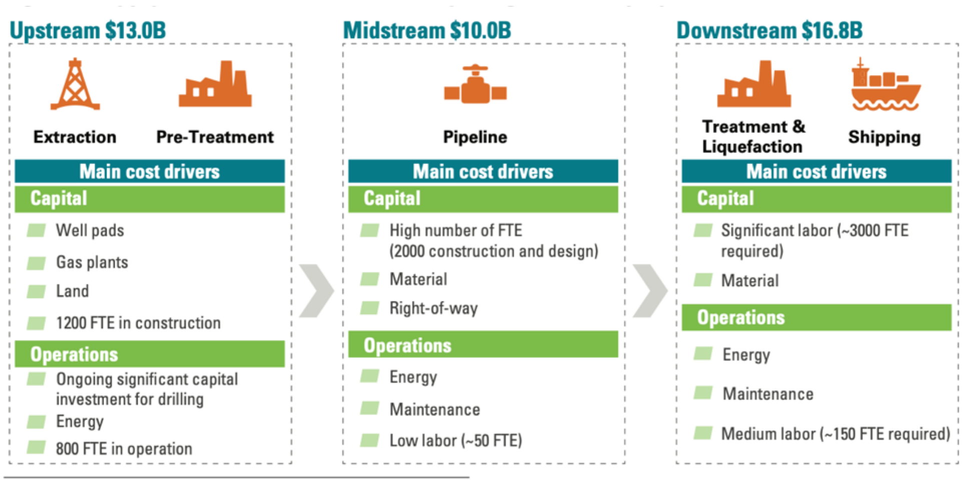


Fig. 4.3.1: Supply Chain elements in a vertically-integrated LNG project
(Lee, Park, Moon, 2017)

The characteristics and endogenous traits of the supply chain will reveal the importance to measure and mitigate the bullwhip effect and its impact to the industry. According to KPMG the main distinguishing lines between the liquified natural gas and the other energy sectors are the below:

1) **Large and complex:** LNG projects are comperatively to other undertakings massive with thousands of construction workers on site during project implementation. In addition, they are placed outside industrialized zones to remote locations. This means that human resources, materials, equipment and supplies have to be transferred to locations either ondshore or offshore, and literally create a city from the scratch, far from any human activity. Except for the huge capital expenditure this signifies the need for synchronized action and efficient organization of the process, which can be quiter difficult to achieve. Therefore, the amount of people involved can intensify the bullwhip effect in relation to smaller projects. However, the scale of the investment provides the tools to monitor the problems of the supply chain and have experienced human resources who are able to develop effective solutions.

2) **Challenging locations:** The easily accessible wells of natural gas and oil have been under human exploitation for decades. Therefore, newer LNG projects are located mostly in remote places far from population centers, and sometimes in challenging terrain which can even be environmentally or politically sensitive. Plant location is usually driven by a balance between the availability of a deep port and the location of the feed gas. The length and complexity of the logistic chain influences lead times and how easy it is to acquire not only materials to site but also key vendor support. The progressed delay usually observed in industries where demand amplification is present, can cause further lead times and supply chain disruption. Especially because it concerns the upstream process these delays can have serious implications to the production. This move to tougher LNG projects and environments, at a time of lower oil and gas prices, demands a more rigorous and innovative approach to the supply chain.

3) **Cumulative impacts:** Multiple projects are being constructed in contiguous locations, putting stress on local workforces and suppliers, and leading to sharply rising costs. In numerous countries across ASPAC (Asia-Pacific), international companies have to comply with local regulations that stipulate the use of local content for ancillary services, resulting in unique and very challenging supply chain requirements. This restriction in many cases applies to the workforce as well, when the regional legislation regulates the employment of a project managed by a third country. This limitation has as a result the hiring of unexperienced and untrained workforce with skills shortages, or with different working philosophies and ethics, elements which can be proven counter-productive for investments of that caliber with strict timelines and high standards of productivity. This results in significant lead times and inevitable lack of communication with the lower parts of the supply chain, whose contribution to the bullwhip effect has been extensively analyzed (Deloitte).

The proper function of the LNG supply chain has social extensions as well. The energy sufficiency of whole nations depends on the reliable delivery of natural gas for electricity production, industrial use, and domestic heating or even home cooking. A disruption in the supply chain, caused by an unpredictable event could put in jeopardy the normality of a country, so it is needless to mention the imperative need to prepare the supply chain for even the most challenging circumstances and extreme spikes in demand. On the other hand, apart from the readiness of the production and distribution company of the natural gas, the national policy making should always consider the possibility of encountering problems with the smooth supply of natural gas or any other energy source. This is where the LNG's superior advantage, its ability to be stored, is proven indispensable for the strategic energy planning of a country. However, the storage of the LNG in special tanks requires a careful planning, since there is the risk of over or under-supply, both negative scenarios for the proper operation of the supply chain.

Oversupply risks:

If the LNG share of total imports is above optimum proportion, that may lead to:

- additional costs deriving from the price difference of LNG and feedgas will have to be met in order to scale the budget
- additional costs paid for "take or pay" agreements that will inevitably increase the financial deficit
- losses for gas traders with no storage facilities, due to the intense competition. In general that would bring disturbances to the market and it would create an unstable ground for investments.

Undersupply risks:

Insufficient LNG storage capacity during an energy crisis or undersupply of natural gas transfered via pipelines, can cause:

- national disturbance
- slow down or even shut down of the industrial production

- use of less environmentally friendly energy resources more accessible to the country at the time of need
- difficulty in price regulation, since the private gas suppliers will tend to exert increasing pressure on the prices.

Another factor that should be added is that almost 90 percent of LNG long-term contracts are committed to delivering a cargo on a specific future date, so reliability and reputation are key. Consequently, any impact, any hiccup in the supply chain is much more damaging than in a typical E&P (oil exploration and production) company. (Company executive of NLNG in KPMG report)

In the conservative scenario forecast of IEA, LNG overtakes pipeline gas as the main way of trading gas between regions by the late 2020s. Developing economies in Asia are the main engines of LNG growth, with the market share of LNG in total gas demand growing from 20% in 2018 to 40% by 2040. The impact of the bullwhip effect and its scale to the LNG supply chain is conspicuous from the above information. Nevertheless, it is important to gather an understanding over the factors that influence the demand of the commodity and provoke these increases and drops observed short-termed.

Price Formation

The demand of LNG is determined by numerous parameters. An important aspect of the LNG market is its strong dependency on the trade of natural gas transferred via pipelines. The price of each commodity is autoregulated in the spot market which operates in the framework of free competition. As far as the mid-term contracts are concerned, lower production costs, achieved through technological advancements and higher natural gas prices either due to the time of signing or the location of delivery, push producers to feed more LNG into the market. This trend also contributes to the expansion of the spot market (Maxwell and Zhu 2008, pp.156-158). While the spot market share was only 2 % in 1990 it reached 16% in 2009 (Teekay). Some reasons behind this shift are:

- New LNG production and export terminals which do not have long term buyer
- Seasonal peak of natural gas demand
- Speculative players, increase in number of LNG vessels with no existing long-term charters or not renewing their finishing contracts

However, it must be highlighted that this price difference does not mean that the drop in the price of natural gas will increase the demand for LNG. It is the same product at a different chemical state, the same substance, methane, so a change in demand indicates the tendency of the market towards this hydrocarbon as an energy source. The prices are mostly determined by the logistics cost.

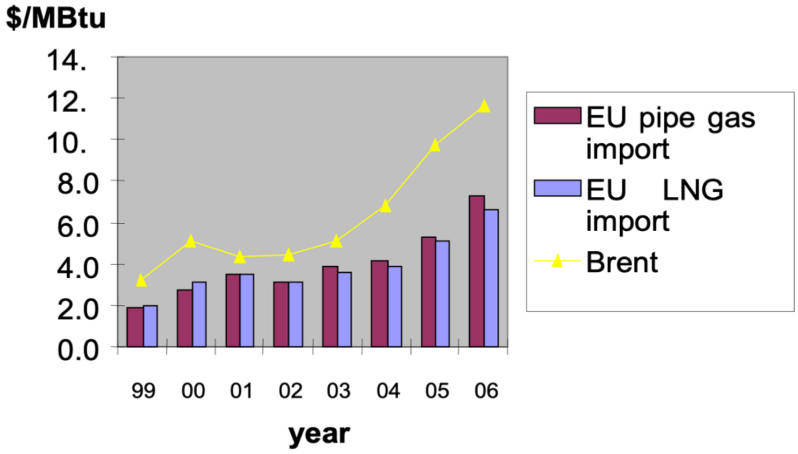


Fig. 4.3.2: Gas Imports Average Price in Europe (1999-2006)
(Energy P&T, 2007)

The price of LNG, as it was said in the analysis of the costs of the supply chain is partly formed (roughly by 20%) by the cost of transportation by sea. Because of the nature of these capital-intensive projects, the majority of LNG carriers are chartered by long-term contracts, most of which signed before the building of the ships with pre-arranged freights. However, the spot market is regulated by the product's demand. Therefore, the supply of the ships and consequently the freight asked by the shipping companies is directly correlated with the actual price of the LNG. For instance, if the demand for LNG rises suddenly and there are little LNG carriers in the market available to transport the cargo, the price of LNG will rise as well. The opposite occurs when there is excessive ship supply in comparison to the LNG demand. Nevertheless, this change in price will affect the decision making of the LNG importers, so this process can be characterized as a vicious circle not leading to safe conclusions about the final demand. Generally the demand of LNG

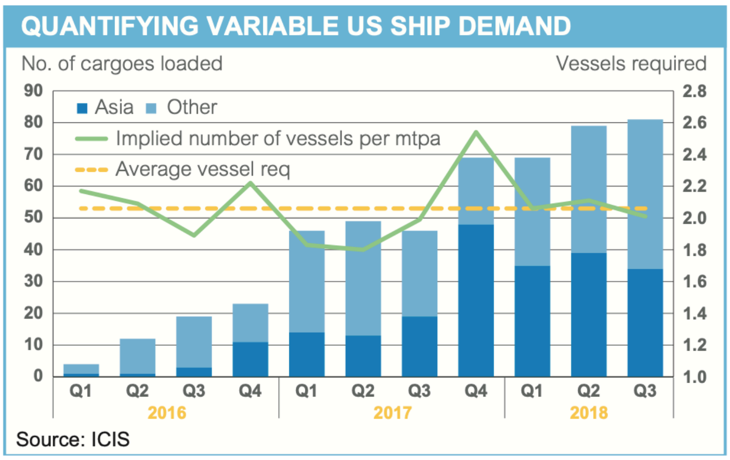


Fig. 4.3.3: LNG carriers demand in the US per mtpa
(ICIS, 2019)

Electricity Production

Electricity lies at the heart of modern economies and it is providing a rising share of energy services consolidated by the tendency to adopt electrification in more aspects of human activity. Moreover, electricity demand is set to increase further as a result of rising household incomes in the developing economies, of the electrification of transport and heat, and of the growing demand for digital connected devices and air conditioning.

