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CONCEPTUAL FRAMEWORK FOR MATERIAL AND INFORMATION FLOW OPTIMISATION IN NATURAL GAS SUPPLY CHAIN

Preliminary communication
UDK: 658.7:622.324.5
JEL classification: Q41, D3, L95
DOI: 10.17818/DIEM/2021/1.7
Accepted for publishing: July 8, 2021

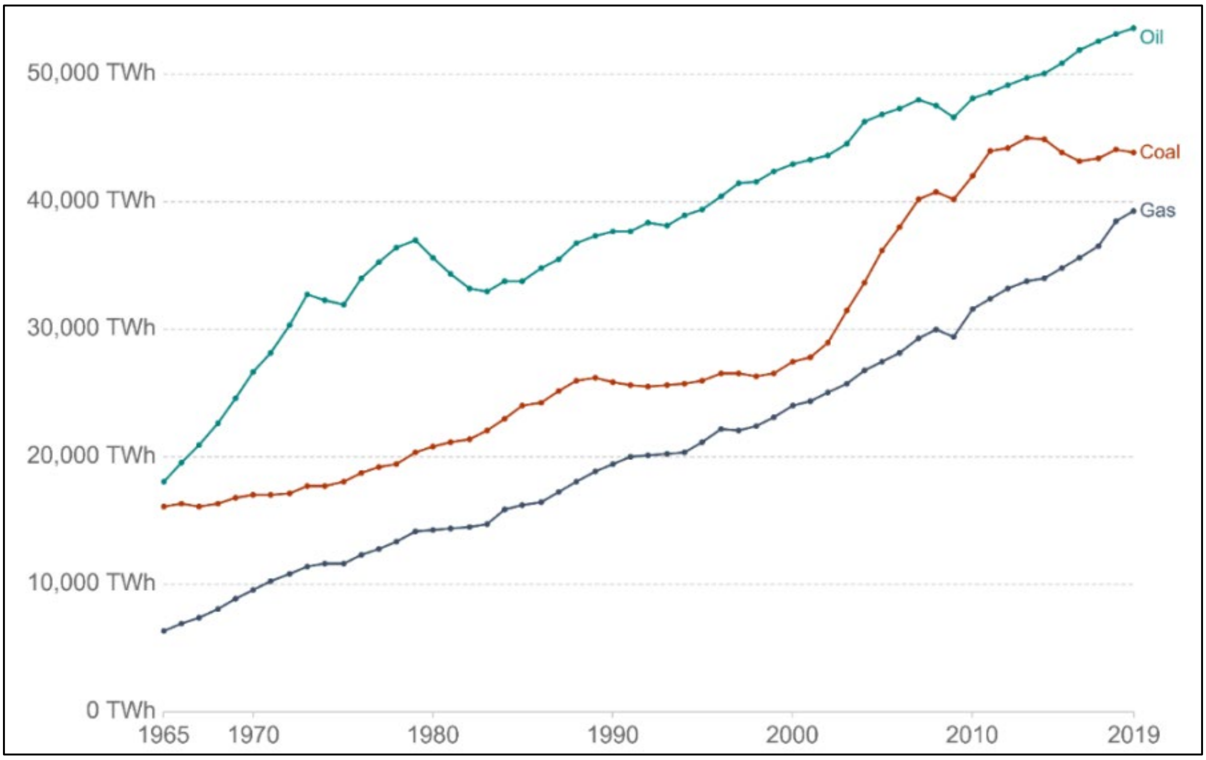
Abstract

Natural gas is third most used fossil fuel and energy resource in the world, with significant increase in its consumption over last 20 years. As a consequence, research in optimisation of its supply chain processes are becoming increasingly significant. This paper aims to develop conceptual framework for material and information flow optimisation in natural gas supply chain and suggests its future use. Based on previous researches on mapping natural gas supply chain, bullwhip effect in natural gas supply chain and simulation models in natural gas supply chain, paper proposes new conceptual framework for material and information flow optimisation in natural gas supply chain. Results of implementation of this framework in natural gas supply chain of Republic of Croatia are presented with all suggestions for improvement explained.

Keywords: natural gas supply chain, simulation model, bullwhip effect

1. INTRODUCTION

Natural gas is third most used fossil fuel and energy resource (not renewable resource) in the world, with significant increase in its consumption over last 20 years. According to *British Petrol Statistical Review of Global Energy (Petroleum, 2020),* 39292 TWh of gas was consumed in the World in 2019, while oil (53.690 TWh) and Coal (43.849 TWh) still prevail (Figure 1). But it is important that natural gas has 2% increase in consumption in 2019 when compared to 2018, with share in primary energy of 24.2%. At the same time frame coal was decreasing for 0.6% with share of 27%. Oil is still growing with 0.9% (but less then natural gas) and has highest share in primary energy fuels of 33.1 %. Obviously, natural gas is fastest growing component of world primary energy consumption (Demirbas, 2006). Other important energy sources and their share in primary energy are renewables (5.0 %), hydro (6.4%) and nuclear (4.3%). Another crucial benefit of natural gas is a fact that it is a most environmental friendly fossil fuel (it emits less quantities of harmful emissions in environment).



