RESILIENT SUPPLY CHAINS – ROBUSTNESS AND DYNAMICS IN GLOBAL SUPPLY CHAINS

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Abstract

The emergence of global pandemics and increasing geopolitical instability in the short term – and the advent of the hydrogen and clean energy economy in the longer term– uncovered the need for resilient supply chains to address complex dynamics caused by regional and global disruptions. This work presents a framework for supply chain resilience and discusses the main challenges and opportunities that arise in academia and industry. We predominantly focus on industrial gas supply chains, directly impacted by COVID-19, geopolitical instability and the increasing availability of renewable energy sources.

Keywords

Supply Chain, Resilience, Dynamics, Robustness, Uncertainty, Disruptions, Industrial Gases

Introduction

Dynamics and robustness in supply chains call for resilient supply chains, an area that has historically been underexplored by both academic and industrial communities. With the emergence of global pandemics and increasing geopolitical instability, it became evident that to have reliable products and services, there is the need for supply chains that guarantee efficiently and effectively the management of information and material flows. However, it is not enough to have efficient and effective supply chains, they also must be resilient such that will be able to deal with disruptions – unexpected events – such as the scenarios created by COVID-19 and recently by the Ukraine-Russia war.

As defined in Ribeiro and Barbosa-Póvoa (2018): "*A resilient supply chain should be able to prepare, respond and recover from disturbances and afterwards maintain a positive steady state operation at an acceptable cost and time*".

To this end, four fundamental components must be considered when dealing with resilient supply chains: adaptative framing; speed; performance level; and focus event (Figure 1):

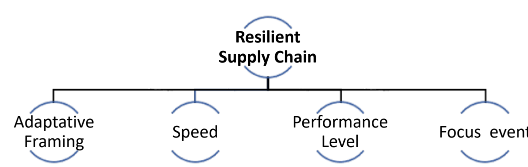

Figure 1 - Components of resilient supply chains (adapted from: Ribeiro and Barbosa-Póvoa, 2018)

Adaptative framing: traditionally resilience has been seen as just the ability to react to disruptions, a shortsighted view. The right adaptative framing needs to incorporate the planning, response, recovery and maintenance of the *status quo*. Thus, after responding, it is important to recover, reaching and maintaining a positive steady state, which may translate the supply chain operation as previous or even better.

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Speed: supply chains should guarantee fast response, but also fast recovery, thus the quick adaption of the entities exploring collaboration is critical.

Performance level: the assessment and quantification of the chain's resilience must be clear, such as costs and service levels as well as sustainability goals.

Focus event: this is not a simple perturbation, but abruptly interrupts operations, completely blocking value creation activities along the chain – a disruption. Disruptions are characterized by a totally unknown risk in terms of probability and volume of occurrence and are uncontrollable.

For example, in March 2011 when a tsunami hit Japan, Toyota had its production closed for almost two months. This fact caused a 30% decrease in the United States production, due to the scarcity of parts produced. As a result, Toyota invested in making its supply chain more resilient, namely by building a database with thousands of suppliers for the hundreds of thousands of parts used in its production lines. This allowed Toyota to quickly identify alternatives in a context of disruption and thus reduce global consequences. When in 2016 and 2019 Japan suffered new earthquakes, Toyota was able to control its production, having downtime of just two weeks, avoiding interruptions worldwide.

Companies have been previously reluctant to invest in resilience, believing that the benefit simply does not outweigh the cost. However, the current increase in the frequency and impact of disruptions has been changing this perception. Supply chains typically created to operate "just-in-time" now need to prepare for "just-in-case" eventualities. System disruptions, once seen as rare occurrences, are now becoming very probable.

In May 2021, a computer attack disrupted operations on a major pipeline along the east coast of the United States creating a shortage of product. One month earlier, a combination of climatic events culminated in a giant cargo ship stranded in the Suez Canal, disrupting a critical global trade route, and creating shortages of essential goods. These events came to show the fragility of supply chains, a fact that the COVID-19 pandemic has made even more evident with consequences around the world.

Top management considers supply chain resilience as a top priority for strategic investment, from 70% to 93% before and after the COVID-19 pandemic, respectively (Anstey et al., 2020). Hence, it becomes critical to forecast and plan – not just react to the risk. Visibility and agility to change sourcing, production and distribution activities across the supply chain must be therefore achieved.