In the conservative energy scenario of IEA, global electricity demand will grow at a rate of 2.1% per year until 2040, twice the rate of primary energy demand. This will increment the share of electricity in total energy consumption from 19% in 2018 to 24% in 2040. Electricity demand, as well as energy growth will be stronger in developing economies

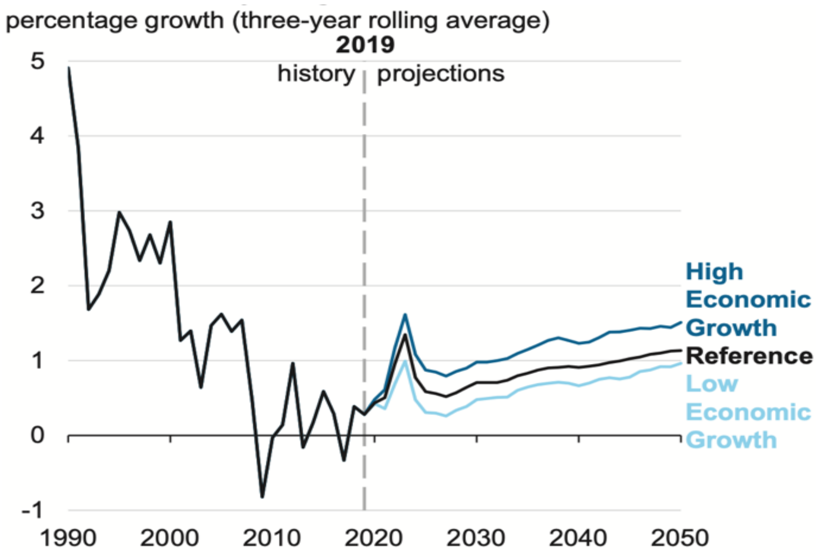


Fig. 4.3.4: Global electricity use growth rate

(Annual energy Outlook 2020- IEA)

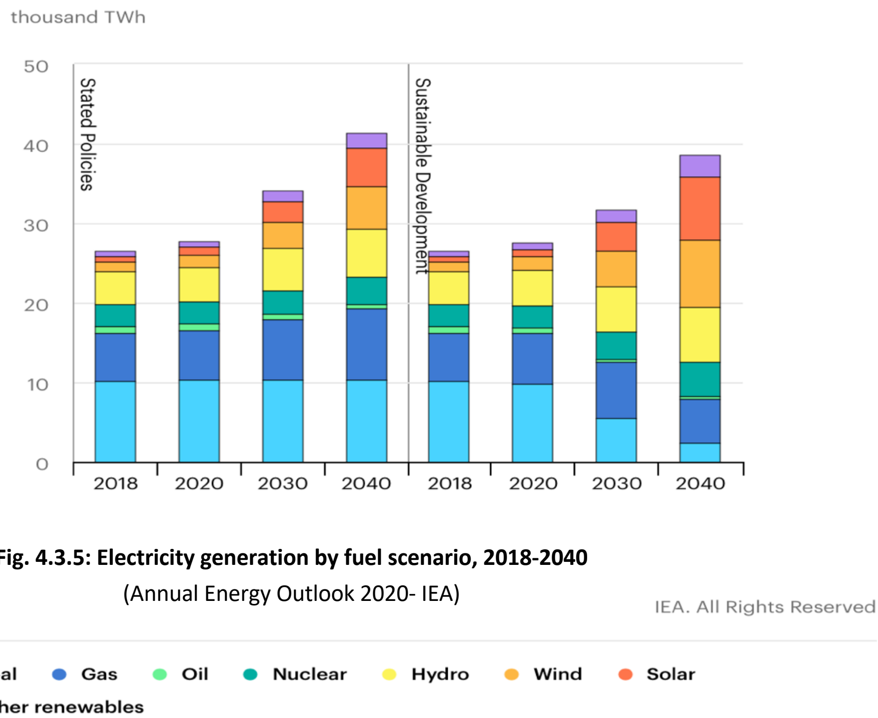


Fig. 4.3.5: Electricity generation by fuel scenario, 2018-2040

(Annual Energy Outlook 2020- IEA)

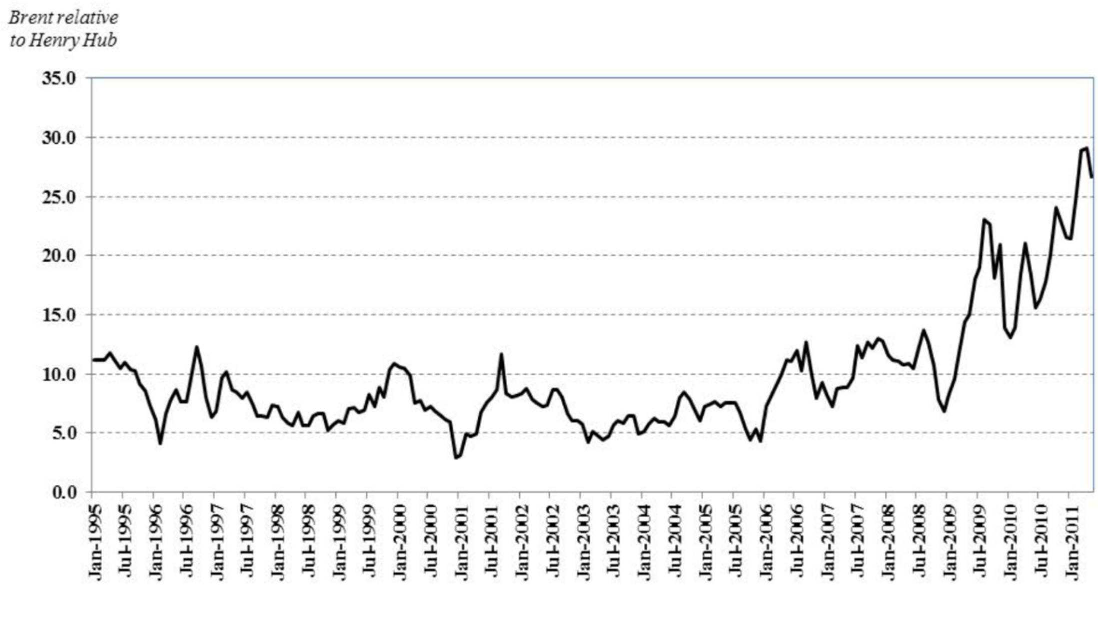
As it can be seen in the second figure, natural gas, according to both scenarios will surpass coal as the primary source of electricity generation. However, the integration of renewable energy sources in the energy mix will play an important role to the formation of future demand for gas. It is evident that the use of natural gas implies the increase in the use of LNG, which will be cheaper in the future with the advancement of technology that will enable the drastic cost reduction.

Oil Products

The price of Brent Crude Oil is a basic component of every natural gas demand study, because it defines the competitiveness of the commodity against the Brent Complex, a physical and financial market for crude oil based around the North Sea that includes numerous elements that can be referred to as Brent crude:

- Brent crude oil monthly futures contracts
- Brent crude oil monthly forward contracts
- Brent crude oil weekly Contract-for-Difference (CFD)
- Dated Brent short-term assessed prices
- Brent-Forties-Oseberg-Ekofisk-Troll (BFOET), Dated Brent, or Brent spot market
- Brent oilfield crude oil blend
- ICE Brent Index

The exchange rate of the trade is an important systematic determinant of the relative price of natural gas to crude oil. Crude oil can be referred as a competitive product to the natural gas, but it also describes the general potential of the market and the current need for energy production, so the trend of the market remains comparatively similar if one looks at the price indexes of the two commodities. In the past, researchers supported the opinion that they are cointegrated ("when two or more non-stationary time series are integrated together in a way that they cannot deviate from equilibrium in the long term"- corporate finance institution), but with further development of the econometric models, they now conclude that the relation between them is not stable and it depends on technological progress. (Hartley, Medlock, 2012)



Sources: US Energy Information Administration

Fig. 4.3.6: The relative Price of crude oil to natural gas (Jan 1995-Dec 2011)

This difference in demand however, is mostly allocated to power generation, rather than to heating purposes, because this aspect of usage is more pre-defined, given that it relates to domestic infrastructures.

Rising Industrial Demand

Natural gas is considered the fuel of the industry thanks to its clean and efficient combustion. Since 2009, demand for natural gas among U.S. industrial users has risen by 33%, an increase driven by the petrochemical, refining, fertilizer, and chemical industries. These industries according to the image of the market are expected to continue their successful course, so it's possible that this consumption will stay intact, if not increase. This augmenting industrial demand keeps prices from dropping, and moving forward it should even provide upward price pressure for the U.S. natural gas (Habacivch, 2017), which will have a similar result globally, increasing the prices of both feed-gas and LNG, given that the U.S. currently accounts for 20-25% of the world's liquefied natural gas LNG supply.

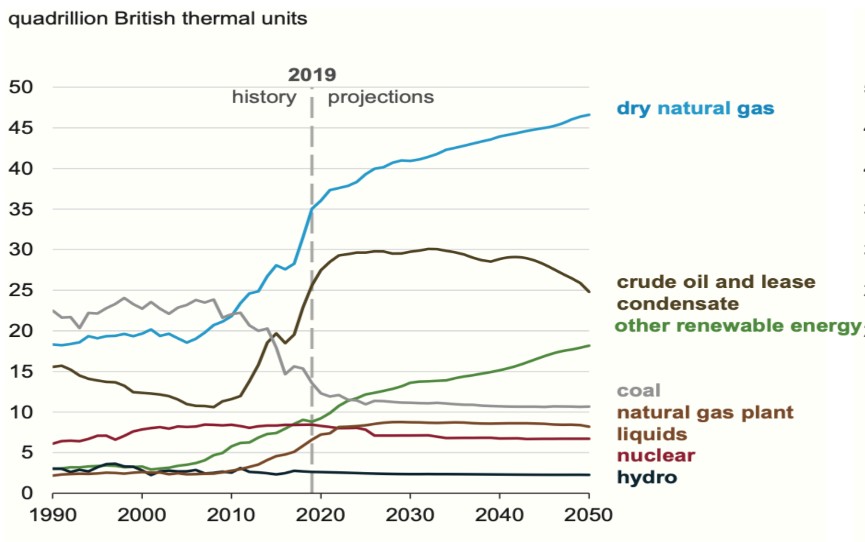


Fig. 4.3.7: Electricity Production
(Annual energy Outlook 2020- IEA)

Gross Domestic Product

LNG imports are directly related to the level of industrial activity in the community, the amount of gas consumed in the domestic and commercial sectors, as well as the amount of agricultural production (Arbex, Perobelli, 2010). The growth of the GDP of a country is a representative index of these attributes and it also indicates the economic situation and consequently the purchasing power of its people. Therefore, the level of consumption of any product or service is depended on it. The increase of the GDP might involve the above dependents of the LNG demand , such as the electricity consumption, or the industrial growth, but it must be separately mentioned and studied as a variable of the problem.

Table 2: Electricity Consumption Growth in Greece (DESFA)

	Percentage growth of GDP [%] *2020-2024 IMF projections	Greek interconnected power system growth of electricity consumption [%] low scenario	Greek interconnected power system growth of electricity consumption [%] intermediate scenario	Greek interconnected power system growth of electricity consumption [%] high scenario
2020	2,16%	0,74%	1,02%	1,29%
2021	1,63%	3,17%	3,27%	3,36%
2022	1,22%	0,60%	0,70%	0,80%
2023	1,24%	2,68%	2,76%	2,86%
2024	1,17%	0,65%	0,75%	0,84%
2025	1,20%	0,65%	0,75%	0,85%
2026	1,20%	0,65%	0,75%	0,85%
2027	1,20%	0,65%	0,75%	0,84%
2028	1,20%	0,65%	0,75%	0,85%
2029	1,20%	0,65%	0,75%	0,85%

The forecast of DESFA on the growth of electricity consumption in Greece, based on the growth of GDP for the years 2020-2029 is illustrated above. However, the data, at least for the next two years cannot be taken into consideration, since the forecast was made before the pandemic, which will change completely the domestic growth and the economic figures.

Environmental Policy

The demand of LNG is closely related to the enactment of environmental legislation globally, which can define new limits regarding the proximity of the global carbon tax, enhancing the need for clean fuel by increasing the plant production costs. The map of the environmental policy as it will be drawn the next decades in Europe has been made public with the Paris agreement. Nonetheless in countries like China, the US and in emerging markets in Asia and Africa the energy policy depends highly on the political situation and the government policies, given that they have shown contradicting behaviors in the past. Another issue for the world's energy production and consequently the demand for LNG is the future of nuclear energy, as in some cases such as in European countries, following the Fukushima incident in 2011, a decision was made to move towards nuclear power phase-out. For example, Germany decided to have all its nuclear reactors shut by 2022 (Reuters, 2011). The same applies to the scale of development of the renewable energy sources the next years and their potential to replace fossil fuels. This of course, does not solely depend on the political will, but also on the technological advancements that will enable higher levels of efficiency and on the investment environment. Therefore, the demand of LNG can change dramatically by these indeterministic factors.

CHAPTER 5

5.1 Modeling section- Introduction

Up to this point, an extended view of the LNG Supply Chain and the problems found in the supply chains of various industries that derive from demand amplification have been presented to the reader. After having a clear view of the core processes of the natural gas production and distribution in a holistic approach, it is possible to apply the knowledge concerning the bullwhip effect and the LNG market in order to model the phenomenon for that particular case. Most academic papers that study the LNG industry from this perspective, as presented above, only acknowledge the existence of the problem and try to measure the scale of the effect, using the metrics found in the bibliographic references.

In the present thesis, the aim is to model the bullwhip effect to forecast its occurrence. The model is based on specific parameters that according to the above study, have a direct effect to the structure and performance of the LNG supply chain. Nevertheless, it is impossible to indicate every single process and factor, that affects the level of the orders of the commodity in the context of a diploma Thesis. This is the reason for which an artificial intelligence technique will be used to accumulate and assess the impact of the parameters to the final result, as recorded in the bullwhip effect ratio, which was extracted from data collected and processed as part of the study.

The field of interest of the case study, lies at the downstream level of the supply chain, as it focuses on the national market of Greece, which is an LNG importer. The orders consequently are determined first and foremost by the domestic demand and the electricity production, as is the main consumer of natural gas. Except for the consumers of LNG, an important part of the process is the level of inventory, as it was the main influencing factor of the bullwhip effect in the papers involved with the problem.

