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Master in Business Administration

Postgraduate Dissertation

‘Transforming supply chain in the pharmaceutical sector for
resilience and efficiency: A COVID-19 pandemic analysis’

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Patras, Greece, September 2026

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‘Transforming supply chain in the pharmaceutical sector for
resilience and efficiency: A COVID-19 pandemic analysis’

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I dedicate this thesis to my family.

Abstract

During the COVID 19 pandemic the pharmaceutical sector faced structural weaknesses especially in the supply chain sector. The production was disrupted the transportation faced major obstacles and low availability of critical medicines and healthcare products worldwide was crucial for public health in general. Pharmaceutical systems that had previously focused heavily on cost efficiency, lean inventories, and globally centralized sourcing models faced severe operational instability once lockdowns, export restrictions, transportation interruptions, and sudden increases in healthcare demand emerged simultaneously across the globe. Thus, the importance of resilience, flexibility, and risk management within pharmaceutical supply networks, particularly in relation to medicine accessibility and public health protection during large-scale emergencies is already of major importance.

This thesis aims to give details on how pharmaceutical supply chains can be transformed to improve both resilience and operational efficiency in the post-pandemic environment, derived by literature and studies on this filed.. Information is given on key dimensions affecting pharmaceutical supply chain performance, including global distribution systems, shortages of active pharmaceutical ingredients and critical medicines, logistics and transportation challenges, inventory management practices, digital transformation, regulatory interventions, and collaborative crisis management strategies. The role of technological innovation, supplier diversification, regionalization of manufacturing, and adaptive inventory systems are also discussed.

The methodological approach of this thesis is based on secondary academic literature, institutional reports, and contemporary research studies related to pharmaceutical logistics and healthcare supply chain management during COVID-19. Through systematic evaluation of peer-reviewed publications and policy-oriented sources, the study identifies recurring operational vulnerabilities and examines the strategic responses implemented by pharmaceutical organizations and governments throughout the pandemic period. The analysis also explores how resilience-oriented practices can be integrated with efficiency objectives without creating unsustainable operational costs or excessive system redundancy.

The conclusions that are discussed in this thesis demonstrates that future pharmaceutical

supply chains must evolve toward more adaptive, digitally integrated, and regionally resilient operational models capable of responding effectively to global uncertainty and healthcare crises based on given and in detail discussed strategies.

Keywords

Pharmaceutical, logistics, resilience, COVID-19, supply chain

‘Μετασχηματισμός της εφοδιαστικής αλυσίδας στον φαρμακευτικό τομέα για
ανθεκτικότητα και αποτελεσματικότητα: Ανάλυση περιπτώσεων κατά τη
περίοδο της πανδημίας COVID- 19.’

Μαρία Χαροκόπου

Περίληψη

Κατά τη διάρκεια της πανδημίας COVID-19, ο φαρμακευτικός τομέας αντιμετώπισε διαρθρωτικές αδυναμίες, ειδικά στην εφοδιαστική αλυσίδα. Η παραγωγή διακόπηκε, οι μεταφορές αντιμετώπισαν σημαντικά εμπόδια και η χαμηλή διαθεσιμότητα κρίσιμων φαρμάκων και προϊόντων υγειονομικής περίθαλψης παγκοσμίως ήταν ζωτικής σημασίας για τη δημόσια υγεία γενικότερα. Τα φαρμακευτικά συστήματα που προηγουμένως είχαν επικεντρωθεί σε μεγάλο βαθμό στην οικονομική αποδοτικότητα, τα λιτά αποθέματα και τα παγκοσμίως κεντρικά μοντέλα προμήθειας αντιμετώπισαν σοβαρή λειτουργική αστάθεια όταν εμφανίστηκαν ταυτόχρονα σε όλο τον κόσμο τα lockdown, οι περιορισμοί στις εξαγωγές, οι διακοπές στις μεταφορές και οι αιφνίδιες αυξήσεις στη ζήτηση υγειονομικής περίθαλψης. Έτσι, η σημασία της ανθεκτικότητας, της ευελιξίας και της διαχείρισης κινδύνου στα δίκτυα εφοδιασμού φαρμακευτικών προϊόντων, ιδίως σε σχέση με την προσβασιμότητα των φαρμάκων και την προστασία της δημόσιας υγείας σε καταστάσεις έκτακτης ανάγκης μεγάλης κλίμακας, είναι ήδη μείζονος σημασίας.

Η παρούσα διατριβή στοχεύει να δώσει λεπτομέρειες σχετικά με το πώς οι αλυσίδες εφοδιασμού φαρμακευτικών προϊόντων μπορούν να μετασχηματιστούν για να βελτιώσουν τόσο την ανθεκτικότητα όσο και την επιχειρησιακή αποτελεσματικότητα στο μετα-πανδημικό περιβάλλον, όπως προκύπτει από τη βιβλιογραφία και τις μελέτες σε αυτόν τον τομέα. Παρέχονται πληροφορίες σχετικά με βασικές διαστάσεις που επηρεάζουν την απόδοση της φαρμακευτικής εφοδιαστικής αλυσίδας, συμπεριλαμβανομένων των παγκόσμιων συστημάτων διανομής, των ελλείψεων δραστικών φαρμακευτικών συστατικών και κρίσιμων φαρμάκων, των προκλήσεων στην εφοδιαστική και τη μεταφορά, των πρακτικών διαχείρισης αποθεμάτων, του ψηφιακού μετασχηματισμού, των ρυθμιστικών παρεμβάσεων και των συνεργατικών στρατηγικών διαχείρισης κρίσεων. Συζητείται επίσης ο ρόλος της τεχνολογικής καινοτομίας, η διαφοροποίηση των προμηθευτών, η περιφερειοποίηση της παραγωγής και τα προσαρμοστικά συστήματα αποθεμάτων. Η μεθοδολογική προσέγγιση αυτής της διατριβής βασίζεται σε δευτερογενή ακαδημαϊκή βιβλιογραφία, θεσμικές εκθέσεις και σύγχρονες ερευνητικές μελέτες που σχετίζονται με την

εφοδιαστική αλυσίδα φαρμακευτικών προϊόντων και τη διαχείριση της εφοδιαστικής αλυσίδας υγειονομικής περίθαλψης κατά τη διάρκεια της COVID-19. Μέσω συστηματικής αξιολόγησης δημοσιεύσεων από ομοτίμους και πηγών με προσανατολισμό στην πολιτική, η μελέτη εντοπίζει επαναλαμβανόμενες λειτουργικές ευπάθειες και εξετάζει τις στρατηγικές απαντήσεις που εφαρμόζονται από φαρμακευτικούς οργανισμούς και κυβερνήσεις καθ' όλη τη διάρκεια της πανδημίας. Η ανάλυση διερευνά επίσης πώς οι πρακτικές που είναι προσανατολισμένες στην ανθεκτικότητα μπορούν να ενσωματωθούν με στόχους αποδοτικότητας χωρίς να δημιουργήσουν μη βιώσιμο λειτουργικό κόστος ή υπερβολικό πλεονασμό συστημάτων.

Τα συμπεράσματα που συζητούνται σε αυτή τη διατριβή καταδεικνύουν ότι οι μελλοντικές αλυσίδες εφοδιασμού φαρμακευτικών προϊόντων πρέπει να εξελιχθούν προς πιο προσαρμοστικά, ψηφιακά ολοκληρωμένα και περιφερειακά ανθεκτικά λειτουργικά μοντέλα, ικανά να ανταποκρίνονται αποτελεσματικά στην παγκόσμια αβεβαιότητα και τις κρίσεις υγειονομικής περίθαλψης βάσει δεδομένων και λεπτομερώς συζητημένων στρατηγικών.