Source: BP Statistical Review of Global Energy, 2020.

Figure 1. World fossil fuel consumption (1965-2019)

Natural gas is consumed worldwide but its origins (production areas) are limited and therefore natural gas has seriously complex and long supply chains. Just transmission and distribution of natural gas to final consumers account for more than 30 percent of natural gas price (Hamedi et al, 2009). Huge distances, various supply chain members, different technological, logistical and economical processes, complex law and professional regulations in different countries on the way to final consumer contribute to complexity and potential risks in natural gas supply chains (Dujak, 2017). Growing demand for natural gas in future will be determined by global economy growth as well as with rising consumption that comes with rising living standards, and with a fact that natural gas is good bridge to prevailing or (hopefully) complete use of only renewable resources in the future (Dujak et al., 2019). Significant development and raise of importance of natural gas supply chain as crucial energy resource in future requires additional scientific studies in the field of natural gas supply chain optimisation.

Main goal of this paper is to develop and present conceptual framework for material and information flow optimisation in natural gas supply chain. The framework was developed during scientific project Methodological Framework for Efficient Energy Management by Intelligent Data Analytics (MERIDA) from 2017 to 2020, as a result of whole series of natural gas supply chain researches.

This paper raises two main research question:

RQ1: What is optimal procedure for analysis and improvements of material and information flows in natural gas supply chain?

RQ2: What are main suggestions for improving natural gas supply chain flows?

The Framework suggests optimisation of material and information flow in natural gas supply chain. As prerequisite for all actions, adequate mapping of natural gas supply chain is essential. Afterwards material flows optimisation is done based on developed simulation model while information flow is considered through analysis of potential bullwhip effects in natural gas supply chain.

2. SUPPLY CHAIN MAPPING FOR NATURAL GAS SUPPLY CHAIN

Supply chain mapping increases understanding of supply chain in many aspects (member's relations, geographical positions, process analytics) but also enables opportunities for improvement and process integration (Gardner, 2003). Two essential elements that every supply chain map has to indicate are supply chain entity (member) and supply chain flow. But supply chain maps could also describe different features of entities, supply echelons, flow directions and flow characteristics, and characteristics of other activities in this supply chain or only in its parts (relationships between two or more entities). Dujak (2017) states different classifications and types of supply chain maps, but according to Lambert et al. (2014) relationship–based maps and activity-based maps are main groups. Relationships-based maps are starting point for identifying the key members of the supply chain and are used for the allocation of resources within the network organization. They are usually drawn from the perspective of a company that is in focus (focal company), and usually map is done for the needs of this company. On the other hand, activity-based maps are used for more detailed analysis of processes that occur within a single economic entity, or among the business supply chain and are mostly occurring as a part of material, information or money flow, and there are three main types of activity-based maps for supply chain: time-based process maps, pipeline inventory process maps and extended value stream maps (Lambert et al, 2014). Special group of supply chain maps using Value Stream Mapping approach has been used in natural gas supply chain studies. Analysis by Dujak et al. (2019a) of selected research papers has shown variety of possible applications of VSM in natural gas industry and supply chain activities.

Also, supply chain mapping can be used as a tool for predicting and in advance avoiding of supply chain disturbances that can cause different material, information or finance flow disruptions (Barosso et al, 2011, Carvalho et al., 2012, Norrman & Jansson, 2004, Handfield & McCormack, 2007, Sheffi & Rice, 2005, Nishat Faisal et al., 2006).

When it comes to use of supply chain mapping in scientific papers regarding natural gas supply chain researches, study by Dujak (2017) aimed *to provide guidelines for effective use of mapping method in natural gas supply chain researches.* Methodology of this research is based on search of Web of Science Core Collection database, were 50 most relevant papers were extracted where in more than two thirds of selected and analyzed papers authors decided to use natural gas supply chain maps to ensure clearer and understandable situation, relations or process flow in natural gas supply chain. Results indicate that supply chain maps are essential tool for natural gas supply chain mapping where researcher mostly chooses relationship based maps (in 83% of papers) of evenly whole or part of supply chain, most often with five supply chain tiers, with no explicit spatial aspect, as well as no focal point and no cycle view.