After selecting the appropriate modeling tool (Neural Network Toolbox®- Matlab 2019), a neural network was designed to make a reliable assessment on the demand amplification, based on the factors that were identified above and affect mainly the end-user LNG demand. The data with which the neural network was trained, were extracted in their majority from DESFA, the administrator of the national natural gas network and were previous user's data, essential processing elements in order to achieve a well- regulated market. These factors were the inputs of the network and will be analyzed in the parameters' analysis. Having specified the procedures in the upper levels of the supply chain it will be not necessary to further analyze them, as the imported quantities of natural gas are treated as simple inputs of the system.

The perspective from which the optimization of the supply chain will be investigated is that of the national Transmission System Operator (TSO), the organization responsible for the operation of the LNG Terminal and send-out of natural gas from thereto the consumers. The scope of the TSO is to make the best decisions for the operation of the supply chain, considering the level of LNG imports, feed gas and storage.

The advantage of the deep learning method used to handle the problem, is that it takes into account the irregularities, the special conditions and the market environment of Greece, given that it uses data from previous use of the system and it is not a general modeling technique that could be applicable to a different country with entirely dissimilar structures. That being the case, the disadvantage of limited application of the program is downscaled by the reliability of the final results.

5.2 Artificial Neural Networks

The advancement of the science of informatics, both in software and hardware has constituted the use of artificial neural networks (ANNs), a basic method of performing computations and predictions for multivariable problems that are difficult to analyze in the conventional ways of programming and model structuring. A supply chain that involves all the aforementioned members (oil corporations, countries, administrators, brokers, shipping companies, etc.) is a characteristic example of these systems, so it can be better described by the statistical data that results from previous experience.

The basic functions of a neural network were expanded in the prediction methods section of the thesis. Further analysis of the neural networks will not be presented to the reader, to avoid deviating from the original purpose of the study, as the subject of the thesis is the bullwhip effect across the LNG supply chain. An artificial neural network is used as a tool that will enable the examination of the case studies. Consequently, reference will only be made to the necessary functions to acquire a better understanding of the results of the simulations.

In short, neural networks are an artificial intelligence technique that simulates the functions of human's neural system, consisting of a set of nodes (neurons) and layers (levels of nodes) which receive signals as inputs that affect the weights, the bias and the activation function to create a model that best fits the given data and approaches the target in the best possible way. The three main automated processes following the supply of the network with data, necessary for the design of a neural network are the training, the testing, and the validation of the data. The training of the neural network in which the weights of each node are assigned specific values is the basic operation and consumes the biggest part of the processing power. The validation dataset is the sample of data used to provide an unbiased evaluation of a model fit on the training dataset while tuning model hyperparameters. The evaluation becomes more biased as a skill on the validation dataset is incorporated into the model configuration. Validation can be used as a metric of the efficiency of the architecture of the network. Testing is performed afterward to provide an unbiased evaluation of a final model fit in the training dataset (towards data science).

The type of network chosen to be used is a feed-forward back propagation network. The backpropagation of error algorithm is one of the most widely used training algorithms in the case of neural networks. It is capable of training feedforward networks of any size and number of layers. Its objective is to calculate the values of weights and biases, which are often referred to as learnable parameters of an ANN to minimize the loss function of the neural network. Given a neural network architecture and a loss function, back-propagation calculates the gradient of the loss function, ∇E with respect to all weights to achieve a local minimum using dynamic programming. This is a mathematical process called gradient descent, which is a first-order iterative optimization algorithm for finding the minimum of a function. That is, given a neural network and a loss function, back-propagation algorithm propagates the loss at the output layer backward so that the gradient at all hidden layers can be calculated using the chain rule to readjust the weights at each neuron, as described in the below diagram:

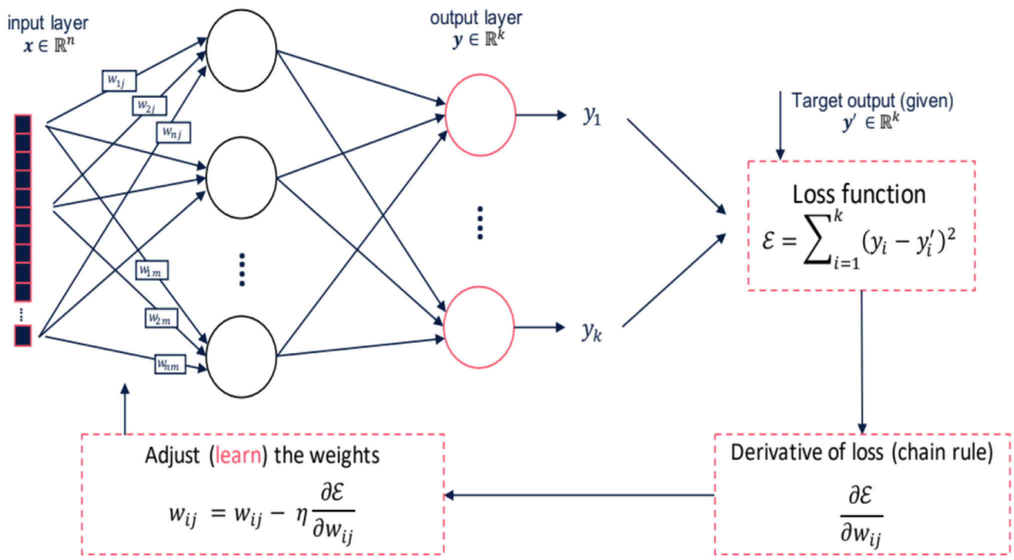


Fig. 5.2.1: Schematic representation of backpropagation algorithm

(L. Fausett, 1994)

5.3 Methodology

First of all, to design a network that will successfully simulate the supply chain problem or any given situation that needs to be modeled, it is indispensable to define the parameters that influence the desirable result. Thus, it is important to have a conceptual image of the mathematical background of the problem and the way each variable affects the problem. In the study performed in this thesis, the change in demand is the major contributor to the bullwhip effect. Therefore, the demand as well as, the factors that play an important role in the formation of the domestic and international demand constitute a field of interest to the realization of the ANN. According to the above conclusions concerning the demand amplification in the LNG sector and taking into consideration the accessible data from the industry, the study concluded to the below factors:

- Natural Gas Demand for electricity production: As was stated above, the lion share of the natural gas traded worldwide is used for electricity production. Also, the alternations in demand for electric power, serve the purpose of the study, as it is a more unstable factor compared to domestic consumption or industrial use, enhancing the bullwhip effect
- Total Demand for natural gas: Total demand for natural gas is required to have a measurement of comparison with the demand for electricity production and to give the model a general overview of the market, during a specific moment.

- Imports of LNG: The subject of the study is the LNG market, so the most reliable way of estimating the relation between the demand and the orders of the commodity is to monitor the imports in the receiving point of the country (Aghia Triada)
- Imports of pipeline feed gas: As it was explained before, there is a direct correlation between the LNG and the gas imported onshore through a pipeline, mostly concerning their cost difference at the time.
- Tank capacity used to store the LNG at the Revithoussa Terminal: The management of the level of the inventory stored at the warehouse is inextricably connected with the bullwhip effect across the different echelons of the supply chain.
- Prices of the Title Transfer Facility: more commonly known as TTF, a virtual trading point for natural gas in the Netherlands. Gas at TTF trades in euros per megawatt-hour and is used by most European countries as the common price of gas exchange.
- Prices of Brent Crude Oil: The importance of crude oil for the energy sector is undisputed. Consequently, its price should be a part of the model, as it is an indicator of the market and the economy. Apart from that, in certain sectors such as house heating, natural gas and crude oil are considered competitive products, so their interaction is worth mentioning.

Thereafter, the model has to process the data, given all the above inputs, and work efficiently to make an accurate estimation of the defined target. The target of the model was chosen as the bullwhip effect ratio, calculated for the next 30 days after the corresponding date (starting from the next).

The bullwhip effect ratio, as it was mentioned in the methods of the quantitative recording of the demand amplification, is in its simplest form the variance of the orders divided by the variance of demand.

$$Bullwhip\ Effect\ Ratio = \frac{Var[orders]}{Var[Demand]}$$

It is a good indicator of the demand satisfaction for a defined period, but due to the statistical nature of the divided quantities, it cannot be calculated for a short time range. For this reason, it is the most commonly found metric of the bullwhip effect in the relevant bibliography. Moreover, it is also applied in "*Towards exploring bullwhip effects in natural gas supply chain" (2019)*, which studies the natural gas supply chain as well.

The duration of the estimation was not based on previous experience from other academic sources because there was not a relevant model. However, it can be considered as a valid assumption of the study. A time limit of a typical month (30 days) is adequate to determine the existence and the scale of the bullwhip effect, as influenced by an interruption in the demand pattern but not extensive to get a disoriented result, which could be influenced by multiple factors and not be able to record the relationship between change in demand and the supply chain disruption.

The basic concept of the optimization of the supply chain which can be achieved through the examination of the bullwhip effect in various scenarios of energy demand in the national market of Greece lies with the proper management of scheduling LNG imports, storage, and regasification. This approach is based on the fact that the LNG can be regarded not as an independent commodity itself, but rather as the storage medium of the commodity "natural gas". In this way, the problem can be seen as a typical application of the bullwhip effect as it has been studied in other industries and should be examined to determine its scale and try to mitigate its impact.

For this reason, the variables through which the demand amplification and its impact on the supply chain will be studied are the below:

- Imports of LNG/ Pipeline feed gas ratio. According to a specific demand scenario, the difference in the percentage of the LNG contribution of demand can show the connection between the direct customer satisfaction, offered by the feed gas in comparison with the stability of the system, established by the LNG inventory.
- LNG Tank level in Revithoussa will shed light on how the replenishment of the inventory can influence the demand amplification.

The energy demand scenarios used for the model will be chosen randomly in the framework of the existing data with a percentile increase to project the future demand augmentation as recorded in the forecast published by DESFA in collaboration with Aristotle University of Thessaloniki (DESFA Development Study 2020-2029). The results of the simulation can show the ability of the existing system to respond to the predicted increase in demand for the next years, described in the previous chapters. Although the accuracy of the results cannot present zero errors, they can be used as a guideline to promote the best practices the administrator of the national natural gas can implement to mitigate the disruptions in the supply chain. Therefore, the below assumptions were made based on the conclusions of the executive summary of the development study:

Table 3: Assumptions of the DESFA Development study used in the input values of the model

	Brent crude $/bbl	Estimated growth of electricity consumption [%] *	Estimated growth of natural gas consumption [%] *
2020	71,75	1,02%	8,43%
2021	71,57	0,71%	6,20%
2022	71,38	0,71%	-2,37%
2023	71,2	0,71%	10,88%
2024	71,1	0,71%	-0,47%
2025	70,83	0,71%	-1,95%
2026	70,64	0,71%	2,19%
2027	70,46	0,71%	0,35%
2028	70,27	0,71%	0,42%
2029	70,8	0,71%	1,48%

* DESFA Development Study 2020-2029

Afterwards, the average of the last two months of 2019, concerning the model inputs, was calculated and then increased in accordance with the above, for the years 2020-2029. The below simulation scenarios were designed to examine the bullwhip effect in the supply chain at each case and check the behavior of the system after the variation of the aforementioned inputs. The projected values of the Brent crude oil were changed and consequently the prices of TTFs, so as to scale the difference between the above forecast and the significant drop of the global economy caused by the recent pandemic of CoVid19.

Table 4: Constant Input Values of the model

	NG Total Demand [kWh]	NG Demand for Electricity Production [kWh]	Brent crude [$/bbl] **	TTF Gas Price [$/kWh] ***
2020	158833063,2	112278245,3	51,75	7,5
2021	168686151,6	113075420,9	51,57	8,2
2022	164687333,2	113878256,4	51,38	9
2023	182602039,3	114686792	51,2	9,1
2024	181738294,5	115501068,2	64,1	9,2
2025	178187343,9	116321125,8	60,83	9,3
2026	182090190,5	117147005,8	60,64	9,3
2027	182730001,5	117978749,5	60,46	9,2
2028	183497774,6	118816398,6	65,27	9,4
2029	186216971	119659995,1	65,8	10

Firstly, a series of import scenarios were simulated in the model, where the quantity of the LNG and the pipeline feed gas were the variables of the problem. In this case, the inventory level in Revithoussa was considered constant at 70% (157.500 Nm^3), an average value of the last two months of 2019. To test a different situation, a typical value considering the initial data of 40% of the tank capacity (90.000 Nm^3) was also tested. The ratio of LNG/ NG was chosen based on experience from the existing data. Presumably, the imported quantity of LNG cannot exceed a certain level due to storage issues and consequently it was limited to an extent, so for instance there was no scenario where the demand was fully satisfied by the imports of LNG. The input data for the simulations along with the details of the simulations are presented in tables 5 and 6.