Critical investment strategies must be in place: 1) redundancy; 2) ability to sense and respond; 3) diversification; 4) adaptability, as in Figure 2. Such strategies should be considered simultaneously.

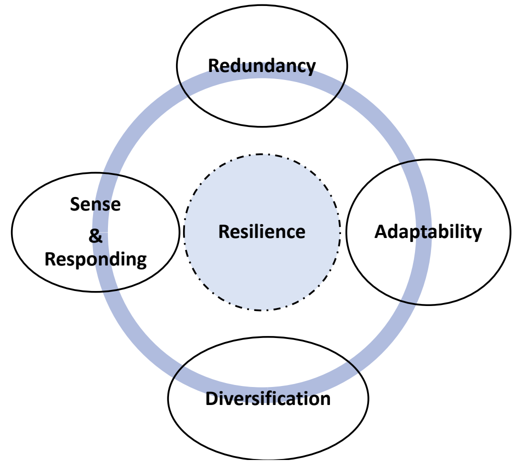

Figure 2 - Strategies for Building Resilience in Supply Chains

Investing in **redundancy** is the most direct way to increase resilience, whether in the form of underutilized production facilities or through higher safety inventory. The challenge is to find the right level of redundancy that guarantees resilience.

Being able to **sense** problems early enough and **responding** appropriately is nowadays accelerated due to the existing digital capabilities that guarantee easier access to information. However, it is important to properly manage the available information, which is diverse and vast.

Diversification, as redundancy, can be achieved in several ways, such as multi-sourcing or nearshoring. In 2011, major natural disasters in Japan and Thailand disrupted supply chains around the world and exposed companies' reliance on single sources of supply. In the automotive industry, nearly finished cars could not be shipped to customers due to a lack of components. The same is happening today as there is a high shortage of automotive microchips that rely on a small number of Asian suppliers.

The search for a multi-sourcing strategy has been characterizing many supply chains in the past two years; such supplier networks must be cost effective as well as able ability to respond to disruptions. Moreover, companies have been focusing on reducing geographic dependence in their global supply chains to shorten product cycle times and becoming more regional. Regional or local supply chains can, on the one hand, have higher costs, because they require more entities, leading to greater complexity in the ecosystem, but on the other hand, allow greater control over the inventory and supply times.

Finally, **adaptability** requires joint work by all elements of the supply chain; it entails a culture of sharing goals and benefits. Any entity of the chain must contribute to the functioning of others affected by disruptions. For instance, collaboration with strategic raw material suppliers and logistic partners is vital to ensure adaptability. In the case of smaller-scale supply chains, worldwide presence is possible through partnerships with global logistics operators (3PLs). These can be vital in diversifying production and distribution to different countries, thus ensuring resilience.

Such investment strategies help to respond to the global economy dynamics by allowing the design and planning of new supply chains as well as retrofitting existing ones, as is the case of the energy and food sectors.

From this perspective, it is important to understand "*How can the* ***Process System Engineering (PSE)*** *community contribute to address these challenges?"*

Academic Contributions and Challenges

The PSE community may contribute to such challenges in multiple forms by advancing the knowledge of supply chain dynamics, spanning from the strategic to the operational levels. Based on this knowledge is possible to build decision tools that will be able to inform the decision-makers in implement the proper strategies to deal with such dynamics. Such tools should be comprehensive but simultaneously flexible to deal within the diverse problems that process supply chain face.

Recent reviews on process supply chains present evidence of its importance within the PSE community (Barbosa-Póvoa and Pinto, 2020; Pistikopoulos et al., 2021). Different approaches and resulting models have been proposed to address the design (Yue and You, 2016; Duarte et al., 2022), planning (Lima et al., 2021; Neiro et al., 2022) as well as scheduling and distribution problems of supply chains (Dong et al., 2017). These problems have been addressed both deterministically and under uncertainty, typically with the objective of minimizing cost or maximizing profit (Barbosa-Póvoa, 2014).