3. BULLWHIP EFFECT IN NATURAL GAS SUPPLY CHAIN

The bullwhip effect is well known phenomena in supply chains defined as *the amplification of order volatility along the supply chain* (Wang & Disney, 2016). Typically, it is resulting in unneeded increasing in upstream inventory levels that consequently results in other problems for supply chain members (Dujak, et al., 2019b). Pilevari et al (2016) highlights, bullwhip generates fluctuation in three aspects in supply chain - information, physical and financial. According to Azhar (2011), bullwhip effect could be observed on: one company level in different industries, whole industry (or more companies from one industry) or in multiple industries. The bullwhip effects measuring could be done according to different approaches (Parra-Pena et al., 2012; Fransoo & Wouters, 2000; Fu et al., 2015; Chen & Lee, 2012; Centeno & Perez, 2008; Cannella et al., 2013), but most common metric is called *bullwhip effect ratio* (BEratio). According to Chen & Lee (2012), BEratio can be calculated in two ways:

- as ratio of variance of orders and variance of demand, or
- as ratio of variance of production and variance of demand.

In first case BEratio depicts distortion of information flow (by comparing variance of orders with variance of demand), while in second case BEratio represents distortion of material flow (by comparing variance of production and variance of demand). In all options there is consensus that bullwhip effect exists if BEratio value is larger than 1.

Bullwhip effect research in natural gas industry are extremely sporadic and are conducted jointly with oil industry (Chima, 2007; Miron & Zeldes, 1988; Cachon et al., 2007; Azhar, 2013). Binlootah & Sundarakani (2012) elaborate using of Vendor Managed Inventory as a tool for mitigating bullwhip effect in oil and gas industry. There is even less or no studies on lower downstream natural gas supply chain level, and this is area where Dujak et al. (2019b) filled the gap. Tomasgard et al. (2007) gave a review of optimization models for the natural gas value chain. Sherhart (2013) studied bullwhip in British Petroleum (uses Theory of Constraints to mitigate the bullwhip effect). There are only few studies of bullwhip effect on multiple levels of natural gas supply chain (Azhar, 2013; Jacoby, 2012). Azhar (2013) have found bullwhip effect in most of studied companies but not totally consistent increase in demand variability upstream the supply chain. Author also concluded that smaller companies had larger bullwhip effect, while larger integrated companies exhibited a lower bullwhip effect.

Recent studies in the oil and gas equipment industry have shown existence of bullwhip effect in upper parts of oil and gas supply chain (Jacoby, 2012). As a result of this study, Jacoby (2012) points out on for types of economic inefficiency: paying higher prices, having excess inventory during "the boom", making excessive capacity investments near the peak with low or negative return on investment on it, and loosing orders because of inability to fulfil them (inadequate capacity and long lead time in time of increased orders – "peak").

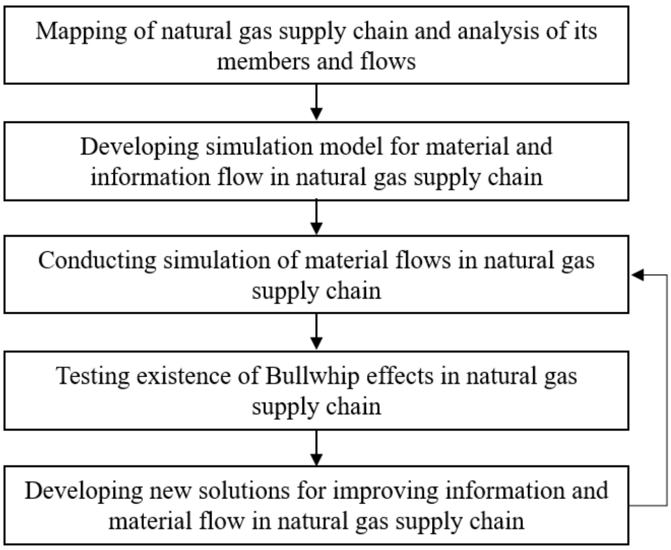
4. SIMULATION MODEL IN NATURAL GAS SUPPLY CHAIN