**https://www.investing.com/commodities/brent-oil-historical-data

*** https://www.quandl.com/data/CHRIS/ICE_TFM1-Endex-Dutch-TTF-Gas-Base-Load-Futures-Continuous-Contract-1-TFM1-Front-Month

Table 5: Variable Input Values of the model- 40% Terminal Capacity

LNG Imports [% of the total demand]	Pipeline Gas Imports [% of the total demand]	Tank Level /Tank Capacity [%]
20	60	40
20	70	40
20	80	40
30	80	40
30	70	40
40	70	40
40	60	40
40	50	40
50	50	40
60	40	40

Table 6: Variable Input Values of the model- 70% Terminal Capacity

LNG Imports [% of the total demand]	Pipeline Gas Imports [% of the total demand]	Tank Level /Tank Capacity [%]
20	60	70
20	70	70
20	80	70
30	80	70
30	70	70
40	70	70
40	60	70
40	50	70
50	50	70
60	40	70

Each of the above combinations was used as an input in the artificial neural network for the years 2020-2029, shown in the below chart as continuous lines.

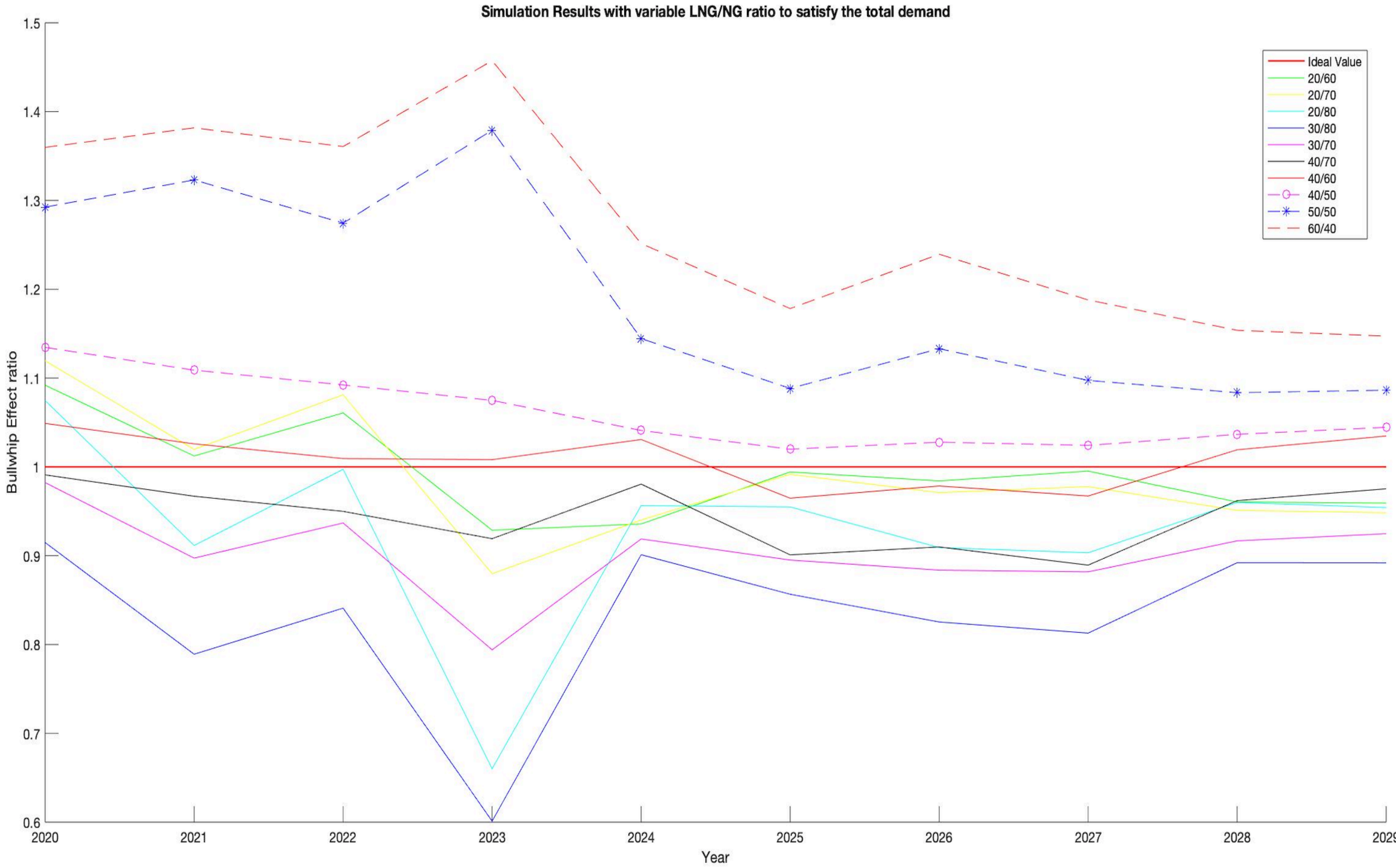


Fig. 5.3.1: Simulation Results for daily demand scenarios for the years 2020-2029 with varying gas imports mix- 70% Tank Capacity

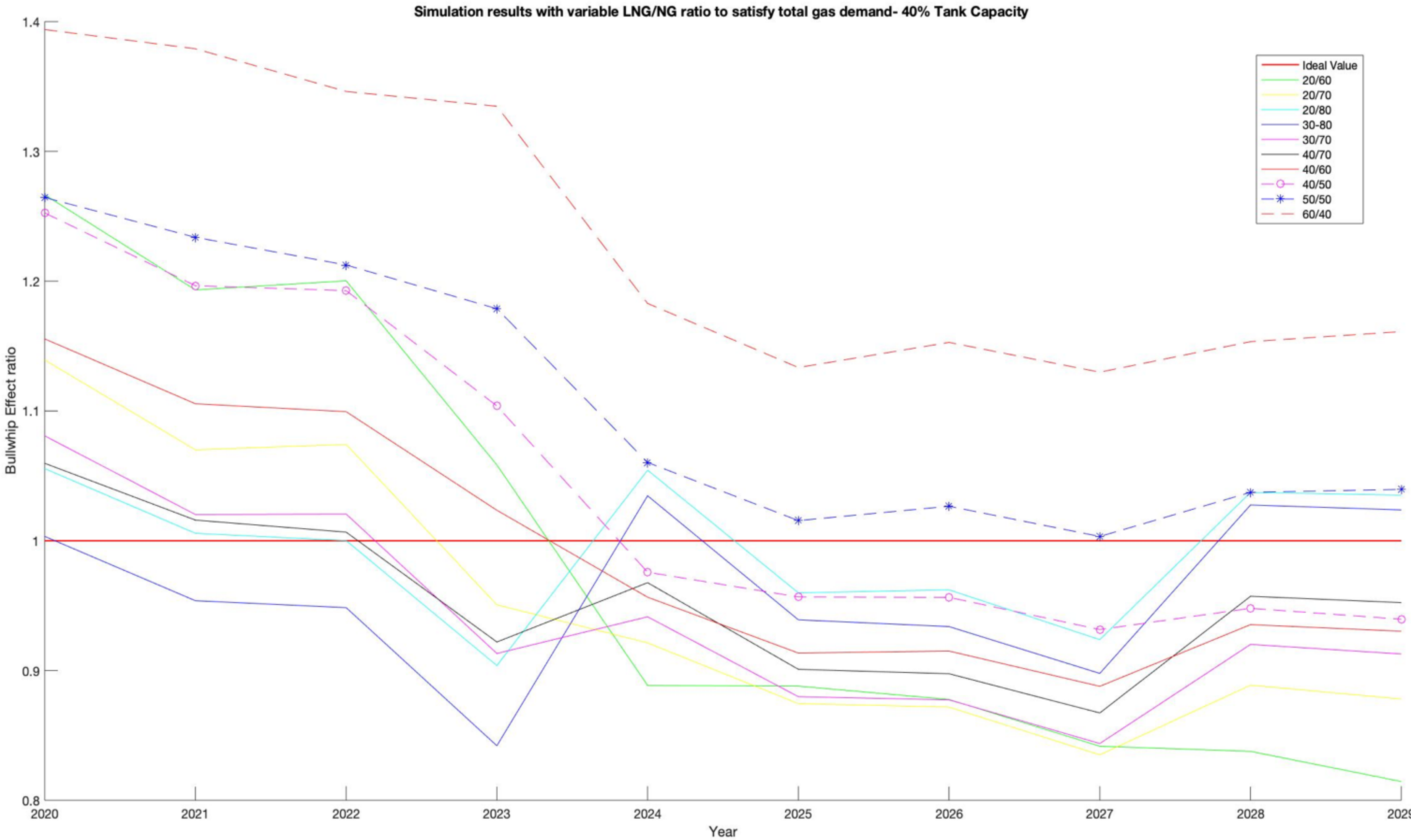


Fig. 5.3.2: Simulation Results for daily demand scenarios for the years 2020-2029 with varying gas imports mix- 40% Tank Capacity

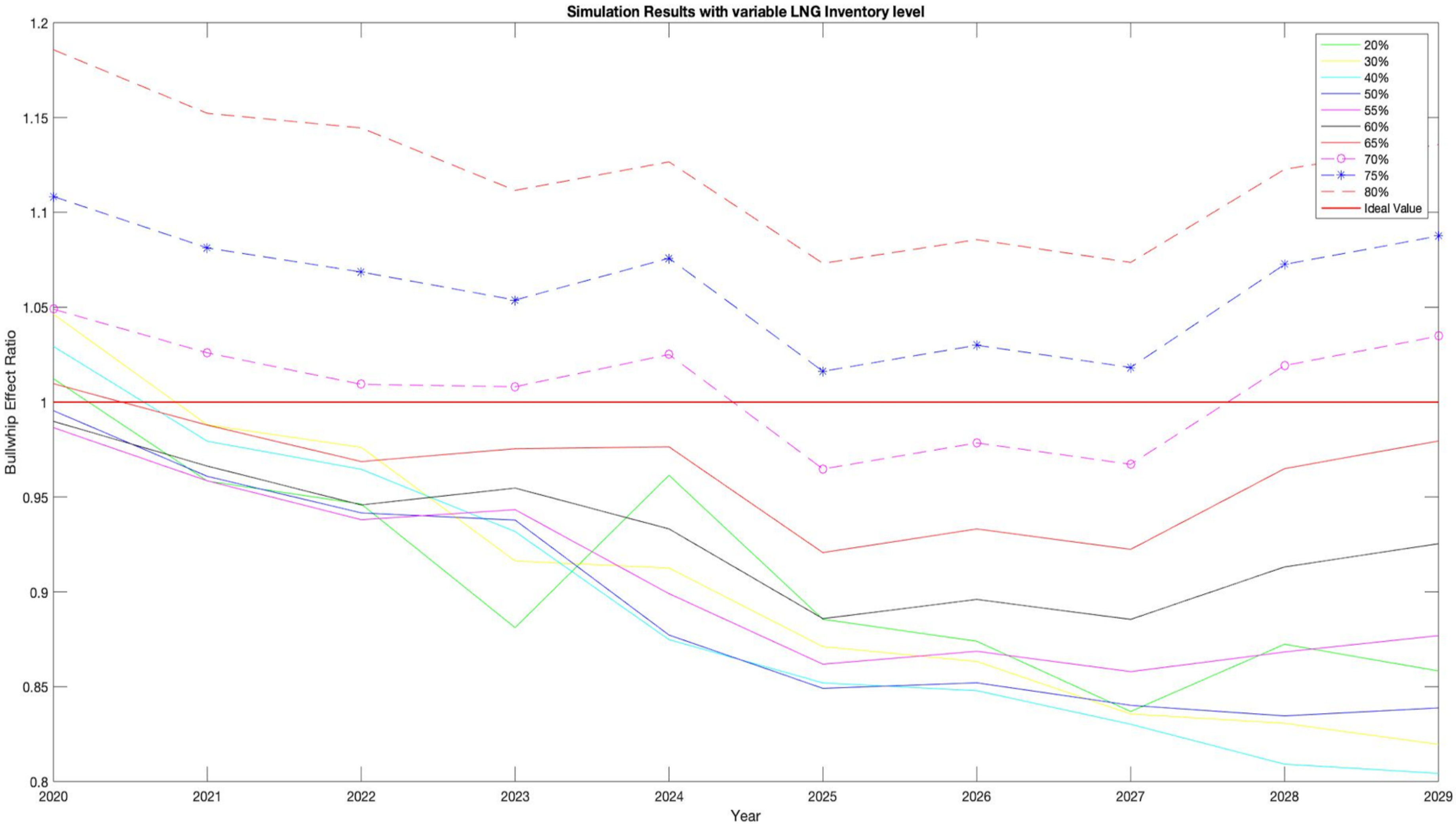


Fig. 5.3.3: Simulation Results for daily demand scenarios for the years 2020-2029 with varying LNG Inventory Level- 40/60 LNG/NG ratio