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Introduction

1.1 Research Aims and Objectives

This research objective is to investigate the potential of a strategic re-design of the pharmaceuticals supply chain in order to increase its resilience as well as its efficiency. The current pharmaceuticals supply chain is a global network with major weaknesses been more obvious during the COVID-19 pandemic. Most of these weaknesses can be linked to supplier concentration, lack of visibility in the supply chain and a lack of stock buffers for critical products. Research into disruption modeling has found that highly efficient supply chains lack flexibility and are therefore not able to deal with major disruptions.

For this purpose, the dissertation will investigate different strategies for the development of supply chains based on published sources. The strategies are built on four pillars: 1) the diversification of suppliers; 2) nearshoring and regionalization; 3) the strategic buffering of essential drugs; 4) the increased involvement of all relevant stakeholders. All of these measures have to be investigated in order to find out how they deal with any kind of disruptions and at the same time how they can be implemented while keeping within the rules and while maintaining the quality of the medicines. The research study will make use of the latest literature as well as of concrete cases of the COVID-19 pandemic.

A further key objective of this study is to analyze current technologies in the field of Industry 4.0 and their potential for a digitalization of the Pharmaceutical Supply Chain, such as blockchain, AI, IoT, digital Twins as well as Big Data/Analytics are discussed by means of their potential for both efficiency and resilience of the Supply Chain. An important point of view also is analyzed, whether current Technologies of the Industry 4.0 have the potential to improve the Forecasting, in particular with respect to accuracy as well as to a reduction of the Information Asymmetry and increased real time abilities for a better coordination worldwide.

The aim of this study is also to investigate existing ways of managing inventory and forecasting demand in order the companies to be prepared for a future crisis. COVID-19 pandemic exposed the limitations of the majority of the current approaches to forecasting as

well as the failure of the majority of the lean inventory management approaches currently used within the sector to manage high levels of uncertainty (Pathy & Rahimian, 2023). Considering this, an evaluation of the current approaches towards uncertainty and potential risks to the supply chain will be conducted as well as recommendations will also be made as in order to add value to the existing approaches.

Finally, risk management with cost efficiency in the pharmaceutical supply chain are topics that are discussed as the vast majority of strategies are focused on cost efficiency, which is crucial not to increase vulnerability of the sector to external or internal crisis. The study shall attempt to examine several different strategies, methods, and tools that can be used to integrate risk management into cost-optimization models of supply chains.

Another aspect of this sector that is explored is the role of regulatory flexibility and public-private collaboration as, production, distribution and commercialization of medicines are strictly regulated in many countries. For this reason, it is very important to emphasize that adaptive regulatory measures, effective governance structures and policy changes can support different strategies towards resilience.

The research will combine the best available theoretical models of supply chain resilience with the insights gained from in-depth case studies of companies in the pharmaceutical sector. as well as will give a review of the current state of digital supply chain, strategies for improving the accuracy of demand forecasts as well as of the management of inventory in pharmaceutical supply chains, balancing risk management and cost efficiency. The strategic framework developed within this research will provide a theoretical review with a set of guidelines on how to develop efficient as well as resilient supply chains that will continue to meet the needs of their customers in case of future disruptions.

1.2 Significance of the Study

The study aims to explore ways to develop and manage pharmaceutical supply chains in order to make them more resilient and efficient during and after the global health crisis caused by the COVID-19 pandemic. The study looks at the structural vulnerabilities in the production and distribution of medicines worldwide that the global health crisis has

uncovered. The results of this study will contribute to the field of supply chain management, particularly in terms of developing supply chains in the pharmaceutical sector that are more resilient in order to deal with future global health crises. Therefore, there is a need for robust models and strategies for managing and mitigating risks in this sector.

Pharmaceutical supply chains are distinct from supply chains of most other industries. Firstly, the products of the pharmaceutical industry are very important for health of humans and therefore are subject to a multitude of strict rules and regulations by health care authorities all around the world. For this reason, any disruption to the supply of medicines not only leads to financial losses for the respective company but above all also poses a risk to patients and the public health in general. For this reason, the consequences of a lack of essential medicines for patients and the public health during the COVID-19-pandemic have been emphasized by various researchers and scientists of many scientific fields.

Furthermore, a major contribution of this research study is the integrated analysis for the above objectives of improving the supply chain performance. Traditionally, supply chain performance is viewed as trade-offs between competitive objectives cost effectiveness. However, over-optimization of the supply chain design could expose a firm to greater risk of supply chain failure and this study aims to present ways for improving supply chain's resilience while achieving sustainable cost.

The study is also of particular relevance to global health security. Like other sectors of society, the pharmaceutical sector is part of the global health care systems of countries around the world. The logistics of the pharmaceutical sector are therefore a critical part of the health care system as a whole. The sites for the production of medicines and vaccines, as well as health care logistics providers, health authorities and healthcare distributors, are found all over the world, thus failures in any of these can have an impact on supplies of essential medicines and vaccines. While responsibility for global health security primarily lies with public institutions, there are many private actors in the pharmaceutical sector and global health care system, making even more essential the coordination of both actions in the long term.

A further feature of the study is its focus on the potential for digital transformation to improve the resilience of the Pharmaceutical Supply Chain. The study includes an examination of the

ways in which Industry 4.0 technologies are being used by organizations in all sectors of industry and specifically within the pharmaceuticals sector to improve a number of Supply Chain metrics. In particular includes an in-depth analysis of the use of a number of technologies including blockchain, IoT and predictive analytics and their application within vaccine logistics.

Risk management and strategic planning are also aspects that are investigated in this dissertation, as cost efficiency is maybe the most important goal of any company. For the pharmaceutical sector possible ways for creating resilient supply chains can be derived from literature on different types of diversification, on different types of inventories, on different types of flexibility of regulations as well as on types of governance. A framework could help pharmaceutical companies to analyze their own supply chain and to derive measures for increasing the resilience of their supply in a world with more and more geopolitical conflicts, a changing climate as well as the risk of future pandemics.