The researches, in which various simulation models of the natural gas supply chain (and fossil fuels in general) were used, are very scarce. Most simulation models show only one part of the supply chain. For example, they focus just on transmission or distribution system. Models of transmission system can be found in several researches. Some authors developed such simulation models with an accent on the compressor stations (Wu et al., 2000; Chebouba et al., 2009; Woldeyohannes and Majid, 2011). Matko et al. (2000) performed a simulation of three different models of the natural gas transmission system in order to show deviations of those models from a real system. The model of the gas pipeline system was developed by Nimmanonda et al. (2004) as well. That model enables the user to choose the properties of natural gas, pipe diameter and compressor capacity and to create a natural gas pipeline system afterwards. The most comprehensive simulation model was developed by Romo et al. (2009), who created GassOpt, a program solution for decision-making during natural gas transmission. The basic function is the maximization of the gas flow to the market. The limitations include the system capacity, gas demand, gas flow, pressure limitations in the gas pipelines etc. Eparu et al. (2013) created a simulation of the natural gas transmission system in Romania. Their simulation model included pipelines, valves, regulators, compressor stations, gas sources, and consumers. They concluded that the household consumption (hourly, daily and yearly) and the fluctuations in the industrial consumer supplying influence gas flow dynamics the most. Two papers dealt with modelling of the LNG supply chain (Stchedroff and Cheng, 2003) and the simulation of building the LNG terminal (Dundović et al., 2009). Villada and Olaya (2013) created a computer simulation model based on a real gas system in Columbia. They tested for different scenarios and compared the influence of greater contract flexibility and import and storage capacities to the safety of gas supply. Even though there are various different alternatives for the increase in security of supply, the authors focused on the transmission system because they found that adequate regulation and development of this system may contribute to an increase in security of gas supply. The computer simulation method has been used to discover gas leakages in the pipelines as well (e.g. Fukushima et al., 2000). In some papers a combination of discrete and continuous simulations was used. For instance, Kbah et al. (2016), by using such combination, created a model of an oil and natural gas supply chain. After setting the model and its validation in order to confirm concurrence with a real oil and natural gas supply chain, the "what-if" scenarios were analysed. They tested the system behaviour after an increase in petrol and LPG production and attempted to find an optimal number of trucks for oil and LPG transport.

However, none of these papers deal with the whole or wider part of the natural gas supply chain nor include information flows such as natural gas nominations (orders) or consumption.

5. DEVELOPING FRAMEWORK FOR MATERIAL AND INFORMATION FLOW OPTIMISATION IN NATURAL GAS SUPPLY CHAIN

To enable and encourage more focused and successful research in the field of natural gas supply chain optimization, the authors propose a new framework for material and information flow optimisation in natural gas supply chain (Figure 2). The framework has been developed on the basis of long-term studies and research in the gas supply chain using a number of methodologies, of which only some have been mentioned previously.



Source: authors.

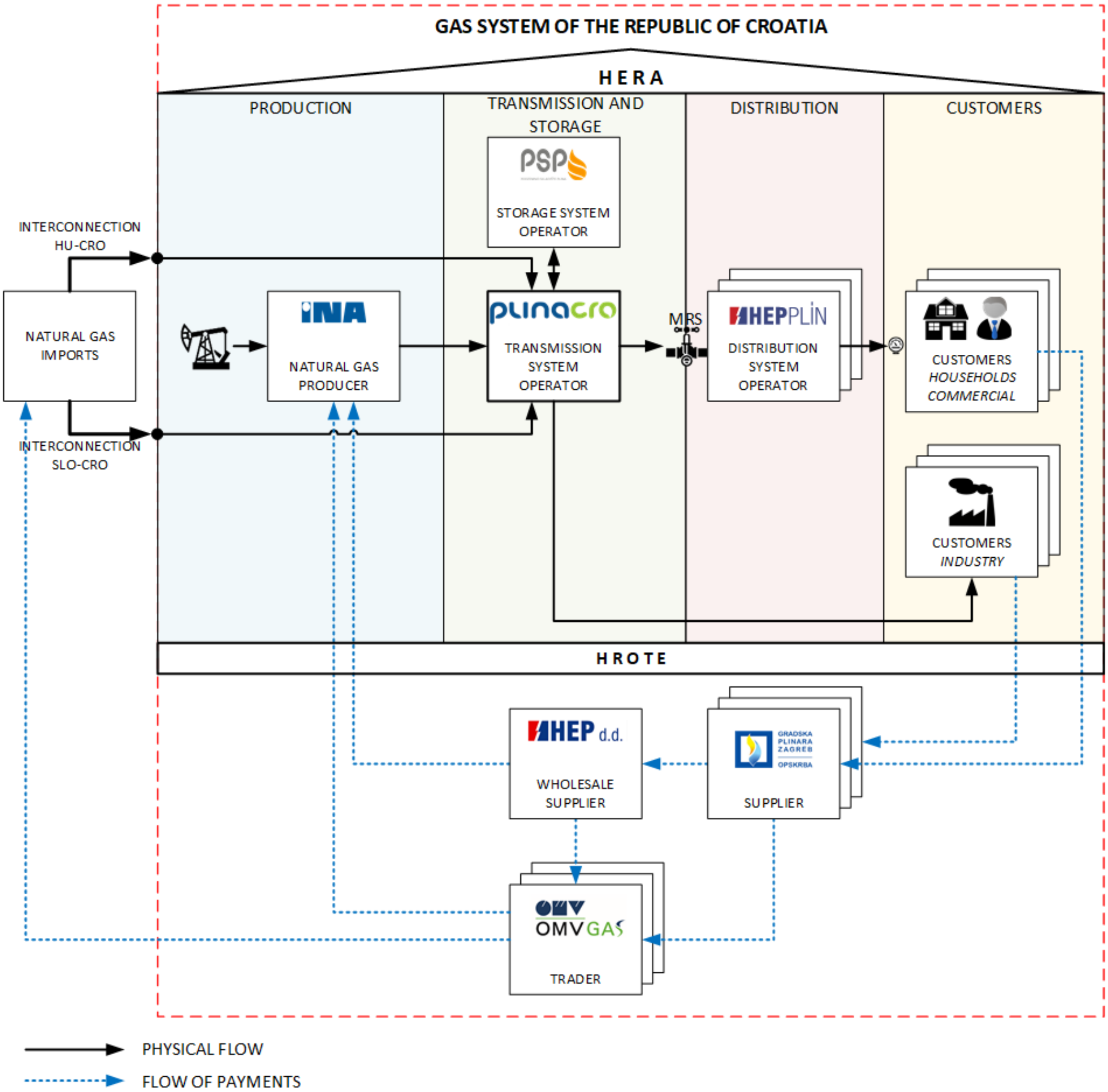
Figure 2 Conceptual framework for material and information flow optimisation in natural gas supply chain