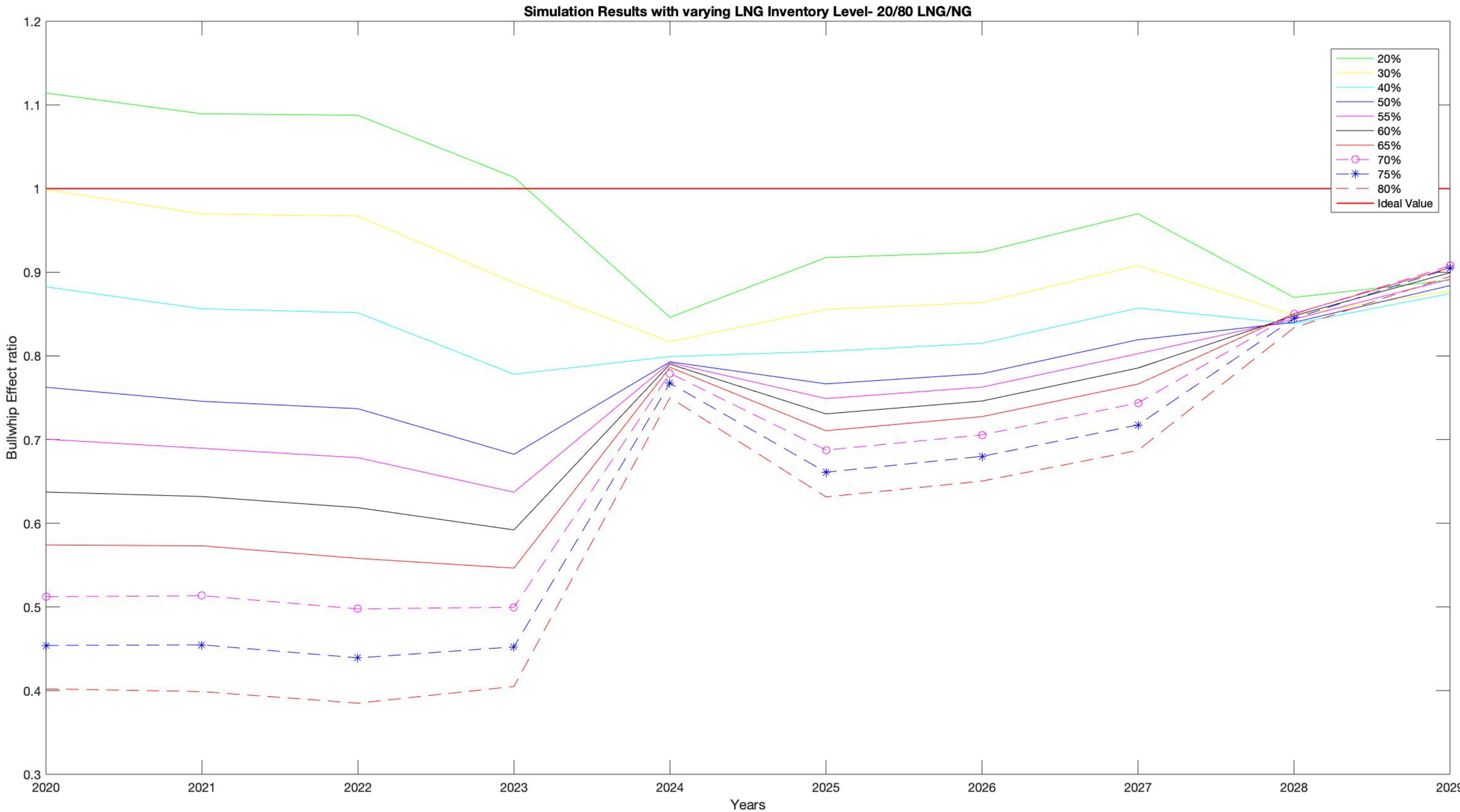


Fig. 5.3.4: Simulation Results for daily demand scenarios for the years 2020-2029 with varying LNG Inventory Level- 20/80 LNG/NG ratio

From the figure 5.2.2, it can be seen that the best behavior overall as far as the bullwhip effect is concerned, is observed in the first case by the 40/60 ratio of the LNG- Pipeline Gas proportion (red continuous line), while in the second case, by the 20/80 ratio (cyan continuous line). Therefore, for the next simulations, where the level of the LNG inventory will be the subject of examination, the 40/60 and 20/80 ratios were chosen as constants of the problem. However, it must be underlined that the factors imposing influence on the model, act holistically, so the optimization of the problem cannot be broken down into simulations that maintain constant values. Nevertheless, the purpose of this study is first of all to examine the existence of the bullwhip effect in the LNG supply chain in different demand scenarios. Given the opportunity though, an optimum import tactic is proposed, based on the results of the simulations. Moreover, these specific demand scenarios are part of a forecast for future demand and do not reflect the abnormalities presented daily to the administrator of the natural gas.

5.4 Software: Building the model

For the realization of the model in the form of an artificial neural network, the program used was Matlab® 2019 and more specifically, the Neural Network Toolbox (nntool), a suite offered by Matlab that automates most of the procedures relating to the programming of the neural network.

First of all, it gives the user, the opportunity to import variables from the workspace to the graphical user interface of the NN toolbox. The inputs mentioned above were the data exported by the reports of DESFA concerning the daily imports in the 3 reception points (Sidirokastro, Aghia Triada, and Kipoi) and the real-time consumption by the natural gas users at a national scale. The users were divided into three categories: the electricity producers, the industrial users, and the domestic users to be able to distinguish the natural gas destined for electricity production, which accounts for the majority of the total demand and constitutes an object of examination in the study. Because of the difference in the scale and the metric units of the input values, they were normalized to fit the range of [0,1], with a simple linear interpolation to get a better response from the neural network. The results presented thereafter were restored to their proper values, using the inverse function. Afterward, the target was imported to the model, which was an array with the bullwhip effect ratio values, also normalized. The interface of the Neural Network/ Data Manager, where the input and the target data are imported is shown below.

The creation of the network follows, in which the programming of the neural network takes place, with the definition of the necessary parameters. Initially, the basic algorithm has to be set, which in this case is typical for the neural networks Feed- forward backpropagation. The least mean square error (LMS) algorithm is an example of supervised training, in which the learning rule is provided with a set of examples of desired network behavior:

$$\{\mathbf{p}_1,\mathbf{t}_1\},\{\mathbf{p}_2,\mathbf{t}_2\},\dots,\{\mathbf{p}_q,\mathbf{t}_q\}$$

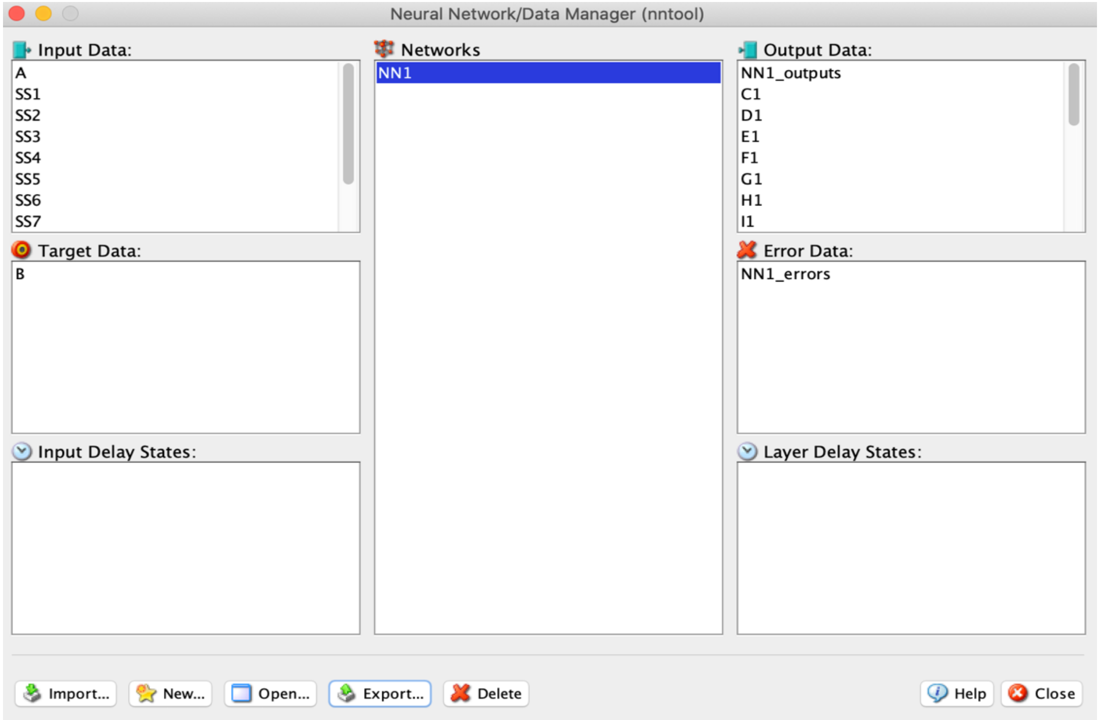


Fig. 5.4.1: Data Manager GUI

(NN Toolbox, Matlab 2019)

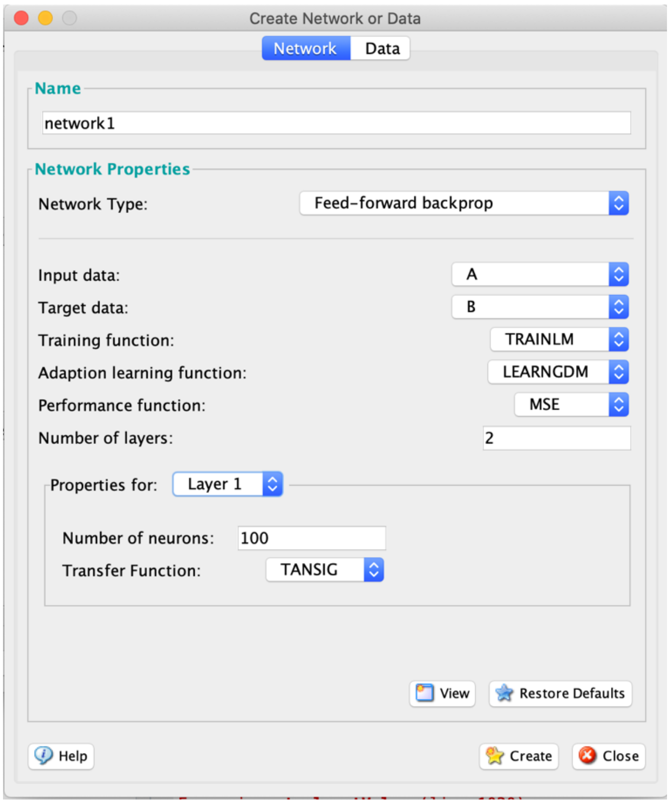


Fig. 5.4.2: "Create Network" Tab in nntool

(NN Toolbox, Matlab 2019)

Here $\mathbf{p}_q$ is an input to the network, and $\mathbf{t}_q$ is the corresponding target output. As each input is applied to the network, the network output is compared to the target. The error is calculated as the difference between the target output and the network output. The goal is to minimize the average of the sum of these errors:

$$mse = \frac{1}{Q}\sum_{k=1}^{Q} e(k)^2 = \frac{1}{Q}\sum_{k=1}^{Q}\big(t(k) - a(k)\big)^2$$

The LMS algorithm adjusts the weights and biases of the linear network to minimize this mean square error.

Fortunately, the mean square error performance index for the linear network is a quadratic function. Thus, the performance index will either have one global minimum, a weak minimum, or no minimum, depending on the characteristics of the input vectors. Specifically, the characteristics of the input vectors determine whether or not a unique solution exists.

The simplest implementation of backpropagation learning updates the network weights and biases in the direction in which the performance function decreases most rapidly - the negative of the gradient. One iteration of this algorithm can be written

$$x_{k+1} = x_k - \alpha_k g_k$$

where x_k is a vector of current weights and biases, g_k is the current gradient, and α_k is the learning rate.

There are two different ways in which this gradient descent algorithm can be implemented: incremental mode and batch mode. In the incremental mode, the gradient is computed and the weights are updated after each input is applied to the network. In the batch mode, all of the inputs are applied to the network before the weights are updated.

Feedforward networks often have one or more hidden layers of sigmoid neurons followed by an output layer of linear neurons. Multiple layers of neurons with nonlinear transfer functions allow the network to learn nonlinear and linear relationships between input and output vectors.