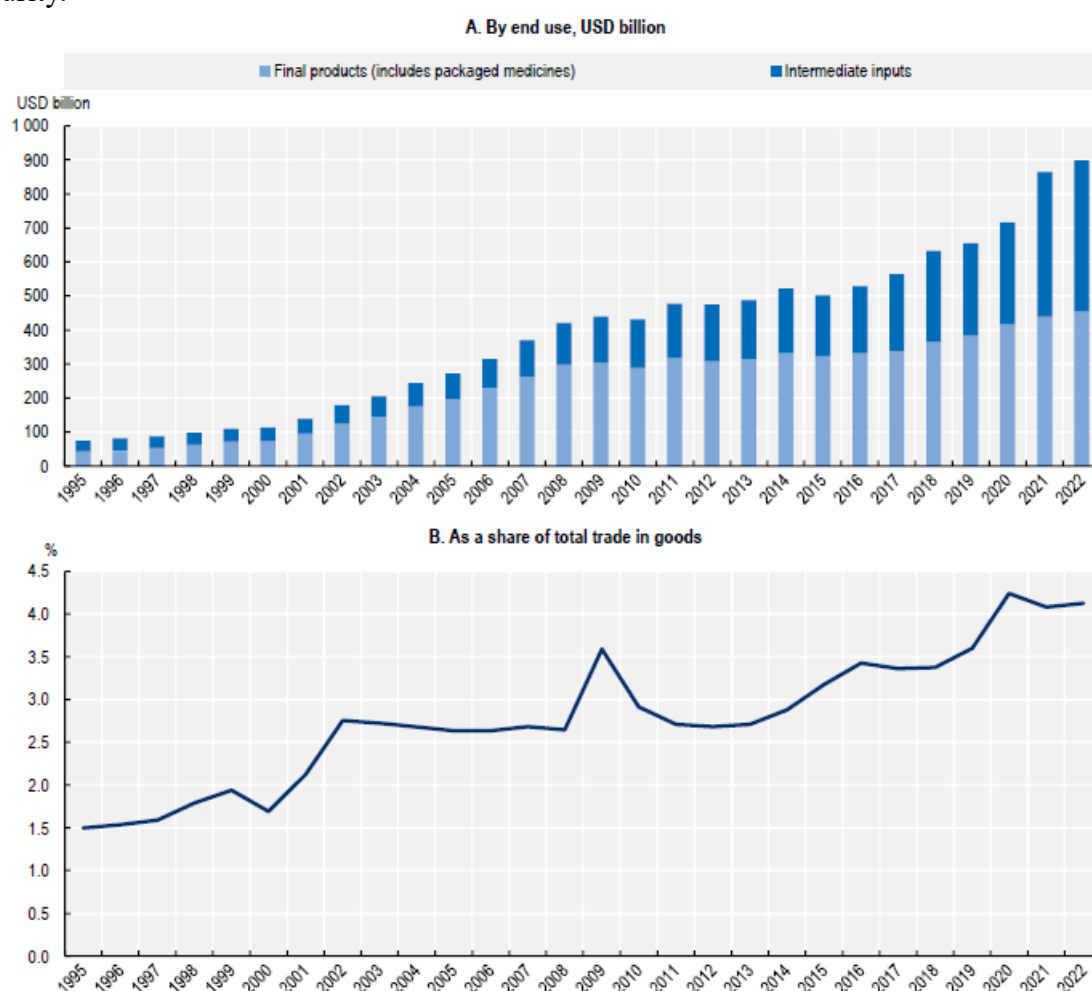
Academically, this thesis contributes to accumulate as more as possible information on the ways that companies handled the COVID 19 crisis in terms of their logistics strategies, as this sector faced the biggest obstacles not only to the resources but also to reach the products to reach the final patient. The research reported in this paper has also been designed to contribute to the development of the wider field of study into supply chain resilience by the development of a more comprehensive framework for the study of the pharmaceutical sector. That sector is characterized by a very special set of risks and is subject to a very strong set of formal and informal regulatory frameworks. The study draws upon a very wide variety of different sources of primary data in order to provide a detailed empirical study of the way in which the pharmaceutical sector was able to resist the impact of the COVID-19 pandemic and to recover from it. But the study also aims to contribute to the wider theoretical analysis of supply chain resilience that is required by a wide variety of different researchers and practitioners, working in a very wide variety of different environments. Supply chains of all types are required to be able to resist as wide a variety of different types of disruption as possible, but they are also required to be able to recover very quickly from any such disruption that does occur. Also, what is reported here focuses upon a number of different dimensions, or variables, that together provide a very complete analysis of the ways in which any pharmaceutical supply chain is able to resist any disruptions to supply and to recover

from any such disruptions that do occur. The dimensions or variables that are studied here include an assessment of the ways in which the sector sources the drugs that are required by patients, an assessment of the ways in which the sector buffers against any possible disruptions to the flows of medicines required, an assessment of the ways in which the sector is currently making use of a very wide variety of different digital technologies and an assessment of the ways in which the sector is currently regulated, both formally and informally. Each of the different dimensions or variables that have been studied here are examined in turn, in what follows, with a view to developing as complete and as detailed an understanding as possible of the ways in which pharmaceutical supply chains are able to operate in order to resist any possible disruptions to supply, and to recover very quickly from any such disruptions that do occur.

The reason that pharmaceutical sector is chosen to be investigated is that this market its actors in times of global crisis is of particular importance. In the last decades the trade of pharmaceutical products has increased strongly on global markets. Also the growth rate of last years is very high and also applies to the years after the COVID-19 pandemic. This is driven by an increasing number of new medicines put on the market for treatment and prevention of diseases as well as by a strongly increasing integration of production systems worldwide. In the meantime, an increasing part of the pharmaceutical trade consists of so-called intermediate goods, e.g. active pharmaceutical ingredients (APIs) for final medicines. Thus, an analysis of the pharmaceutical trade on global markets is especially meaningful. Firstly, the market and its actors have to be analyzed in times of global crisis. Secondly, restrictions and challenges of an analysis of the trade flow of single products on global markets have to be named, particularly for very specific products as face masks during the COVID-19 pandemic.

Trade in the pharmaceutical sector has been rapidly increasing over the past 25 years or so and, in terms of value, has become an even more significant sector of trade in recent years. Figure 1 below illustrates this growth in trade of the sector as a proportion of global trade in merchandise. As has been reported above, the sector's value has grown fast over recent years in terms of trade in health care products as well as medicines in developed countries and rapidly increasing numbers of newly industrializing countries as well as in transition and developing economies, wherever there is demand for an increasing range of health care

products. The growth has been so fast in the last couple of years, especially, that the sector's value as a share of total global trade of all merchandise is greater than the total for all other sectors of trade and clearly indicates the very important place that trade in pharmaceutical products has assumed in the global economy, especially as all countries around the world have to respond to health issues. That the sector has managed to increase its trade so much is, no doubt, due to the fact that it is able to draw on trade from around the world and so avoid any local shortages as well as minimize the effects that any production disruptions may have. Thus, pharmaceuticals trade clearly plays an increasingly crucial role in global health security.



Note: Pharmaceutical products as defined by the WTO Pharma Agreement (HS Chapter 30, and headings 2936, 2937, 2939, 2941). Data prior to 2017 are based on older versions of the HS classification and may not accurately reflect the list of products.
Source: BACI (CEPII) (2023^[2]), *BACI Trade data*, www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37; and Drevinskas, E., E. Shing and T. Verbeet (2023^[3]), *Trade in medical goods stabilises after peaking during pandemic*, www.wto.org/english/blogs_e/data_blog_e/blog_dta_23may23_e.htm.

Figure 1 World trade in pharmaceutical products (1995-2022), by value. (OECD)

Literature Review

2.1 Importance of the Supply Chain Resilience and Efficiency

In the pharmaceutical industry, the supply chain plays a crucial role during times of crisis, such as the COVID-19 pandemic. The specific nature of the pharmaceutical supply chain, including the number of suppliers in each tier, strict rules and regulations, the need to coordinate temperature-sensitive products, and that most products within this industry are life-saving and often have no alternative medication, means that maintaining a supply chain that is able to function in a successful and efficient manner is critical. A simple diagram of the pharmaceutical supply chain in the pharmaceutical industry, developed by the OECD in Figure 2 below highlights the complexity of the supply chain in the pharmaceutical industry. Unlike many other industries, any disruptions to the supply chain in the pharmaceutical industry are not simply expensive, they can also have a direct effect on patients and public health and health, and therefore a high level of vitality must be given to making sure that such a supply chain is able to function successfully. Resilience in supply chains is the ability to anticipate, absorb, adapt to, and recover from disruptions.