It becomes important to incorporate the concept of resilience by exploring its main four components and strategies discussed in the previous section. The first challenge is to measure the performance of a resilient supply chain. Cardoso et al. (2015) considered a set of metrics to assess supply chain resilience, grouping them into network design and operational metrics. Its incorporation into design and planning models allow to identify which structures presented better resilient performance. Ribeiro et al. (2022) also addressed this challenge and developed a responsiveness metric for the design and planning of resilient supply chains, where profit and service level are accounted into a combined metric. Different focus events (i.e., disruptions) were studied and the usage of the proposed metric when designing and planning supply chains reveals to be representative, thus generating more resilient supply chains with higher adaptability and redundancy.

Additionally, the incorporation of risk, linked to the presence of uncertainty, has been also the focus of some studies. Cardoso et al. (2013) analyzed different risk measures considering the decision-maker's risk profile and concluded that the *CVAR* measure, apart from being a coherent measure, resulted as the more adequate measure for risk takers, while the variability index appears to be more aligned with risk averse decision-makers. The application of such metrics under uncertainty supports the decision of the investment profile in supply chains.

Moreover, the incorporation of resilience into supply chains cannot be achieved at the expense of environmental or social goals. One way is to incorporate sustainability targets into the models/tools, such as minimization of environmental impacts and maximization of social goals (Barbosa-Póvoa et al., 2018). This is a research area not yet too much explored.

Additionally, the incorporation of big data to support the resilience in supply chains requires further research. Data can support the development of efficient solution methods that may in shorter time provide the right solution for the complex supply chain models (Jiaze and Zavala, 2022). Data will also support the development of reliable and robust models that will increasingly allow to better predict how to respond to disruptions (Pistikopoulos et al., 2021).

The above-mentioned topics addressing robustness and dynamics in process supply chains are illustrated next, in the context of case-studies related to industrial gas supply chains. It is important to note that although the focus is on industrial gases, any system that deals with chemical, bio-based networks and involve a diverse and large set of entities, materials and information face resilience challenges and can be analyzed under this framework (Barbosa-Póvoa and Pinto, 2020).

Industrial Contributions and Challenges

Several case studies subject to disruptions that would benefit from a systematic supply chain resilience analysis are here covered. In the first, we focus on a liquid oxygen supply chain that recently was subjected to order of magnitude changes in product demand due to the COVID pandemic. Next, we briefly discuss the global helium supply chain that is subject to sourcing challenges driven mostly by geopolitical events. Thirdly, we focus on the hydrogen supply chain that will benefit from resiliency analysis in a clean energy future as well as in the transition period, both in isolation or as a component of a larger energy supply chain that serves residential, commercial and industrial customers. Lastly, we focus on a systematic method to improve resilience in industrial gas plants, namely Reliability, Availability & Maintainability (RAM) analysis that could be expanded to address supply chains.

Oxygen Supply Chains

Continuous and secure provision of oxygen to coronavirus patients is of utmost importance for their survival. To address this challenge, healthcare supply chains must be designed and operated to the prompt and continuous response to patient demand. Supply shortages in personal protection equipment (PPE) as well as ventilators have attracted the interest from decision makers and academics, while potentially devastating impacts from medical oxygen supply chain inadequacy remain largely unexplored (Finkenstadt and Handfield, 2021).

The production of medical oxygen happens in air separation plants (ASU) that separate atmospheric air into primarily nitrogen, oxygen and argon. The supply chain of medical oxygen comprises of three parts: (i) production of high-purity liquid medical oxygen in ASUs, (ii) distribution and storage from the plants to the hospitals through vendor managed inventory systems & (iii) on-site vaporization of liquid oxygen (LOX) into gaseous oxygen (GOX) through installed vaporizers (VIE) for direct use to the patients. To secure thus uninterrupted oxygen flow to COVID-19 patients, apart from agile production and distribution the efficient design of the on-site system at hospital level (LOX storage tanks and VIEs) must be simultaneously considered to avoid unnecessary capital expenditure and optimize replenishments.

However, this necessity for robust end-to-end operations is endangered by the following two aspects. On the supply side, medical gases companies' production capabilities were pushed to their limits, having to five- to tenfold their usual demand (Scott, 2020). On the hospitals' side existing infrastructure is deemed inadequate in many cases with the need of retrofitting/designing new on-site medical gas supply systems. Hence, the need for resilient medical oxygen supply chains becomes imperative.