The function *logsig* generates outputs between 0 and 1 as the neuron's net input goes from negative to positive infinity. Alternatively, multilayer networks may use the tan-sigmoid

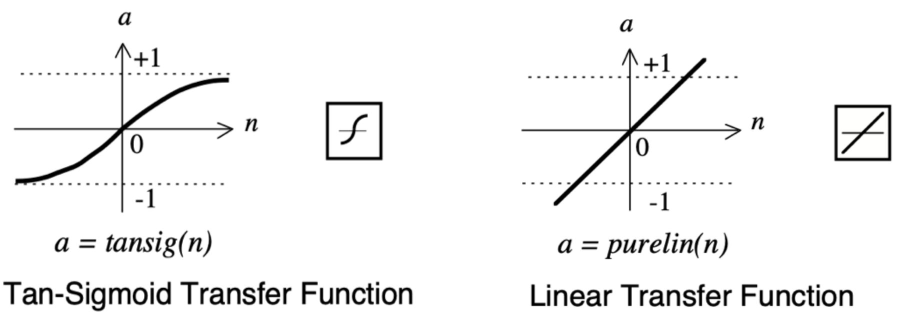


Fig. 5.4.3: ANN Transfer Functions
(Mathworks User's Guide)

transfer function *tansig.* Occasionally though, the linear transfer function *purelin* is used in backpropagation networks.

If the last layer of a multilayer network has sigmoid neurons, then the outputs of the network are limited to a small range. If linear output neurons are used the network outputs can take on any value. In the network of this study, the combination of the two was chosen due to better performance. In a schematic form:

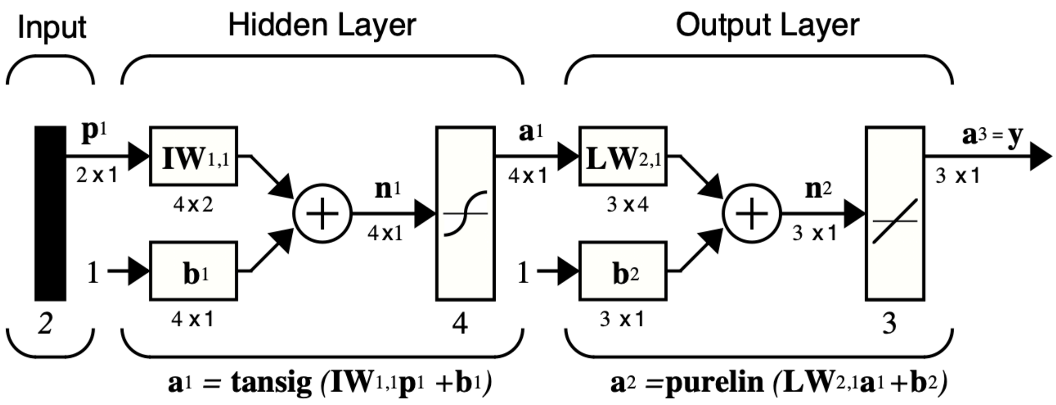


Fig. 5.4.4: Structure chart of the neural network
(Beale, Demuth, 2019)

Except for the performance function (mse) and the network's algorithm (feed- back prop), which are used to perform the recurrence of the procedure making the computations backward and ultimately put a halt to the training of the network, another important aspect of the design is the training function. The latter is the variation of the network's algorithm used to define in a fast and efficient way, the weights, and the biases to create the optimum network.

The basic backpropagation algorithm adjusts the weights in the steepest descent direction (negative of the gradient). This is the direction in which the performance function is decreasing most rapidly. It turns out that, although the function decreases most rapidly along with the negative of the gradient, which does not necessarily produce the fastest convergence. In the conjugate gradient algorithms, a search is performed along conjugate directions, which produces generally faster convergence than steepest descent directions.

The Levenberg-Marquardt algorithm was designed to approach second-order training speed without having to compute the Hessian matrix. When the performance function has the form of a sum of squares (as is typical in training feedforward networks), then the Hessian matrix can be approximated as

$$H = J^T J$$

and the gradient can be computed as:

$$g = J^T e$$

where **J** is the Jacobian matrix that contains first derivatives of the network errors with respect to the weights and biases, and **e** is a vector of network errors. It is reminded that The Hessian matrix of a function f is the Jacobian matrix of the gradient of the function: $\mathbf{H}(f(\mathbf{x})) = \mathbf{J}(\nabla f(\mathbf{x}))$.

$$\mathbf{H} = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1\,\partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1\,\partial x_n} \\ \frac{\partial^2 f}{\partial x_2\,\partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2\,\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n\,\partial x_1} & \frac{\partial^2 f}{\partial x_n\,\partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix}$$

Afterward, the Jacobian matrix can be computed through a standard backpropagation technique that is much less complex than computing the Hessian matrix.

The Levenberg-Marquardt algorithm (***trainlm***) uses this approximation to the Hessian matrix in the following update:

$$x_{k+1} = x_k - [\, J^T J + \mu I \,]^{-1} J^T e$$

Finally, the adaption learning function, learngdm, which has to do with the learning rate. In Neural Network tool box learngdm is gradient descent with bias learning function and momentum weight (Mathworks). Gradient descent, also known as steepest descent, is the most straightforward training algorithm. It requires information from the gradient vector, and hence it is a first-order method. The method begins at a point w_0 and, until a stopping criterion is satisfied, moves from w_i to w_{i+1} in the training direction $d_i = -g_i$

Therefore, the method iterates in the following way:

$$w_{i+1} = w_i - g_i a_i$$

Where α_i is the learning rate.

The final structure included 2 layers, a hidden one with 100 nodes and the tansig transfer function, while the output layer uses the purelin function. The selected layering and the number of nodes was the product of numerous tests conducted to achieve the best validation performance possible.

For the training of the neural network, the available data is divided into three subsets. The first subset is the training set, which is used for computing the gradient and updating the network weights and biases. The second subset is the validation set. The error on the validation set is monitored during the training process. The validation error will normally decrease during the initial phase of training, as does the training set error. However, when the network begins to overfit the data, the error on the validation set will typically begin to rise. When the validation error increases for a specified number of iterations, the training is stopped, and the weights and biases at the minimum of the validation error are returned. The test set error is not used during the training, but it is used to compare different models.

The last parameters needed to design the network are related to the training procedure, but there is no generalized rule to estimate their value, they depend though on various elements, such as the problem, the number of inputs, the target, and input values and the algorithms of the network. Therefore, try and error was the basic tactic followed to calculate their values to have the best solution, that is shown below.

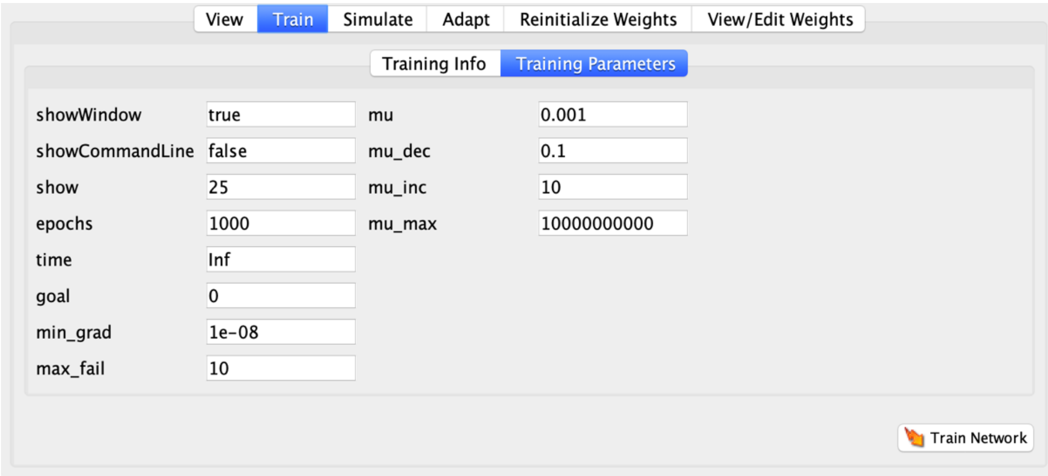


Fig. 5.4.5: Training Parameters

(NN Toolbox, Matlab 2019)

After several runs of the training procedure, the performance of the neural network, along with the relating diagrams are given subsequently.

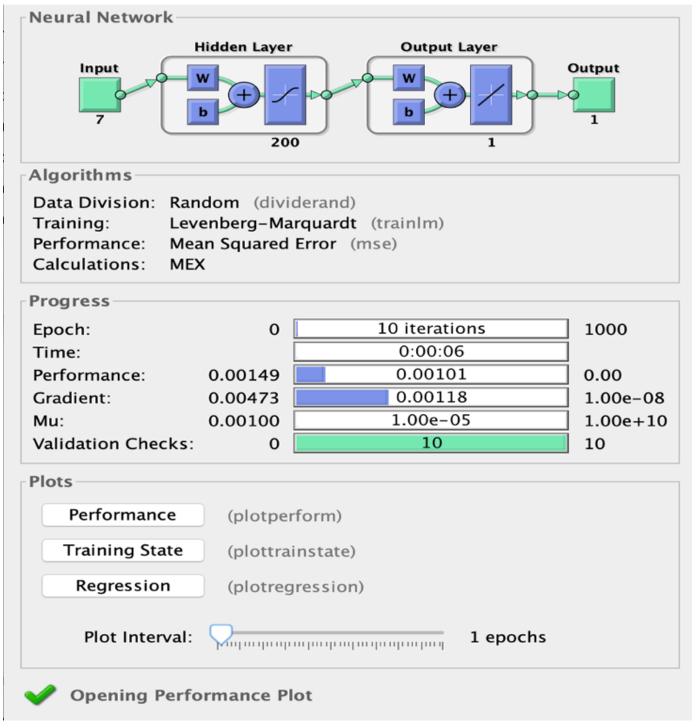


Fig. 5.4.6: Training Results

(NN Toolbox, Matlab 2019)

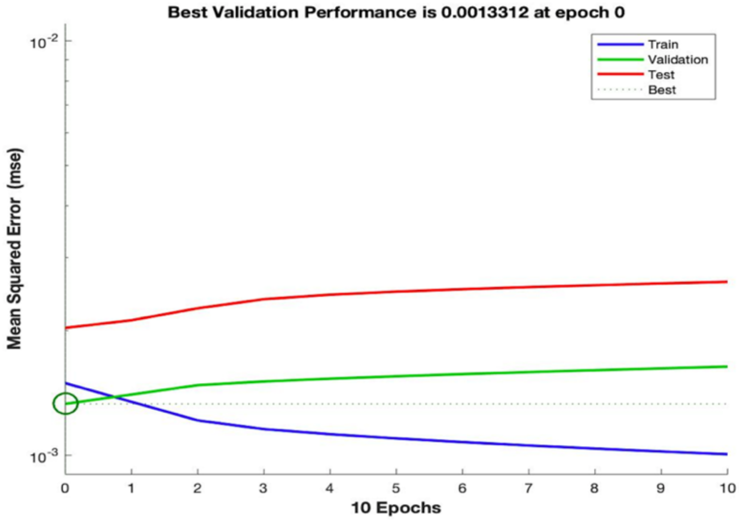


Fig. 5.4.7: Network's Performance
(NN Toolbox, Matlab 2019)

The mean squared error of the output as it can be seen from the above chart, is satisfactory for the framework of the study and seems to have a steady behavior, proof of the successful convergence. The regression chart that follows is also indicative of the network's ability to approach the target values.

A correlation coefficient (R) of above 0,8, as in the graphs, is also a reliable indicator that the model is robust, taking also in consideration the plethora of inputs, the size of the data (7 inputs with data from 1/1/2016 until 31/12/2019) and the complexity of the problem.

The errors of the outputs of the model are shown and a chart with the target data and the outputs of the network to remark the differences between the two.