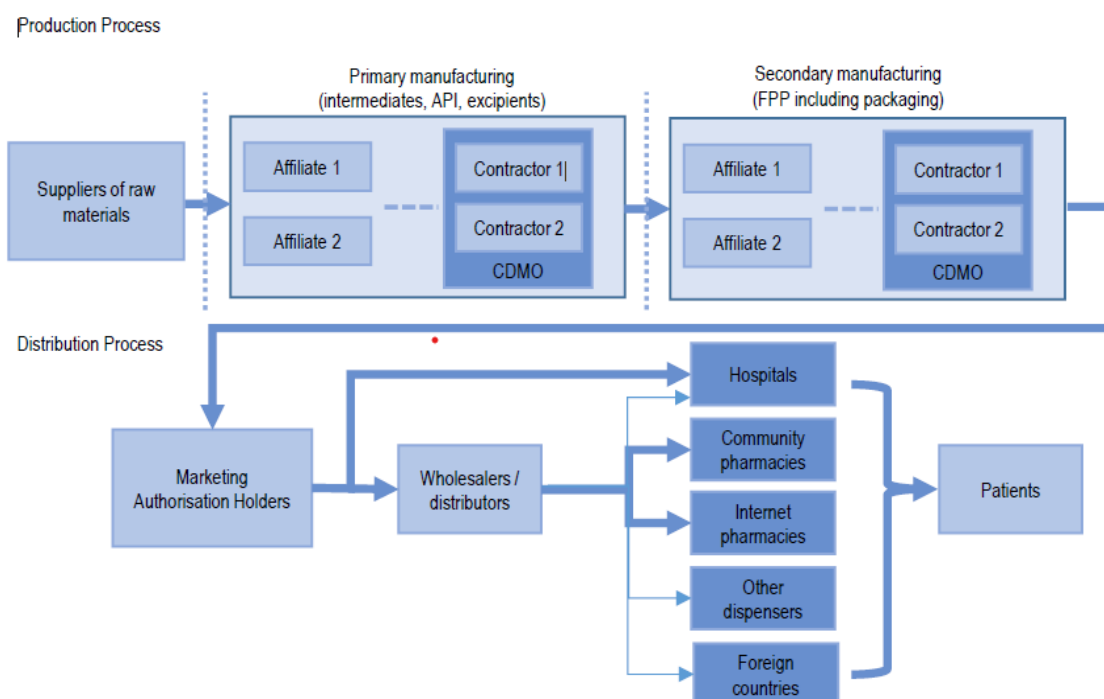


Figure 2 The complexity of pharmaceutical supply chains – OECD (2024)

2. 2 Supply Chain Vulnerabilities During Pandemics

Efficiency and resilience are two goals of pharmaceutical supply chain management that are as closely interrelated as contradictory. The pharmaceutical supply chain was, for many years, optimized for efficiency with a focus on costs in order to remain competitive. The various measures of efficient inventory management, efficient production and efficient sourcing of all required goods and services led to extremely vulnerable supply chains. The COVID-19 pandemic showed just how easily even the most efficient supply chain can be brought to its knees by the lack of any kind of buffer or diversification.

When conducting vulnerability assessments, it is useful to differentiate between triggers, potentiators and buffers. Triggers are precipitating events, whether demand-side or supply-side. Potentiators are factors that scale up the impact of triggers. Buffers are then factors that can moderate the supply chain shock that triggers and potentiators create. These factors are shown below in Figure 3.



Figure 3 Vulnerability assessment, Health Affairs Forefront, 2023.

The ripple effect theory, introduced by Ivanov and Dolgui (2021), better analyses the behavior of a supply chain in case of disruptions. In pharmaceutical supply chain, a large number of entities such as suppliers of Active Pharmaceutical Ingredients (APIs), contract manufacturers, distributors, and health care providers are connected to each other in order to deliver end customers with the required pharmaceutical products. A negative effect caused by an event at a particular node in the network of entities (the ripple effect) leads to stockouts

of key medicines, delayed treatment of patients and in worst case scenario put the products on short term ration. It is not surprise that over 80% of healthcare facilities experienced critical inventory shortages within 14 days, The line graph below shows inventory levels across five key medical supply categories and a steep decline is visible within the first two weeks, emphasizing the system's unpreparedness. This is to stretch out the point that the companies should be always prepared for immediate actions against such crisis.

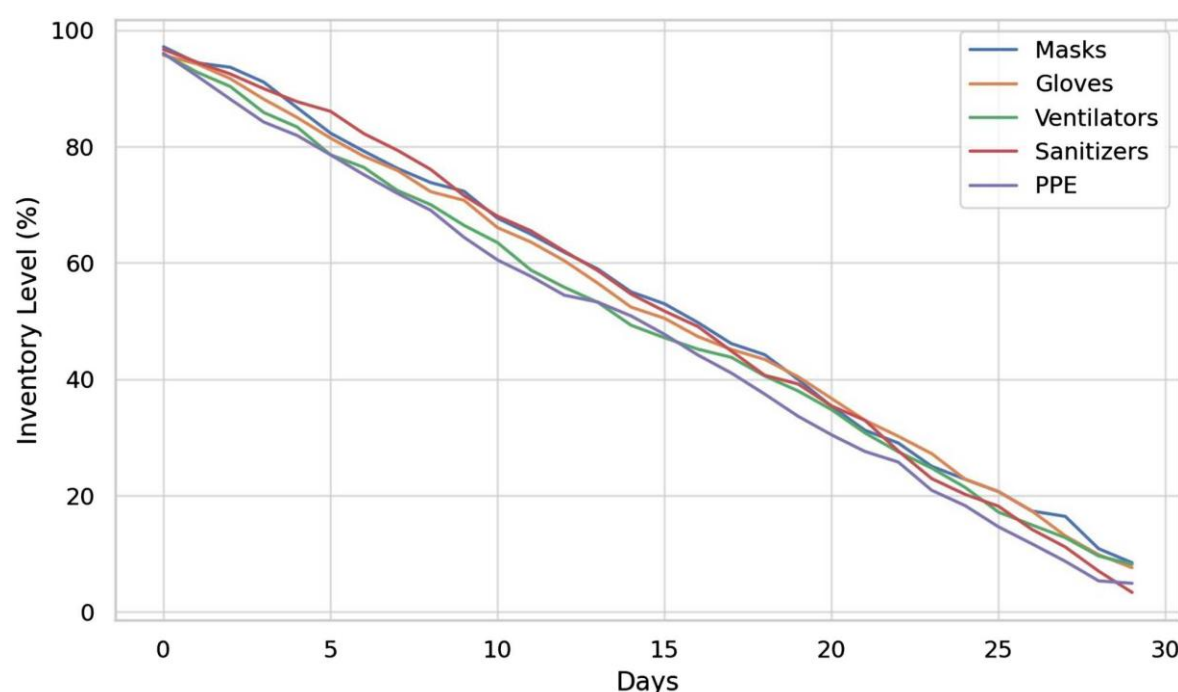


Figure 4 Daily inventory levels during pandemic simulation.

Companies in this industry have to operate at low costs and at the same time have to provide patients with life saving medications at low prices. In order to remain sustainable in the long term, companies have to operate cost effectively and need to invest in risk mitigation. Therefore strategies to increase supply chain resilience have to consider the issues of diversification and redundancy. However, there are also possible inefficiencies and higher costs that have to be considered.