Recently, Lee et al. (2022) addressed the production and inventory routing of a liquid oxygen supply chain comprising production facilities, distribution network, and distribution resources (Figure 3).

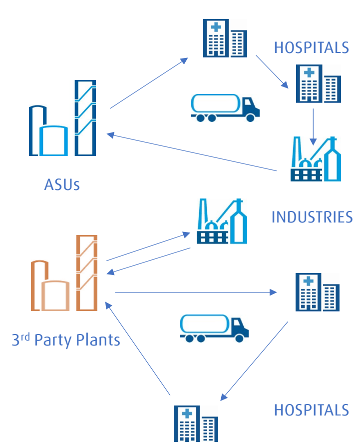

Figure 3 – Liquid Oxygen Network

The problem was solved with a two-level hybrid approach that combines mathematical programming to solve production and inventory levels, and customer allocation; followed by a guided local search metaheuristic to solve the low-level routing problems. The framework was tested in a real-world case study during the COVID-19 pandemic in the UK. In general, a sense and responding strategy as well as an adaptability strategy are clearly requisites in medical oxygen supply chains, in which health organizations and industrial gases companies collaborate in sharing demand forecasts.

Challenges and opportunities to improve resilience in healthcare operations for future waves of COVID and future pandemics involve the incorporation of uncertainty with respect to demand variations of medical oxygen, as well as the impact of production plant downtime and equipment failure in hospitals. Moreover, different pandemic trajectories and thus realizations of uncertain medical oxygen demand as well as the implication of inventory policies such as minimum required level of medical gases could be studied under a multiperiod supply chain modeling framework. A series of what-if analyses could inform decision makers on the trade-off between supply chain adequacy, cost-effectiveness, and policy interventions in the face of uncertainty.

Helium Supply Chains

The helium supply chain relies on a limited number of sources worldwide, concentrated in the US, Qatar and Algeria (Provornaya et al., 2022). Moreover, global demand has shifted from the United States to Asia-Pacific in the past decade.

Raw helium is extracted from natural gas (originally 0.1 to 0.5 % by volume), where it reaches 50-70 % and it is denoted crude helium. This crude mixture is further refined and liquefied. Specially designed intermodal or ISO containers are trucked and shipped to either customers or ports worldwide (Malinowski et al., 2018) and rely on 3PLs.

By 2040, global helium demand is expected to grow to 220 Mm^3 annually compared to 160 Mm^3 in 2018 (Provornaya et al., 2022). The largest known reserves of helium are in Russia and expected to start production in 2023 – these reserves are located in Siberia. Besides the expected logistics challenges of bringing helium to customers, the ongoing sanctions and geopolitical risks further impact the supply chain. Hence the need to develop resilient networks that involve storage strategies as well as long-term agreements with multiple logistics companies; in general, strategies exploring redundancy as well as adaptability are of upmost importance.

Hydrogen Supply Chains

Current hydrogen supply chains primarily operate with steam methane reformers (SMRs). Natural gas feeds the reformer, it is pre-treated and mixed with superheated steam. Inside the SMR tubes, a catalytic reaction occurs and produces hydrogen and carbon monoxide (syngas). The syngas is then purified to remove CO2 and H2O in a pressure swing adsorber (PSA). The carbon monoxide can be further removed in a carbon capture and storage (CCS) process (Zhang and Pinto, 2022). Production sites at concentrated locations characterize the current setup of existing hydrogen supply chains.

Other *green* technologies powered by renewable energy sources will become more prevalent, particularly electrolysis, and have the potential to cause permanent disruptions to existing hydrogen supply chains that are based on fossil resources. Nevertheless, green hydrogen production processes will have to be operated in a much more dynamic fashion due to the use of intermittent renewable energy sources. Moreover, there will be a shift toward distributed and modular hydrogen supply chains due to the distributed availability of renewables.

Besides its use as an industrial feedstock, hydrogen can be used as an energy vector (Grigoriev et al. 2020), for instance for grid balancing or energy storage. A key challenge will be to coordinate hydrogen, heating, and energy networks simultaneously. In this scenario, production of hydrogen will target heating and cooling for residential, commercial, and industrial sectors.