After the denormalization of the output data, the mean error for the 1430 bullwhip effect ratios calculated by the network, was found

$$\bar{\boldsymbol{X}}[abs(errors)] = \mathbf{0,0622}$$

While the variance of the errors:

$$\boldsymbol{Var}[errors] = \mathbf{0,071}$$

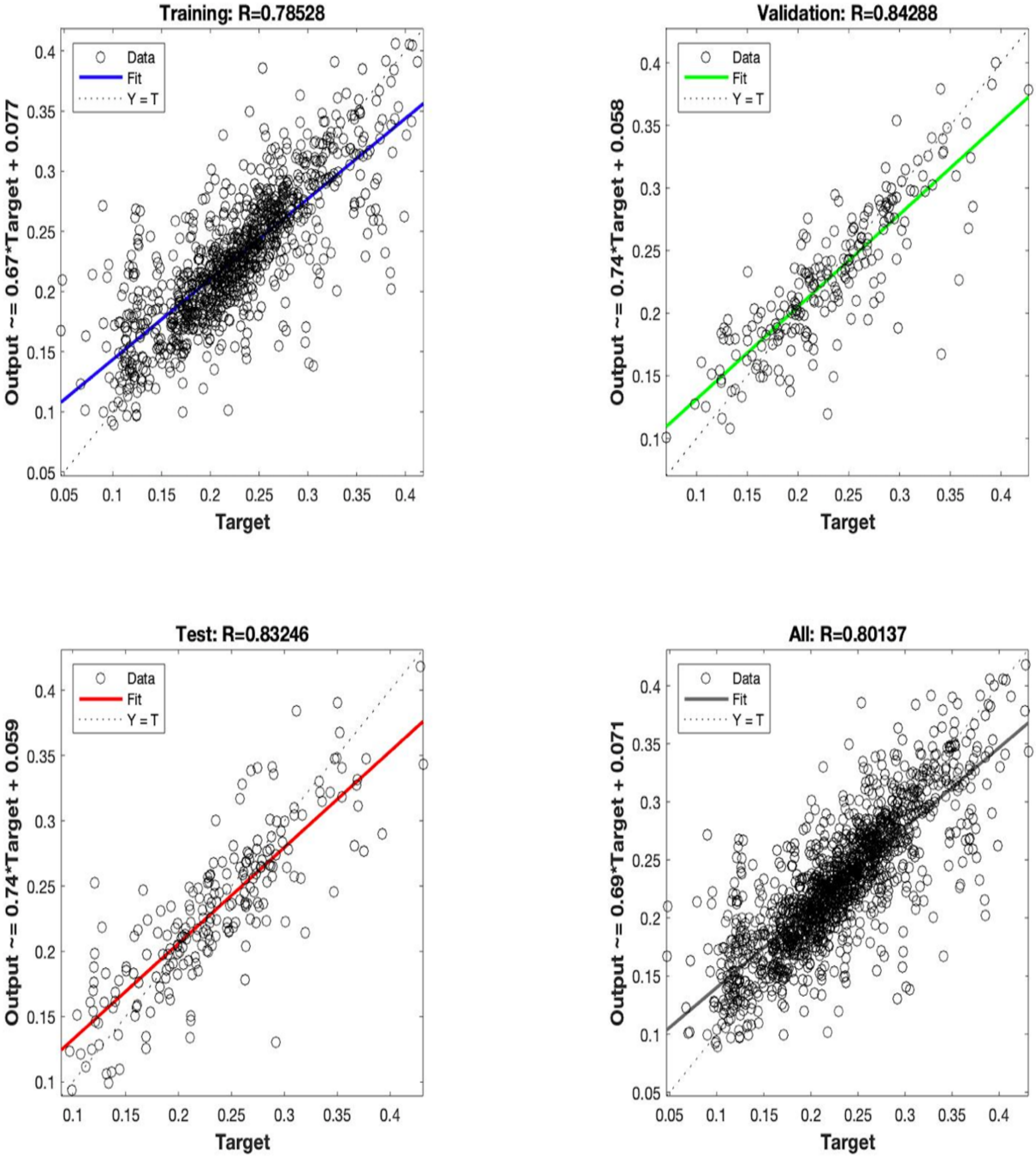


Fig. 5.4.8: Regression of the model
(NN Toolbox, Matlab 2019)

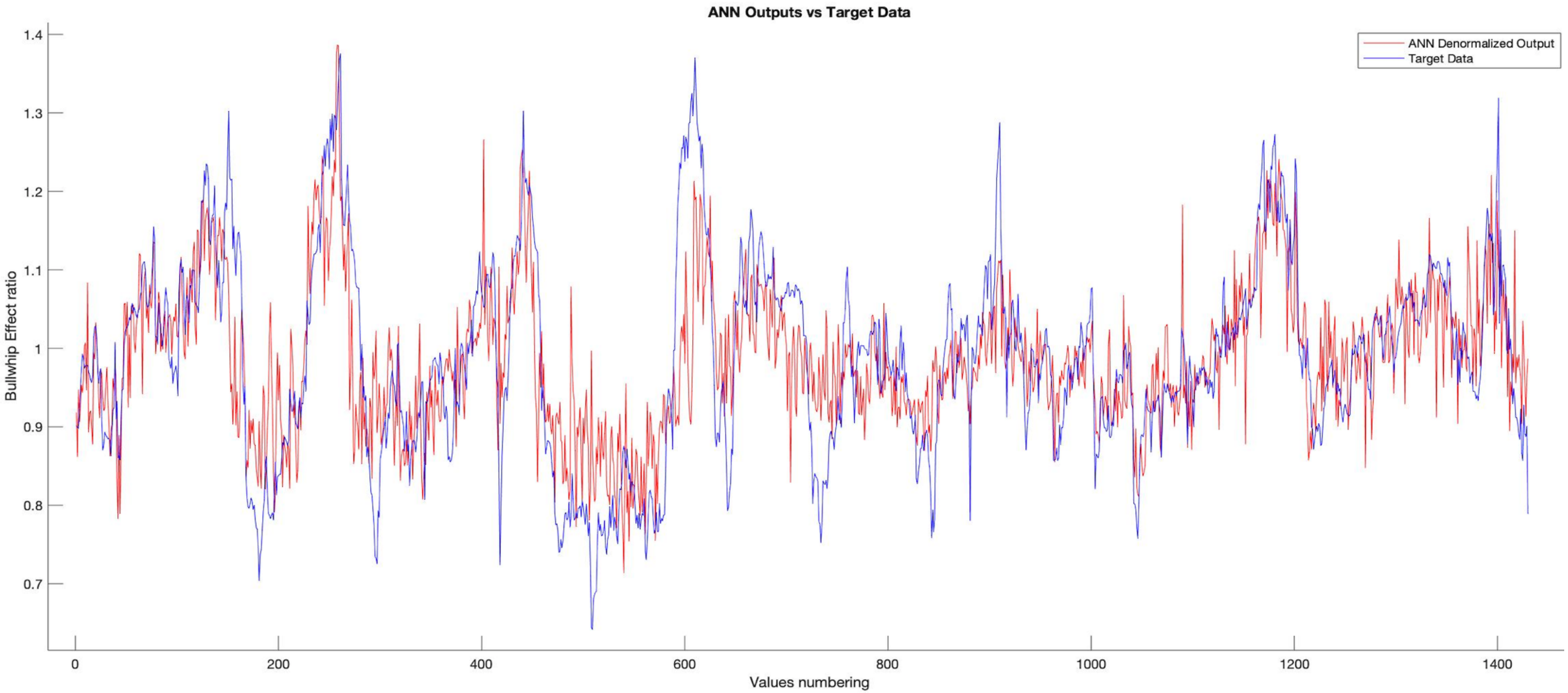


Fig. 5.4.9: Difference between output data and original target data

(NN Toolbox, Matlab 2019)

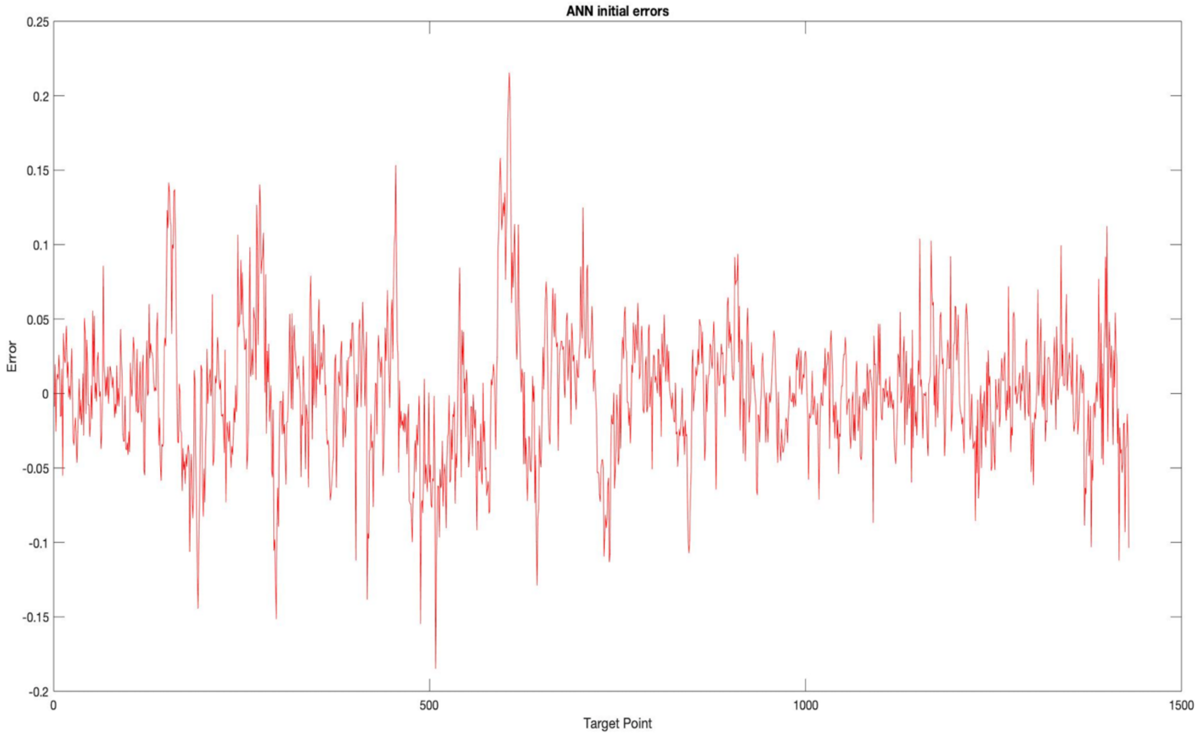


Fig. 5.4.10: Normalized output errors
(NN Toolbox, Matlab 2019)

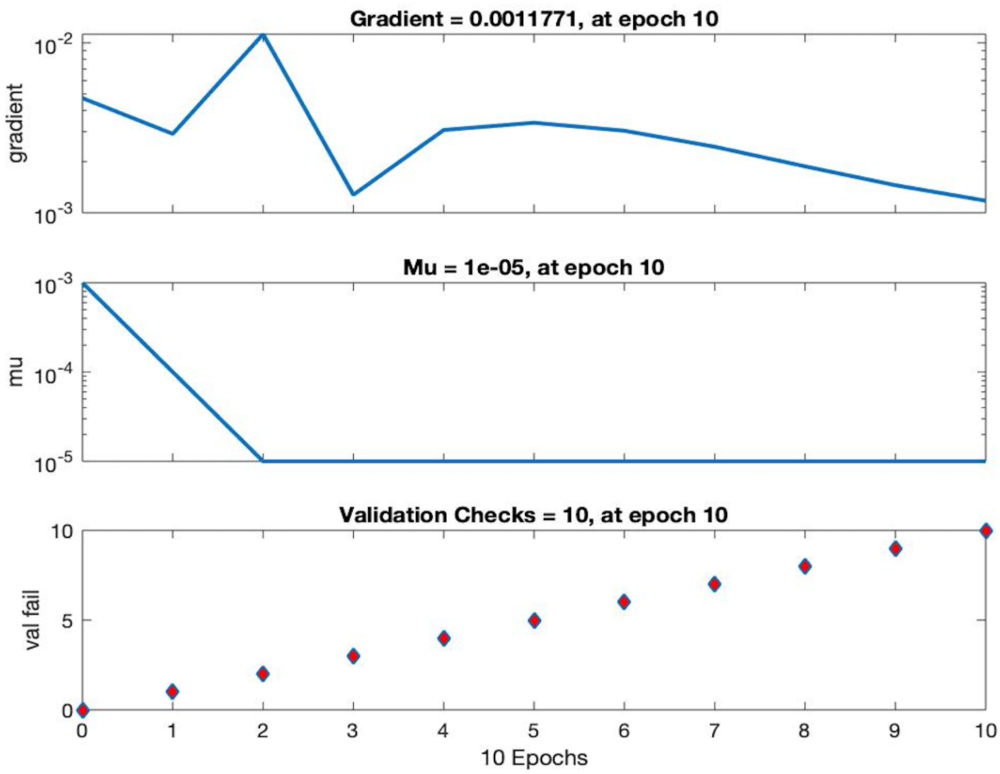


Fig. 5.4.11: Neural Network Training State
(NN Toolbox, Matlab 2019)

CHAPTER 6

6.1 Conclusions

Due to the competitive environment of today's world, the level of antagonism has risen rapidly among companies and organizations rendering the optimization of every business process an indispensable aspect of their every- day operation. Supply chains are considered an essential part of this effort and this is why their management has gained a tremendous appeal over these last years. A serious problem that can provoke severe implications for the operation of the supply chain is the bullwhip effect. In numerous areas of the industrial world, this phenomenon has been extensively analyzed and methods of mitigation have been proposed. However, there are still industries, where their relatively smooth operation and their elaborate processes have made the administrative staff of the value chains focus their attention to other problems. Such an industrial field is the energy sector, and more precisely the natural gas and LNG market that the present thesis examines. In a transitional era, where the renewable energy sources start to enforce their position in the global energy mix and the replacement of the conventional fossil fuels is considered imperative for the following decades, the natural gas will be the lever of this development. The LNG allows storing and transporting the commodity in a fast and reliable way, expanding the potential markets that have access to natural gas and enhancing the value chain. Consequently, the thorough analysis of the business processes the industry includes, and the search for optimization of its supply chain are necessary for the economic sustainability of the energy sector. The examination of the demand amplification in the supply chain has this exact purpose.