Resilience in the pharmaceutical supply chain and efficiency in inventory management are two goals that must be pursued simultaneously by the pharmaceutical company. Optimizing

pharmaceutical supply chain operations to achieve the goals of the company requires the pharmaceutical company to develop strategies and to make decisions regarding a number of variables that affect the pharmaceutical supply chain of the company. For instance, a lean inventory management practice is key to running a pharmaceutical company at the optimal levels and making the company more cost-effective. In developing resilient inventory models for managing medicines, pharmaceutical companies have to consider factors such as increased demand uncertainty and supply chain disruptions. As mentioned earlier, stockout situations for medicines that have occurred during the COVID-19 were caused by demand variability that had been designed to be managed by the safety stocks in the resilient inventory models. It will be through the use of strategic buffering and dynamic inventory optimization practices that the pharmaceutical companies will be able to manage and develop their pharmaceutical supply chain operations in order to meet medicine demand while at the same time achieving greater levels of efficiency and consequently cost-effectiveness. The key to achieving these goals will be for the companies to move from measuring and evaluating their performance by using a set of static efficiency metrics to measuring and evaluating their performance by using a range of more adaptive metrics. These metrics will enable the companies to assess and manage their performance in pharmaceutical supply chain more effectively in changed circumstances. More are mentioned on topic 4.1 Resilience and Efficiency.

An increasing number of companies in the pharmaceutical industry are using so-called Industry 4.0 technologies in their supply chain management, including for example blockchain, the Internet of the Internet of Things (IoT), and advanced analytics. Such intelligent systems can improve the way in which companies manage their supply chains in many ways, for example by increasing transparency, enabling faster responses to any potential shortages, and better forecasting supply. Moreover, the use of such digital systems can also improve the efficiency of the supply chain in many ways, for example by automating processes, reducing the number of manual interventions, and reducing information asymmetry. The lack of digital integration with suppliers, as well as among different entities in the supply chain can lead to disruptions that companies are unable to anticipate and respond to on time (Queiroz et al. 2022).

Finally, policy and regulation are critical in the pharmaceutical supply chain. They can positively influence the increased resilience of supply chains by enabling the rapid increase of supply during public health crises by for example using ‘fast-track’ licensing procedures or temporary manufacturing licenses to introduce new products to the market (Raj et al., 2022). On the other hand, restrictive global regulatory requirements can add to the current inefficiencies in the pharmaceutical supply chain during a crisis. Here, for example, administrative requirements for operating across borders can reduce efficiency by increasing costs and restrictions on possibilities. In the pharmaceutical industry, there are additional, specific regulatory requirements. Therefore, regulatory constraints on production and distribution of medicines in crisis situations need to be more flexible to ensure safety and quality of these products. Already in normal situations, production and distribution of medicines is subject to strict rules and regulations but in crisis situations such measures can put a huge burden on all players in the chain and even may be in contradiction with the crisis management. The beginning of the COVID-19-pandemic for instance was delayed by several regulatory measures that made it difficult to immediately start alternative sourcing of medicines and modifications of already approved medicines in production.

Pandemics expose the limitations of supply chains operating globally and none are more challenged than those in the pharmaceutical sector. Operating globally for the API, as well as for a number of excipients, packaging and finished pharmaceutical products, the potential for a ‘domino’ effect down the supply chain following a disruption at a single location is high. The increased internationalization of pharmaceutical supply chains, combined with the very complex rules and regulations governing the manufacturing, packaging, labeling, storage, distribution, import and export of all pharmaceutical products, create additional challenges in a pharmaceutical supply chain which are heightened by a pandemic.

In addition, the geographic concentration of pharmaceutical manufacturers worldwide and the hyper-connected supply chain of the industry have created a high degree of risk. Cost-optimized production processes have led pharmaceutical manufacturers to concentrate their production in low-cost regions of the world. However, when factory shutdowns or export controls are implemented in these key production hubs of the world, downstream markets are affected by severe shortages. This is due in part to the lack of geographic diversification

of API and finished drug products, which would enable manufacturers to rapidly switch to an alternative location to meet demand.

The pharmaceutical sector adopts “just-in-time” (JIT) inventory management practices for ensuring cost effective operations. Most companies follow lean inventory practices to maintain minimum stock holding and purchase products in small quantities and frequently. In order to respond to increased demand as well as any supply disruptions, no safety stock is maintained by the companies practicing JIT inventory management. Therefore, during sudden increase in demand for products and vaccines, stock out of critical medicines can occur immediately due to lack of safety stock holding. See Figure 4 for instance.

Demand uncertainty during a pandemic puts an extreme strain on an already vulnerable pharmaceutical supply chain. As a global health crisis rapidly spreads from continent to continent, uncertainty about the demand for medicines and other medical supplies to treat the affected increases. Early into the COVID-19 pandemic, panic and misinformation fueled a speculative surge in demand for medicines generally considered to be low-demand products. Pharmaceutical companies were forced to grapple with trying to manage fluctuating demand for their products while at the same time trying to obtain the most accurate and up-to-the-minute information available about the spreading health crisis. Challenges that pharmaceutical companies have faced in meeting the high demand for medicines and other medical supplies early into the pandemic include in part having to deal with constantly changing information surrounding the severity and spread of the illness and in part having to deal with the effects of being part of a highly vulnerable global supply chain.

A final area of vulnerability within pharmaceutical supply chains is their dependence on the global logistics and transportation systems. In the case of airfreight, for example, products can become ‘stuck in the air’ and be of no use to anyone. Land and sea-based transportation can, likewise, be ‘stuck’ in transit due to a variety of restrictions, including those that restrict the crossing of borders by trucks. As mentioned, many products, especially vaccines and biologics, require to be stored at refrigerated temperatures. This can make their long-distance transportation, by air and by land, very problematic. Indeed, during the COVID-19

pandemic, this has created many problems, around the world, in terms of accessing medicines that are required. These imbalances in access to required medicines during health crises are highlighted by Socal, Sharfstein and Greene (2021) as being critical to the overall pharmaceutical supply chain. The use of a variety of different routes to a final destination, regional storage facilities, and contingency planning are all key to overcoming these kinds of problems and creating a robust pharmaceutical supply chain.

To sum up, the major factor that make the pharmaceutical supply chain sector vulnerable are:

- Inventory flow and management
- Cost effectiveness
- Policy and regulations
- New technologies and digital integration with suppliers
- Geographical limitations
- Demand uncertainty
- Global logistics and transportation system dependence

2.3 Risk Management Strategies in Pharmaceutical Supply Chains

The supply of pharmaceuticals is exposed to the risk of various operational disruptions. The focus, however, must be on risk management in the pharmaceutical supply chain in the post-COVID-19 period. Systemic risks in the supply of pharmaceuticals mean that supply and demand as well as the areas of transportation and regulatory issues can be affected by a disruption at the same time. Risks in the pharmaceutical supply chain must therefore be managed from an interdisciplinary perspective – from an operational, financial, geopolitical and public health perspective.

Risk Mapping of all levels in the pharmaceutical supply chain is an essential part of the Risk Management. Since most companies are not in full control of their complex pharmaceutical supply chains and thus lack transparency, Risk Mapping is especially important to identify

potential risks of the supply chain and to analyze interdependencies of suppliers. By using systematic assessment tools for the risk evaluation, Risk Management identifies crucial elements of the supply chain, single points of failure, and potential bottlenecks. On the basis of the potential risks and their impacts, companies can then prioritize the potential risks and set up corresponding Risk Mitigation Measures in order to minimize the negative effects of potential risks on the company. This is especially relevant if high levels of uncertainty are involved, because under such circumstances most decisions are made with uncertainty and, thus, expose companies to risks. By reducing uncertainties of potential risks and their impacts, Risk Mapping of the Risk Management supports effective decision-making.