Moreover, the framework was developed on the basis of numerous interviews with employees in the natural gas supply chain whose experience had a significant impact on certain phases of this framework (e.g. on the development of a simulation model of the natural gas supply chain).

In the continuation of the paper, the phases of the implementation of this framework will be presented on the example of the natural gas supply chain in the Republic of Croatia.

5.1. Mapping and analysis of members and flows in the natural gas supply chain in Croatia

The Figure 3 presents the natural gas supply chain in Croatia, its physical flow from production to the end-customers, as well as the main participants on the natural gas market.



Source: Šebalj et al., 2018.

Figure 3 Natural gas supply chain in Croatia

The natural gas supply chain in Croatia starts with the production and import. Natural gas can be injected into the transmission system from the domestic production system or it can be imported via two interconnections (on the Slovenian and Hungarian border). Then, natural gas flows through transmission system until it gets to the distribution system that brings gas to the customers. At the beginning of the distribution system a measuring-reduction station (MRS) is placed. That station measures the volume of the incoming gas and reduces the pressure to the distribution system limit (3 bar). On the other hand, a large, industrial customers are directly connected to the transmission system since they constantly consume a large amount of gas. There is also the underground storage for storing (during summer months) or withdrawing gas (during winter months).

The bottom part of the Figure 3 shows the flow of payments. Every customer in the gas market (household, commercial or industry customer) has to sign a contract with the supplier who supplies gas on his behalf. In Croatian gas market, there are two conditions of supply – under regulated conditions (for households) or under market conditions (for commercial or industrial customers). In the case of gas supply under the regulated conditions, the supplier must purchase the gas from the wholesaler who supplies gas directly from the domestic producer or from the import. In the case of gas supply under the market conditions, the supplier purchases the gas directly on the market.