Nowadays, the processes of ordering, storage, and inventory replenishment are being realized with the implementation of modern IT systems and the development of artificial intelligence. The parameters taken into consideration often overlook the efficient long- term satisfaction of the demand and put their attention more to the shortage avoidance and the safe and reliable transportation of the commodity. Nevertheless, even with systems that offer a high level of accuracy and automate most of the processes, the presence of the human element is necessary for the implementation of the decisions taken, after having received and processed the information from the corresponding digital tools. Therefore, proper interaction among people and IT systems is the key factor for productive automation and information processing. For this reason, the results of the study will be commented on to grasp a better understanding of the actions needed to be taken with the contribution of the deep learning programming techniques.

For the selected case study, firstly a holistic view of the LNG supply chain was provided to the reader, from the upstream supply, liquefaction, shipping, and regasification of LNG into the downstream markets. Nevertheless, the end-user of the product receives natural gas for consumption, so the market is hardly distinguished from the natural gas industry. Therefore, to determine the scale of the bullwhip effect in the LNG supply chain for the market of Greece, which is a part of the downstream production process, it was necessary to compare the imported quantities of natural gas and LNG to the country with the actual consumption. The final result of the model was the metric of the bullwhip effect, but in order to determine its value, given that it is a complex and multivariate problem that entails the element of the forecast, the use of artificial intelligence was imperative. The data collected was adequate to create a robust and reliable model that can determine the scale of the effect given the demand and the corresponding imported quantities of LNG and pipeline feed gas.

Matlab® and more specifically the Neural Network Toolbox was selected to perform the programming and design of the neural network. The inputs of the model were the natural gas demand for electricity production and the total demand, that could be part of a forecast available to the TSO, the proportion of LNG and pipeline feed gas, the Revithoussa terminal's loaded capacity, and the daily prices of TTF and Brent crude oil. The output of the network was the bullwhip effect ratio for the following month in order to indicate the ability of the supply chain to satisfy the total demand, respond to disruptions in the demand patterns, and determine the contribution of the LNG terminal to that. The model used daily data from 1/1/2016 until 31/12/2019 and to approach their values, a structure of 2 layers with 100 nodes was selected for the network.

The purpose of the study as mentioned before was to determine the scale of the bullwhip effect at every occasion, especially when there are rapid shifts in demand that can cause disruptions to the supply chain. For this reason, the demand scenarios refer to consumption forecasts of the following decade, where according to estimations, the demand will reach its peak. The system was considered unprepared for this increase, without the addition of new LNG terminals to the equation. This way, the study can better examine whether the existing infrastructure is adequate for the upcoming augmentation of consumption and how will the supply chain be affected. As far as the results of the simulations are concerned, figures 5.3.1 and 5.3.2 give a clear view about the behavior of the bullwhip effect in comparison to the variation of the selected inputs. In the first case, where the LNG/Pipeline NG ratio was examined and the inventory level stayed constant at 70% (an average value extracted from the last 2 months of 2019) the outputs showed that the closest bullwhip effect ratios to the unit were observed on the scenarios that kept a more conservative approach to the satisfaction of the total demand and did not overreact by importing extensive quantities of gas. This is also related to the importing policy that usually follows after the initial response to the demand since the bullwhip effect refers to the next 30 days.

The LNG/NG ratios with the smallest demand amplification were the following: (1) 40/60, (2) 20/60, (3) 40/50, (4) 20/70. As was stated in the methodology of the modeling, not all demand scenarios are targeted to satisfy 100% of the total demand, because the imports of LNG and natural gas are also determined by long-term contracts and importing policies. Therefore, a range of 80% -120% of the total demand satisfaction was chosen to feed the network and various scenarios were tested under this concept. In this way, more realistic results were presented close to the everyday operation of the system. Moreover, as the results show, except for the first scenario, the other 3 do not reach 100% of the actual demand, probably maintaining a steady policy of imports. After these, a relatively good response is met by (5) 40/70 and (6) 30/70. An important deviation from the desired value characterizes the rest of the demand satisfaction scenarios (7) 50/50, (8) 20/80, (9) 30/80 and (10) 60/40, probably due to the unnecessarily high level of LNG (more than 50%) or pipeline gas (80%) percentage of the total demand.

A worth- mentioning remark is that in 2023, where the biggest increase in demand of the model takes place (more than 10%) according to the DESFA study, almost all demand scenarios presented a spike in the demand amplification metric. The smooth response of the first proportions is thanks to the security offered by the extensive inventory in the form of LNG, stored in Revithoussa. This is proven by the entirely different image in the scenarios simulated when the level of the inventory drops to 40%. The values closest to 1, are observed by the ratios: (1) 20/80, (2) 40/70, (3) 30/70, (4) 40/50, (5) 40/60, and (6) 50/50. A bigger difference is recorded by (7) 40/50, (8) 20/70, (9) 20/60, and (10) 60 /40. It cannot be clarified though, if the demand for natural gas requires an immediate supply of the product since the existing inventory cannot reassure the smooth service of the distribution network, or this response can be explained by technical issues of the distribution network.

If the natural gas importers opted for a different supply mix, dependent on the pipeline gas and LNG prices, the results of the second series of the simulations, where the active capacity of the LNG tanks is the variable of the model, could confirm this difference in importing policies. In the first case, with the 40/60 import mix, the range 65-75% presented the best results, a logical outcome given that the import ratio was selected based on the 70% inventory level hypothesis. It is presumable though, that operation of the supply chain with a stable ordering policy and low demand amplification is indicated when there Is an adequate storage capacity, which demonstrates the significance of the LNG in the supply chain. On the other hand, in the 20/80 case and the 40% tank fulfillment, the problem seems to be more linear. The best results are with the 20% and 30% of the total LNG capacity, while the other percentages present a serial inefficient satisfaction of the demand (BE ratio smaller than 1). Nonetheless, this linearity raises questions about the output of the neural network in this case, as it does not follow the patterns observed in the other charts. A possible explanation might be the shortage of data with these characteristics on different inventory levels that lead to the linearization of the problem by the network. This lack of data is an indication that the administrator of the network follows a specific import policy in these situations, probably having in mind the need for direct demand satisfaction. Another conclusion that derives from the results of the simulations is that in sudden increases of demand, the supply of large quantities of pipeline feed gas seems to mitigate the bullwhip effect, whereas, in situations of a more smoothened demand pattern, it must be combined with the supply of LNG to the network. Nevertheless, the aforementioned commentary on the results is an attempt to model the bullwhip effect for the LNG value chain and mitigate its effects and does not constitute a panacea for the phenomenon.

The performance of the model can be deduced from figures 5.4.6 and 5.4.7. The results are sufficient for the modeling of the aforementioned problem and can create reliable output. The correlation coefficient in the regression of the model, as depicted in figure 5.4.8 is at a high value (reaches 0,84 with the ideal value being 1), reassuring the efficiency of the model to relate the input variables with the desired target and create a single output.

However, the absence of errors is impossible, especially in points of sudden alternation of demand, such as in years 2020-2023 as it can be seen from the plotting of the errors in figure 5.4.9. The deviation from the correct outputs even on these occasions according to the estimated errors is not at a numeric scale that can confuse the user of the network as one can observe in figure 5.4.10. It will show the tendency of the bullwhip effect ratio to reach a specific range of values. This fulfills the purpose of the study at this stage, as it enables the examination of the demand amplification. Generally, the realization of the artificial neural network includes numerous parameters and algorithms that impact the final result and the behavior of the system, so it demands multiple tests before concluding to the final network. It is definite though, that an even better outcome could have been achieved, thus requiring deepest technical knowledge relating to artificial intelligence techniques, far from the domain of a naval architect and marine engineer.

From the above, it is presumable that the LNG terminal plays a major role in the mitigation of the demand amplification in the natural gas supply chain since the differentiation of the loaded capacity changed the results decisively. In figure 5.3.1, with 70% of the terminal's capacity loaded (157500 Nm^3), the bullwhip effect ratio responded better than the 40% (90000 Nm3) case of figure 5.3.2 both for the years 2020-2023 characterized by acute changes in demand, and for 2024-2029 with the smooth demand alternations. It is a common observation though, that the bullwhip effect ratio was not very close to the ideal value in all scenarios, especially for the first years, which shows the weaknesses of the existing network. Therefore, to satisfy the increased demand of the following years and to respond efficiently to external disruptions, a solution based on the results of the model would be to expedite the installation of new LNG terminals to the system in order to expand the total LNG storage capacity and the regasification rate. Today, the Sustained Maximum Send-out Rate of Revithoussa is 1350 m^3/h.

A seemingly viable proposal for the expansion of the existing infrastructure would be the construction of FSRUs, which present a plethora of advantages as analyzed in the thesis. Besides, given the geographic features of the country and the total capacity of the Greek- owned LNG carriers, the FSRUs constitute attractive projects. This was also proven by the entrepreneurial interest showed for the terminal in Alexandroupoli. Such projects, along with international agreements, like for the construction of the EastMed and the Tap Line, can make Greece the major energy hub of South-Eastern Europe.

6.2 Future work

Digital transformation is responsible for changing the entire structure of supply chains. It has led to profound development in supply chain efficiency, and resiliency to constant changes. Supply chains have over 50 times more data available in comparison to five years ago (The path to a thinking supply chain, 2018). Therefore, the need for efficient and dynamic data processing, as well as for innovative solutions is growing bigger than ever before. With the use of machine learning, previous data will be taken into consideration together with existing variables to make accurate predictions for future demand. The supply chain will better understand the risks and potential disruptions not only to itself but also to its suppliers and customers. In this way, supply chain executives will also have greater insight into the bottom-line impact of their decisions. Given the existing problems and challenges as described before, today's supply chains, including the natural gas value chain, must be characterized by the five "Cs" to engage the future potential and achieve their viability in tomorrow's competitive environment:

1. Connected
   The accessibility to endless data from different sources is the key to a thinking supply chain. The basic concept of AI algorithms is to learn from previous experience, so it is indispensable to have limitless access to information.
2. Collaborative
   The necessity of collaboration between the different supply chain echelons is thoroughly analyzed in this paper. With the evolution of blockchain technology, greater transparency can be achieved which will secure information sharing, mitigating the bullwhip effect.
3. Cyber-aware (not vulnerable to cyber threats)
   The more dependent on digitalization a system is, the more vulnerable it becomes against cyber threats. Consequently, reliable cybersecurity is of major importance.
4. Cognitively enabled
   Despite the irreplaceable role of humans in a supply chain, self-sufficiency can be achieved through further automation processes which will optimize the capabilities of the system.
5. Comprehensive
   The information generated fast and constantly by the automatic processes should be accessible and understandable to the users.

Therefore, except for the technical adjustments required for the transition of the supply chain to the new technological environment, the human factor should not be neglected. On the contrary, it has to be the center of this evolution to create the proper circumstances for the growth of efficient operational management. The LNG supply chain, considering its importance to the energy industry, and the access it has to the new possibilities offered by contemporary technologies, has to lead this development. In addition, a well-planned network administration policy is indispensable to achieve the best demand satisfaction with the smallest losses due to demand amplification. Besides, the disturbances of the supply chain in times of economic uncertainty should be avoided to ensure the undisrupted supply of energy to the industrial sector and the community, in a time where energy and electricity are more important than ever before.

The monitoring of the bullwhip effect using the aid of artificial intelligence is a step in the right direction, but it has to be applied more systematically. First of all, access to unlimited data from the part of the administrator is required to create a more complete neural network that will cover a bigger part of the operational map. Following this, a different structure of the network would be needed to operate autonomously and optimize the bullwhip effect by recommending the best parametrization for the efficient administration of the network and the minimization of the costs. Therefore, an elaborate feasibility study would add another dimension to the possibilities of the network. There are already programs in use that consult the supply chain executives for the correct decisions, but the demand amplification, as it was presumed by the study, is not prioritized. Therefore, an effective system using the reliability of artificial intelligence would ultimately lead to the full automation of the processes concerning the ordering policy of LNG at a national scale. Finally, another suggestion based on the groundwork of this thesis that is related to the field of study of a naval engineer would be the interconnection of the downstream processes of the supply chain with the shipping industry. If an automated system of imports were in the position to recommend the imported quantities of LNG, it could be also connected to the chartering department of maritime companies and search for ships that could facilitate the transportation of the desirable cargo, minimizing time delays, which is also an important factor of the bullwhip effect. Objections concerning the security of the process, taking into consideration the amount of paperwork for the agreement of the transportation of such a valuable cargo could be overcome with the development of blockchain technology. However, today's experience from automated systems in the chartering area has shown that the human factor of the mediator cannot be bypassed, so such a system would have to be operated with the collaboration of the charterers and the brokers. It must be underlined though, that the above are purely suggestions and thoughts on future work and have not been further researched as part of the thesis.

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