It is expected the industrial gas industry to lead hydrogen production, liquefaction, transportation, and storage. Resilience in this larger, clean energy, ecosystem will require collaboration among the multiple players, including utility and energy companies. Tominac et al. (2022) interpret supply chains as a market with independent stakeholders bid into a coordination system to obtain economic properties; this approach could be extended to add resilience metrics to the supply chain.

Finally, as hydrogen and electricity supply chains transition to renewable energy sources, one must address this multiscale design and operational problem with a very sensible treatment of uncertainty. The underlying multiperiod planning problem must account for endogenous uncertainties such as: (1) local demand impacted by design decisions, (2) demand-responsive tariffs that fit the fluctuating energy prices, (3) operational knowledge acquired from technology implementation, (4) new regulatory frameworks to manage production and distribution networks with high penetration of decentralized and intermittent renewable energy, among others (Zhang and Pinto, 2022).

These complex and integrated supply chains could largely benefit from systematic adaptability, diversification, and redundancy analyses. Furthermore, there must be a strong coordinated effort of sensing and responding among the organizations when required.

Reliability, Availability & Maintainability (RAM) Analysis

A major issue that industrial gases plants face is the potential for disruption in the deliveries of their products due to equipment breakdown. Current state of the art for increasing reliability of these plants or other chemical processes is to use discrete-event simulation tools to assess different design alternatives in terms of equipment redundancy, additional inventory, and preventive maintenance (Sharda and Bury, 2008).

Given the very large number of design alternatives, there is a clear need for systematic tools based on optimization for addressing these problems. Ye et al. (2019) addressed redundant equipment design and preventive maintenance, by proposing an MINLP model that represents the stochastic process of system failures and repairs as a continuous-time Markov chain, with the objective of maximizing profit. This approach was extended to incorporate storage design, which was solved with a custom two-phase algorithm that greatly reduces the required computational effort when applied to a four-stage air separation unit (Ye et al., 2020).

With each of the above strategies, it is possible to reduce plant downtime. When plants are not maintained at the proper frequency it is more likely equipment failure to occur; on the other hand, when maintenance work is too frequent, it interferes with plant operations and adds unnecessary costs. Similarly, the addition of redundant equipment and/or storage capacity increases plant availability at the expense of higher capital costs. For instance, in Figure 4 the addition of compressors or pumps on stand-by would allow almost uninterrupted operation; moreover, larger storage tanks are able to accommodate larger plant downtimes.

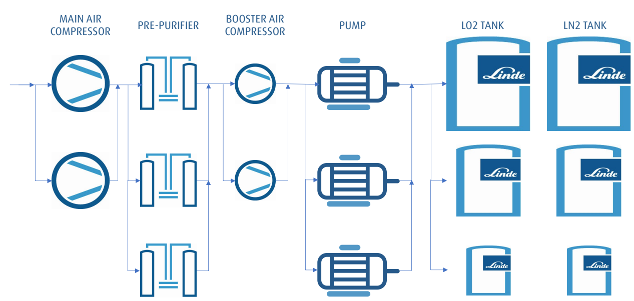

Figure 4 – Simplified Block diagram of an ASU

Besides its use in simulating and optimizing at plant level, RAM has the ability to address supply chain problems. Resilience can benefit from such methods, particularly in the design stage with a superstructure optimization model that contains decentralized plants, storage and distribution routes. Moreover, it would be interesting to focus on the operation of existing plants and carry out joint maintenance policy optimization and spare parts management for multiple sites in a region that have cooperative spare parts pooling. The main challenge resides on the solution of the underlying models, as the number of states can grow well beyond current computational capabilities.

Concluding Remarks

Addressing the dynamics and robustness of supply chains is a challenging problem. A suitable path to follow is to build resilience into such systems. In this paper, contributions from the academic and industrial communities were discussed. However, there are further innumerous opportunities to advance the PSE area with the main components of resilience. This calls for a close integration between academia and industry aiming to explore the relevant problems and the development of the corresponding solution methods.

Acknowledgments

Ana Barbosa-Póvoa acknowledges support from FCT project UIDB/00097/2020.

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