Another important risk mitigating strategy for supply chains of pharmaceuticals is the diversification of suppliers or the so-called spread of production. This refers to the production of active and passive pharmaceutical ingredients as well as of finished drugs at several locations all over the world. In the past, many companies had concentrated the production of APIs mainly in Asia. The consequences of such a concentrated production in one part of the world were obvious during the Covid-19 pandemic. While the risk of failure of single suppliers increases, the potential costs for the company as well as for potential compliance problems with rules and regulations have to be considered and weighted against the risk of a failure of the production in one region of the world. Disruptions at suppliers can be handled faster if production is spread all over the world. In this case, the production can be shifted to other suppliers quickly.

Stock keeping for the purpose of preventing and / or minimizing supply disruptions. As has already been stated, from a business perspective the aim of classic Lean stock keeping is to keep stock at the lowest possible level and thus keep costs down. In the course of a crisis, however, an increase in demand for a short time can no longer be ruled out and the supply of a product can be at risk. To this end, Pathy and Rahimian (2023) recommend the implementation of a resilient stock keeping policy. Here, when determining required stock keeping figures, due account must be taken of future uncertainties and of potential disruptions to supply. Thus, in the area of essential drugs and of critical raw materials, it is recommended to keep safety stocks. A dynamic stock keeping policy also enables a company to respond immediately at all times to any changes in supply and in demand, thus also

managing risks in this area while keeping a close eye on the financial interests of the company.

Analytics, blockchain and the Internet of Things (IoT) can increase situational awareness in the supply chain and make it more resilient. Digital intelligent systems and smart technologies can support and enhance the functions of supply chain management. For instance, in the vaccine supply chain intelligent digital systems increase traceability and transparency. This enables the swift detection of a possible disruption to the supply chain as well as the risk of fake products entering the distribution channel. Furthermore, better information sharing among parties is crucial for contingency planning and for handling any unexpected threats or disruptions to the supply chain in a timely and adequate manner. Digital technology therefore not only makes the supply chain more resilient but also more efficient.

Future crises in the supply chain can be anticipated using scenario planning and simulation modeling when designing the supply chain. Using quantitative models, expected consequences of a possible disruption as well as consequences of different supply chain structures can be calculated in order to choose the best strategy. By testing strategies of the company for crisis management and recovery as well as strategies for increasing the flexibility of the supply chain in virtual scenarios before a real crisis occurs, potential costs can be minimized.

The management of the risks to the pharmaceutical supply chain requires the collaboration of all the stakeholders involved in the chain including the pharmaceutical manufacturers, distributors, retailers, health care providers, and regulatory bodies. For example, the collaboration amongst the API manufacturers, drug manufacturers, distributors, and health care providers during the COVID-19 pandemic not only helped in reducing the uncertainty in the demand and supply for the medicines but also in managing the resources amongst the stakeholders (Tirivangani et al. 2021). Thus, the management of the risks to the pharmaceutical supply chain requires the creation of collaborative risk-sharing agreements and the information sharing amongst the stakeholders.

Regulatory adaptations are also to be considered as a major factor in managing risks for supply chains of pharmaceuticals. Such adaptations are intended to allow companies to meet their obligations during a crisis whilst at the same time being able to respond swiftly to changing circumstances and to deal with new challenges as they arise. In the first place, it must be noted that all regulatory requirements must be complied with at all times in order to ensure that the distribution of medicinal products on the market is in fact safe and of good quality. This said, however, it is equally true that strict requirements can sometimes cause problems during a crisis and that as a result there is a need for flexibility on the part of governments and for the establishment of contingency arrangements that are recognized in advance. These would allow for abridged registration of a medicinal product, for an temporary change in the location where the product is manufactured, etc. The key is to ensure that the measures that are taken are implemented in a manner that is consistent with the requirements of all applicable laws and that all efforts are made to ensure that the distribution of the products concerned is in fact safe and of good quality at all times. As part of their risk frameworks, companies should therefore develop a range of contingency measures and implement them as necessary.

2.4 Digital Transformation and Industry 4.0 Technologies in Pharma Logistics

Pharmaceutical companies all over the world are going through the process of modernization of their pharmaceutical logistics with the help of digital transformation and Industry 4.0 technologies. The supply-chains of the pharmaceutical industry are very complex, global and highly regulated, they need a highly coordinated process. The first steps of this process are the production, the warehousing and the distribution. Many Industry 4.0 technologies are used to create a modern, resilient and efficient pharmaceutical logistics system. These technologies are the Internet of Things (IoT), blockchain, artificial intelligence (AI), big data analytics, robotics and automation as well as cloud computing (Hu et al., 2023).

Another fundamental change that is taking place in pharmaceutical logistics is end-to-end visibility. Without end-to-end visibility companies are unable to anticipate problems until

they have already occurred at the supplier level. Real-time end-to-end visibility into all steps of the supply chain increases efficiency and mitigates risks. With real-time tracking by means of IoT sensors and tracking devices that are connected to a digital system, temperature, humidity and the physical location of products are tracked at any point in time in the supply chain. This is particularly important for products such as biologics and vaccines that have to be kept within a specified cold chain to prevent spoilage. Integrated digital systems increase the chance of preventing delays and counterfeiting (Hu et al., 2023).

Industry 4.0 is a collection of technologies, and many of them have now been incorporated into the pharmaceutical logistics mix. However, particular attention is being given to the most recently introduced technology, i.e. blockchain. The distribution systems of the pharmaceutical industry are exposed to the challenge of the illegal drug trade and, in particular, the problem of counterfeit medicines that is increasing with time. Furthermore, there is also a growing number of cases of document forgery that occur during the different stages of the distribution process in the distribution chain. The use of a tracking system based on blockchain can thus have a positive effect on the coordination between manufacturers and distributors, and also between them and healthcare providers and government authorities responsible for monitoring and controlling the distribution of medicines. A complete, transparent and unchangeable register is created and stored by means of this technology, which – by reducing information asymmetry and increasing data reliability – has a positive effect on the safety of the distribution systems and on their distribution efficiency. In particular, it enables an increase in distribution efficiency in cases where there is an increase in demand for certain products, such as during a pandemic.

The other Industry 4.0 technology that is starting to be implemented in the pharmaceutical logistics is the Artificial intelligence (AI) and advanced analytics. This technology is being used by companies to improve their supply chain and create a data-driven decision-making process. This means that the company is able to forecast better and react to the changes in the market in real time. The demand for vaccines and other pharmaceutical products increased in an unpredictable way during the COVID-19 pandemic and this showed the limitations of the traditional forecasting models. Because of this, the use of AI and advanced analytics for forecasting purposes is becoming more and more popular. Data-driven

modeling is enabling companies to improve their adaptive capacity. They are able to reorganize dynamically their supply chain networks and to make decisions in real time in order to improve the levels of inventory, the distribution routes as well as the production schedules. All of this while trying to keep the costs under control.