5.2. Developing simulation model of natural gas supply chain in Croatia

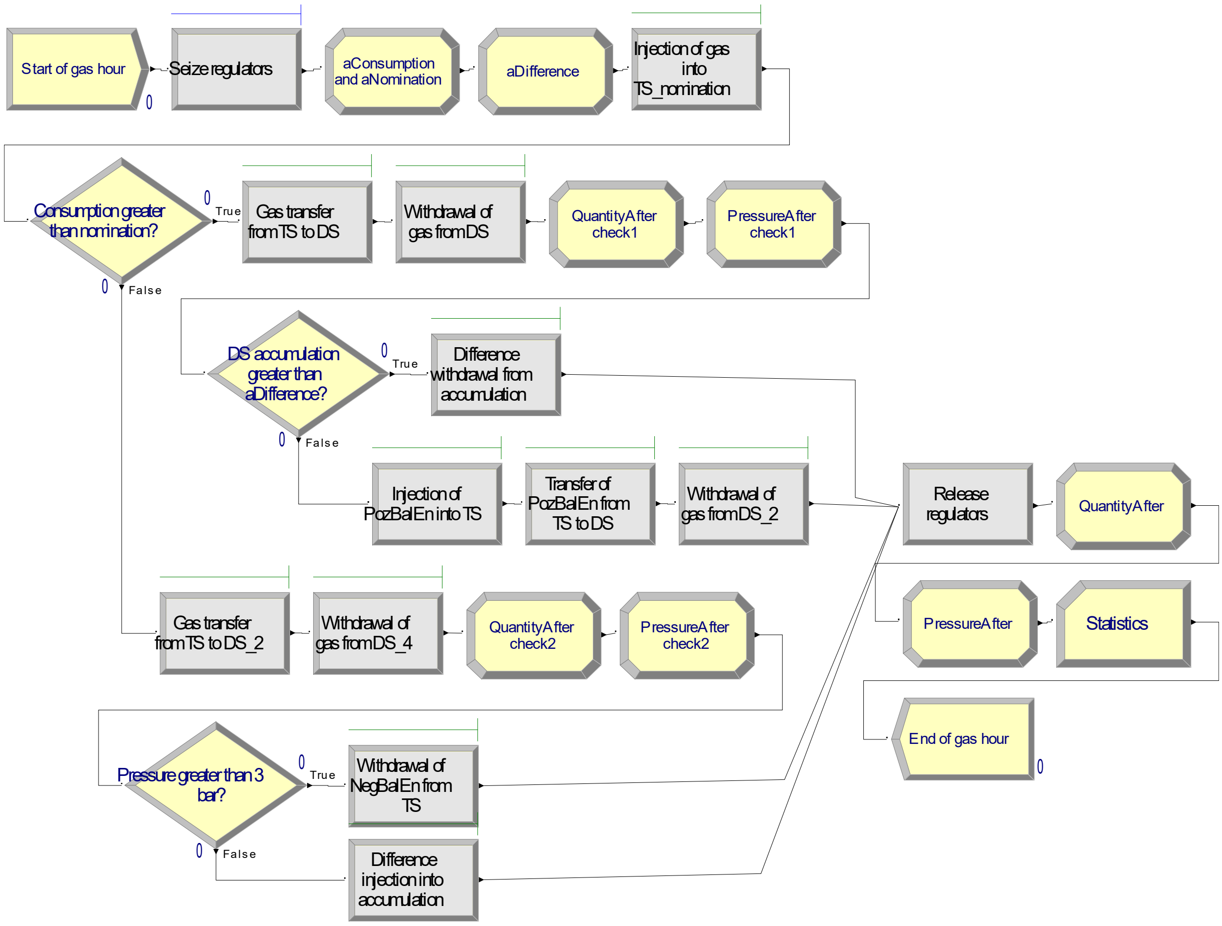
The main reason for developing a simulation model is to see if there is possibility to optimize the current supply chain. The challenge of the research was to develop simulation model that shows the behaviour of the real natural gas system in order to conduct simulation experiments. The actual natural gas supply in the Republic of Croatia is based on the balancing principle and the balance groups model. The way of organizing of the gas market is governed by the Rules of the gas market organization (Official gazette 50/18) adopted by Croatian Energy Market Operator (HROTE). The Rules define the balance group as a "interest group of gas market participants, organized on a commercial basis, primarily for the purpose of balancing and optimizing balancing costs, for which the balance group manager is responsible". It means that members of the balance group can be suppliers and/or traders and one of them must be a balance group manager. His task is to submit requests on behalf of balance group members to the transmission system operator for reservation of capacities, i.e. gas quantities for the following day. He needs to ensure that the total nominated (ordered) amount of gas injected into the transmission system is withdrawn by the distributor. Otherwise, the rebalancing of the transmission system will happen (by activating the positive or negative balancing energy) and the balance group members must be penalized for their wrong order predictions. Every injection of gas into the transmission system in order to balance it out is called positive balancing energy, while every withdrawal of gas from the system is called negative balancing energy.

As can be assumed, it is difficult to precisely estimate the amount of gas needed for the following day and because of that a disbalance of the transmission system emerges. The reason can be a surplus of the nominated amount which was not withdrawn or a deficit of the nominated amount since it was withdrawn more than it was ordered. As it was already mentioned, the balance group members are penalized since they are the ones who caused this disbalance and the penalties depend on how large are the deviations. For example, Šebalj et al. (2018) showed that, according to the data given by the supplier/distributer of the natural gas, hourly level deviations between nominations and real consumption varied from 10% up to 41% in January.

Due to the dynamic functioning of the natural gas system, there can be a limited possibility of adaptation that could be used for mitigation of prediction errors. That can be achieved by distribution system accumulation and this is exactly what the simulation model is trying to test. Since the owners of distribution systems are responsible for the development and maintenance of the distribution network, which is currently under maximum capacity, they could consider using the reserves in regard to the acceptance of errors in the over-nominated gas amount. This could be interesting to the vertically integrated energy companies which are distributors and suppliers on the market at the same time. In that way, the over-nominated gas amount will be accumulated in their distribution system, there is no need for transmission system rebalancing and the suppliers (balance group members) will not be penalized.

Such a solution can be tested by conducting computer simulation experiments. The system on which the simulation will be done relates to the transmission and distribution system. It will be shown as a gas pipeline into which gas enters into the transmission system (from the production, import or gas storage), flows through it, and then exits the distribution system towards the consumers. It is important to determine the performance metrics of the model. In this case it will be the gas pressure which must not exceed 3 bar. If the system can normally function with an additional gas accumulation in the system itself without the gas pressure going below around 1.5 bar (which is minimum level) or above 3 bar of the allowed limits, it can be considered that the simulation experiment was successful.

After defining a problem and before the creation of the simulation model it is necessary to create a conceptual model which is a basis for functioning of the simulation experiment. The example of the conceptual model of the natural gas supply chain in Croatia can be found in Šebalj (2019a). In order to show the functioning of the real system the input data that shows the hourly consumption and nominations for the household sector was needed. By using these real data, simulation software (in this case Arena Simulation) simulates the values for hourly consumption and nominations and uses them in the model. The model consists of different modules (processes, attributes, decisions…) that are connected and represent the functioning of the real system. The final simulation model can be seen on Figure 4.



Source: Šebalj, 2019b.

Figure 4 Simulation model of the natural gas supply chain

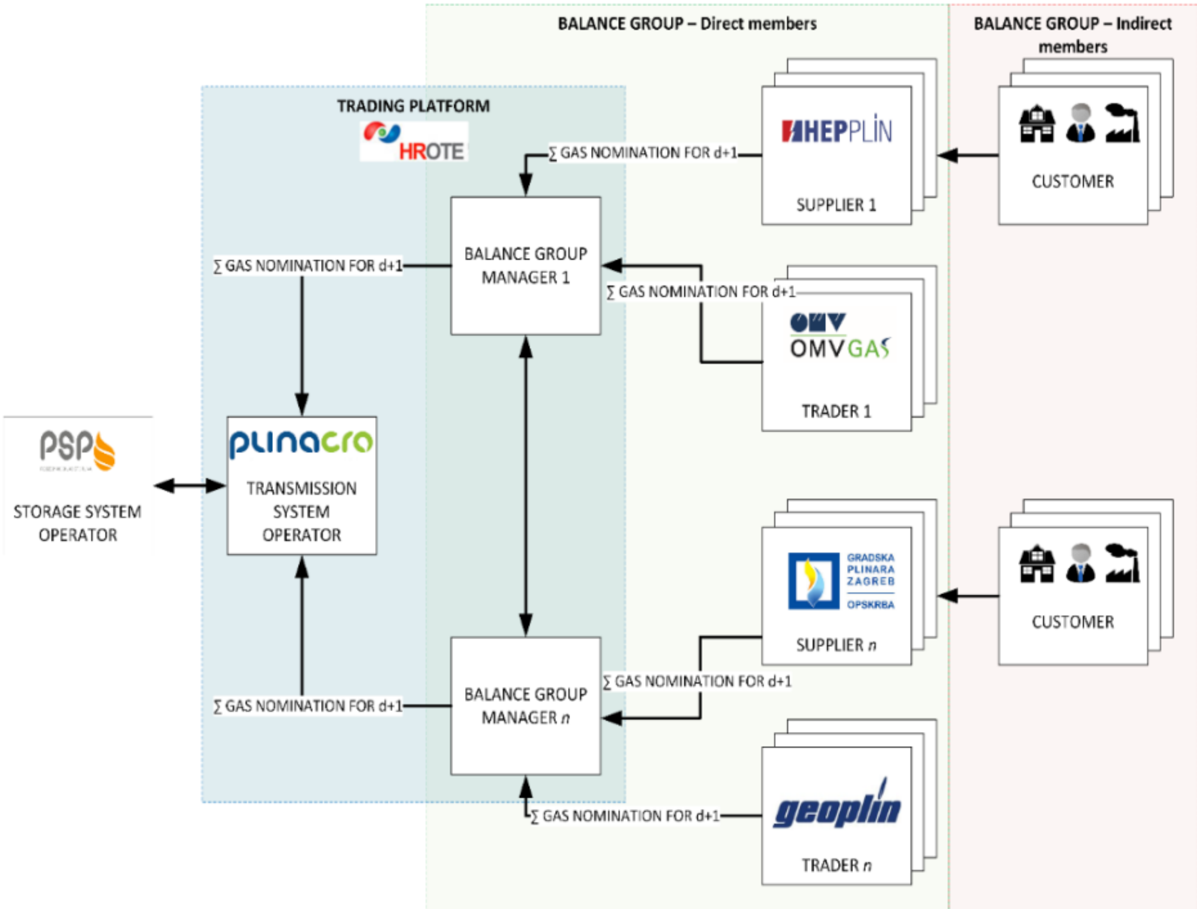
5.3. Conducting simulation model

The simulation model starts with every gas hour based on the input data. This means that a total of 8,754 entities (total number of gas hours in a year) will go through the simulation. After the simulation model is developed and simulation was run, the procedure of model verification and validation must be performed. Verification confirms that the model is flawless and operates as it should, and validation means that the model faithfully represents the behaviour of a real system. If both verification and validation are satisfying, one can proceed with running the model and conducting experiments. After the first run, a comparison between the total simulated nomination and consumption and the total real nomination and consumption for each month was performed. We found satisfactory if the difference is under 10%. It means that model simulates the values that are close to the real ones. However, the first run showed that it was not possible to simulate the values for summer months. Within the Arena Simulation software there is also the Input Analyzer tool which serves to analyse the input variables. All the 8,754 entries were analysed using this tool but for the months of May, June, July, August and September, Input Analyzer did not provide satisfactory results since the distributions of hourly values of nomination and consumption being too low in those months. Those are months when gas is not used for heating households and its consumption is significantly reduced in relation to the other months. Therefore, the simulation experiment was not conducted for the aforementioned 5 months.