In order to implement pharmaceutical logistics in modern manner, the application of latest solutions from Industry 4.0 is possible. The area of automation in pharmaceutical logistics encompasses a wide scope of possible applications, and it starts from the use of automatic storage systems, and through the use of automated pick-and-place machines, up to the use of automatic guided vehicles (AGVs). The highest advantage of the application of automation in the distribution processes in the pharmaceutical sector is above all the increased accuracy of the processes as well as the speed of execution, in comparison to the distribution processes which are implemented by humans. As a result of the application of automation, the productivity of pharmaceutical distribution increases, which at the same time enables the pharmaceutical distribution system to respond in case of possible future shortages of human resources. In addition, the highest advantage of the application of latest solutions from the scope of Industry 4.0 in the processes of pharmaceutical distribution is the increased robustness of the system in case of human errors, which – it is worth to underline – may occur more often during periods of increased workload of employees, which are imposed by implementation of the rules of social distancing as well as by the spread of pandemics. According to health. As pointed out by Queiroz et al. (2022), the mentioned above automation of pharmaceutical distribution processes increases the ability of the system to respond in case of possible future crises, as well as it increases the long-term productivity of the system.

The Cloud is enabling the development of collaborative digital ecosystems supporting pharmaceutical supply chain modernization. As most pharmaceutical companies are operating on a global scale, the collaborative environment supported by cloud computing is required to deal with different regulatory requirements in different countries. Information exchange and collaborative planning in real time is critical to improve agility and efficiency of complex pharmaceutical supply chain systems.

Furthermore, in order to plan the supply chain of pharmaceutical companies in an adequate

way, digital twins and simulation modeling can be of great use. As mentioned before, a digital twin is a virtual replica of a physical object, system or process. In the context of pharmaceutical logistics this could be the complete supply chain of a pharmaceutical company or only parts of it. On the basis of this virtual representation of the real world different scenarios can be simulated. This, on the one hand, means that the consequences of possible disruptions can be predicted. On the other hand, possible reactions and measures can be tested as well. By using digital twins and simulation modeling, companies are also able to optimize their supply chain and increase their resilience (Ivanov, 2020).

There are many potential advantages and many potential challenges to implementing digital solutions to support pharmaceutical distribution in this new era of Industry 4.0. In terms of advantages, many of the individual digital technologies that are now available to support logistics and distribution have the potential to deliver high returns on investment, therefore it is clearly worth exploring the individual potential of a number of different technologies. In terms of potential challenges, however, the initial investment required to implement individual digital technologies can be very high, meaning that in the short term at least the financial implications of the adoption of individual digital technologies may outweigh the benefits for individual organizations. In addition to these potential financial implications, a number of potential cyber threats currently exist to the use of digital solutions, particularly where large amounts of sensitive data are involved. The issue of integrating large amounts of data in order to gain value from individual technologies is also a challenge, particularly when multiple different digital systems are in use across an organization. Finally, there are also a number of different compliance issues that must be taken into consideration. For example, information about prescription medications will be kept and managed by digital solutions, and it is therefore essential that all information is kept secure and that the organization using the digital solutions is compliant with all applicable laws and regulations at all times. According to research published by Raj et al. (2022), the successful digital transformation of the pharmaceutical distribution sector is heavily reliant on the organization's culture, and the range of technological initiatives that are developed in order to support logistics and distribution, in addition to the range of measures that are put in place in order to govern a number of different initiatives, all needing to be aligned with the organization's culture and with the existing, applicable, rules and regulations that must be

followed by the organization in order for the organization to develop logistics and distribution that are highly resilient (Raj et al. 2022).

In summary, modern pharmaceutical logistics in the context of digital transformation and Industry 4.0 technologies are based on a new supply chain paradigm. This supply chain is transparent, automated, of high quality prediction and highly collaborative. The COVID-19 pandemic was a catalyst of digital change in pharmaceutical logistics. However, in order to increase the degree of resilience and efficiency of a globally acting pharmaceutical supply chain in the long term, the digital technologies currently in use must be continuously developed and optimized in order to be able to handle future challenges.

2.5 Diversification, Nearshoring, and Regionalization of Pharmaceutical Manufacturing

In order to avoid single-supplier dependencies with respect to critical components, such as APIs, for instance, which were purchased in large stockpiles by pharmaceutical companies from a single main supplier, the distribution of sourcing, i.e. supplier diversification, prevents the same kind of problems from occurring with all supply chains at the same time. As a result, supplier diversification leads to a higher number of qualified suppliers which in turn results in higher complexities for the quality control, the compliance with all regulations as well as for the coordination that have to be managed by adequate governance and supplier management.

Nearshoring of production, i.e. relocating production to a country which is near to the market of a company, again is in the focus of interest of companies in the pharmaceuticals sector in the wake of the COVID-19 pandemic. Air and sea freight of APIs from Asia to the European market has been subject to severe delays, due to lengthy supply chains, bottlenecks at seaports and an increased risk of failures in long-distance supply chains of highly specialized products. As a result, the relocation of production of APIs as well as of finished pharmaceuticals for the EU market to Europe of companies in the pharmaceuticals sector is considered to be a promising strategy to increase flexibility and to reduce lead times of companies in the pharmaceuticals sector, even if production costs are higher than for offshore

production.

Regionalization of pharmaceutical manufacturing refers to the development of regional production hubs or regional supply chains that can independently service the local market. The aim of regionalization of pharmaceutical manufacturing is to minimize the risks that can be created by intercontinental supply chains for pharmaceuticals and to increase the resilience of pharmaceutical supply chains within regions. This requires significant investments in new production capacity as well as in regulatory compliance within countries as well as alignment with the industrial policy of countries.

Governments from around the world have introduced a variety of policies, and incentives, to promote the local production of certain drugs and to strengthen their domestic pharmaceutical sector. Many of these health policies, and interventions, have the objective of improving health security, but in doing so they create a variety of new trade barriers between countries. Governments will have to reconcile their objective of promoting local production, and the increased health security that it brings, with the need for global cooperation to develop and distribute, on a sustainable basis, essential medicines for all.

To promote supply chain resilience for APIs and finished products of medicines in the pharmaceutical industry by means of measures on the diversification of suppliers as well as on nearshoring of production, a strategic alignment within the framework of a risk management approach is fundamental. Measured on the basis of a strategic analysis by means of quantifiable indicators on the probabilities of disruptions as well as on the corresponding risks of the transport, as well as on the costs versus benefits of the measures to be taken, measures on diversification of suppliers and on nearshoring of production which are merely formally intended to increase the resilience of supply chains of a company, e.g. by means of “reshoring” of production, can lead to a clear increase of the operational expenses without any corresponding increase of resilience.

While increased diversification and regionalization of production locations can create new types of inefficiencies, above and beyond those that already exist due to redundancy, they must be weighed against the clearly negative effects of a concentrated supply chain with a lack of redundancy. A lean global supply chain is a highly efficient type of supply chain that

is designed to be cost-minimal. Such supply chains are based on a central production location and make use of the related economies of scale. However, by distributing production locations all over the world, companies can lose out in terms of scale and, in addition, be confronted with a large number of different regulatory requirements. The related trade-offs between increased redundancy and cost competitiveness must be analyzed and weighed by companies in order to avoid a potential decrease in profitability. In the future, supply chain designs will be based on hybrid models that aim to achieve the efficiency of global supply chains and, at the same time, offer sufficient resilience in regional markets (Queiroz et al. 2022).