For the stability of the model and getting the most accurate possible final results, the simulation experiment should be performed in several of replications (for example 50 replications). In order to analyse the results of the simulation experiment it was necessary to create a simulation of the existing system (so-called As-Is model). By doing so, the comparisons can be made between those two models in terms of total positive and negative balancing energy needed for rebalance of the transmission system. Based on that it can be seen do the changes introduced in the simulation model affect on the reduction of the penalties costs and is the simulation model successful.

5.4. Testing of existence of bullwhip effect in natural gas supply chain in Croatia

Material flows in natural gas supply chain are planned and managed based on information flow. According to Mesarić (2020), sources of the inefficiency of operations on the natural gas trading platform are purchase and sale transactions due to deviation from the nominated quantities and balancing energy required for the normal functioning of the transmission system. To test existence of bullwhip effect in natural gas supply chain study by Dujak et al. (2019b) was conducted in lower (downstream) parts of Croatian natural gas supply chain. As members of Croatian supply chain were explained in Figure 3 (material flow), next prerequisite for calculating bullwhip effect was to understand information flow in supply chain. Map on Figure 5 presents map of order flow and/or nominations (order announcements) in Croatian natural gas supply chain.



Source: Šebalj, et al., 2018.

Figure 5 Order flow of natural gas supply chain

The specificity of natural gas supply chain (both in Croatia and in most of other countries in the world) is that final consumer demand (original demand) is always entirely fulfilled and therefore equal to actual consumption. For calculating bullwhip effect purposes authors used a formula that indicates distortion of information flow as a ratio of variance of orders from supplier "X" to balance group manager (regularly daily send), and variance of demand (actual natural gas consumption from customers). This approach was chosen due to data availability. All data are from January as it is traditionally a month with highest natural gas consumption in Croatia. While differences between nominations and consumption in January sometimes reach even 22% BEratio value was only 0,25319, indicating that on monthly level in January, there is no bullwhip effect at supplier "X". Furthermore, based on monthly orders and demand data, a BEratio for the whole year 2017 was calculated with value of 0,937505. Research has concluded that there is no bullwhip effect at supplier "X" at yearly level, it can be noticed that BEratio value is increasing on longer periods of analysis. Authors argue that reason of such low level of BEratio is really short lead time in natural gas supply chain which is enabled with pipeline system of gas delivery, as well as rare changes of consumer prices for natural gas in Croatia (Dujak et al., 2019b).

5.5. Developing new solutions for improving information and material flow in natural gas supply chain

After the simulation experiment is finished, the new models and analysis, based on the finished experiment, could be developed. For example, it can be tested how can balancing energy (positive or negative) be additionally reduced if the pipeline pressure increases for just 1 bar. If the final (the chosen) simulation experiment shows that it is possible to use distribution system as an accumulation of additional amount in order to compensate for the errors in nominations, the next step should be finding the way for implementation of this solution. In this case, it could be some special electromotor valve, which would be set at the entry of the distribution system and would control the accumulation in it.

Recommendations for decreasing differences between orders and demand, and for avoiding possible development of bullwhip effect are (Dujak et al., 2019b; Šebalj et al., 2019):

- Organisations should use more information sharing in supply chain with aim of making more accurate forecast and orders (nominations) for gas.
- In future, organisations on different levels of natural gas supply chain should make one joint demand forecast, based on original demand and larger number of other variables collected from more supply chain members. This should be easily feasible especially in supply chain from this research in which in some cases even three levels of natural gas supply chain are vertically integrated by ownership.

Organisations should use different and forecasting methods with higher accuracy like neural networks, ANFIS, genetic algorithms, grey model or some other mathematical and statistical models.

6. DISCCUSION

Natural gas supply chain is complex supply chain with huge volumes flowing through it. Therefore, benefits of avoiding consequences of even smallest bullwhip effect could play significant role in natural gas supply chain member's process optimisation. After literature review and conducted studies by author, conceptual framework for material and information flow optimisation in natural gas supply chain was build. Additionally, the framework was tested in Croatian supply chain which resulted in proposition for significant material and information flow improvements. Author believe that this Framework is suitable for implementation in many other natural gas supply chains, especially for those in countries of Central and Eastern Europe which are most similar to Croatia and their supply chain condition.

Acknowledgement

This work has been fully supported by Croatian Science Foundation under Grant No. IP-2016-06-8350 "Methodological Framework for Efficient Energy Management by Intelligent Data Analytics" (MERIDA).

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