2.6 Regulatory Flexibility and Policy Responses During the COVID-19 Crisis

Health crisis have always put an enormous strain on governments, on regulatory bodies and on all other policy makers. For management of the pharmaceuticals' supply chain within the framework of strictly regulated environments for guarantee of safety, of efficacy and of quality of the pharmaceutical products of a health crisis of unprecedented proportion as the one generated by the COVID-19 all the measures of an emergency nature were introduced by governments and by regulatory bodies for enabling the pharmaceutical companies to increase production of their medicines and of their vaccines and to distribute them promptly.

Another approach that can increase the short-term supply of vaccines, medicines and medical devices in the short term is the introduction of so-called expedited approval pathways. Such new approval pathways are granted within a shorter period of time than usual and are often granted as so-called Emergency Use Authorizations (EUAs) or as so-called conditional marketing authorizations. Ivanov and Dolgui (2021) stress the importance of the so-called “regulatory agility” of pharmaceutical governance systems in times of a crisis in order to manage the supply of medicines. The supply of vaccines, medicines and medical devices in times of a crisis not only requires an increased production of these products by the manufacturers, but also a timely distribution to the customers. Therefore, the regulatory systems also have to become more agile in order to allow for fast approval processes of new products while ensuring the required safety standards for these products.

There was also relaxation in terms of how medicines and medical devices could be made. For example, there were temporary permissions for manufacturers to deviate from standard methods of production, permission to source alternative ingredients or to use completely new manufacturing sites. This flexibility in supply was critical in order to avoid shortages of individual products as a result of localized lockdowns, as well as to avoid the risk of bottlenecks caused by supply chain failures as a result of interruptions to the supply of raw and other materials. Socal, Sharfstein and Greene (2021) highlighted the benefits of greater flexibility in terms of the sourcing of raw and other materials, as well as finished products. Not only would this reduce a facility's dependence on a single supplier and therefore reduce the risk of shortage as a result of failure by that supplier. But it would also help to spread the risks of increased demand, and facilitate rapid scaling up of supply where needed. As with all such flexibility, however, it is crucial to increase corresponding quality assurance activity. As medicines move across borders as raw materials, intermediates or finished products as part of global pharmaceutical supply chains, it is not uncommon for products to cross borders multiple times before they reach the patient. Therefore, from a regulatory perspective, it is increasingly important that requirements for human and veterinary medicines are increasingly harmonized between countries, that information and regulatory support are shared between national competent authorities for human and veterinary products.

However, there were also several constraints on pharmaceuticals' supply chains, put into question by governments and by the general public during the health crisis and imposing upon the traditional framework of pharmaceuticals' governance. Such constraints concerned, for instance, the supply chain contracts. From a regulatory perspective, the greatest challenge lies in finding a balance between very strict controls on safety as applied to the pharmaceuticals sector and sufficient flexibility to be able to face a crisis.

Export restrictions for medicines and medical equipment during the ongoing COVID-19 health crisis in many countries of the world are solely intended to ensure that also in times of a crisis the local population is supplied with adequate quantities of needed medicines and medical equipment. Absolute export bans are the extreme case. The negative consequences of such measures, however, are often not restricted to the countries that impose such restrictions. Rather, the measures also trigger new shortages in other countries that are unable

to purchase the needed medicines and medical equipment from abroad due to import restrictions. As such, these measures are highly ineffective and expose the fragility of global supply networks for pharmaceutical products more than health protection would. Instead, they could lead to a new crisis. The lessons to be drawn from the current health crisis for future health crises of a similar magnitude, therefore, are measures to safeguard the health security of the population of a country and, at the same time, promote global cooperation.

Governments around the world also temporarily changed their public procurement policies and practices for health products such as medicines and vaccines during the early stages of the pandemic. They entered into advance purchase agreements with health products manufacturers and provided financial incentives to increase production rapidly of health products for which the agreements were entered into. Such health products were to be available first and foremost for the population of the country in question, and therefore, public procurement for health during the COVID-19 health crisis required a coordinated approach among governments worldwide to improve predictability and facilitate distribution rapidly of health products such as vaccines and critical medicines to places where they immediately were most needed. However, the unequal distribution of vaccines to rich countries as opposed to the poor countries of the world exposed deep rooted inequity and highlighted the urgent need for greater global health solidarity.

Innovative digital-based tools have also been utilized for enabling the supply of life-saving vaccines, products, medical and diagnostic devices during the ongoing COVID-19 health crisis. These include measures for enhanced pharmaceuticals' regulatory efficiency, such as facilitation of remote-based inspection activities, introduction of electronic-based submission of documents and related data, and monitoring of compliance by all regulated entities on a real-time basis to ensure that such products are being distributed while ensuring safety and quality. Ivanov (2020) noted that by incorporating these digital-based tools into the pharmaceuticals' regulatory frameworks, a host of increased system efficiencies can be created while enhancing the overall system's resilience on a 24/7 basis by creating increased transparency which will allow for all issues to be handled speedily without any individual intervention.

2.7 Inventory Management, Safety Stocks, and Strategic Buffering in Critical Medicines

Managing the pharmaceutical products inventory within the pharmaceutical supply chain of the healthcare system is a very critical activity. Many “lean” inventory management models were developed in order to manage the inventories of the pharmaceutical products in the pharmaceutical companies during a stable market situation in the market place. In a moment of sudden change, with high demand for some of the products used to treat patients suffering from COVID-19, as well as from supply chain situations, the minimal safety stock that is held for such products does not last long, and therefore a ‘stock-out’ situation is created soon enough. Such situations may lead to serious shortages of some of the critical products used for the treatment of patients suffering from very serious conditions. Any shortage of such products will cause serious health risks.

A safety stock is a protective stock of products held in stock to cover against demand variability and supply lead time variability. A surge in demand for medicines to be used in intensive care as well as for sedatives and antiviral products, and in particular for vaccine products, occurred during the recent COVID-19 health crisis that far exceeded the best available forecasts. As such, an effective inventory management in pharmaceuticals requires a stochastic-based stock holding quantity formula that considers demand uncertainty as well as supply chain disruption likelihood. A Stochastic-based Stock Holding Quantity Formula for an effective inventory management in the pharmaceutical sector may lead to better management. This formula will allow pharmaceutical companies to hold efficient stocks of their products and, at the same time, be prepared for unknown future events.

Strategic buffering therefore goes beyond safety stock. It involves a wide range of risk management factors that are stored in a buffer in the form of safety stock, regional stocks, public or private stocks and even in decentralized storage hubs or facilities. The major characteristic of a strategic buffer is that a purely centralised global supply chain is not able to handle disruptions in the transportation system. Therefore, strategic buffering aims at enabling supply chain partners to handle disruptions in the region where they occur. This

kind of approach requires an analysis of costs and benefits as well as effective coordination with all stakeholders involved.

Inventory management of critical and intensive care medicines during a pandemic, such as the current COVID-19 health crisis, is subject to extreme and unpredictable increases in demand for such products, and thus can be difficult to manage using traditional methods of inventory management. For example, public stockpiling of such items as well as last minute changes to patient treatment could occur. Demand forecasting is generally based on historical data that does not exist for a pandemic and thus, there is great risk to health as well as tremendous financial loss when attempting to manage the inventory of critical care and intensive care type products during a health crisis. Therefore, there is a need for re-planning of demand management during a health crisis using a dynamic system to manage the inventory in real time using the latest available information.

Public policy and interventions by other stakeholders in the market for purchasing and holding for use of essential medicines, vaccines and medical products for dealing with infectious diseases for prevention and treatment also affect the safety stock holding and the strategic buffering for such products. Thus, stockpiling of such essential medicines, vaccines and medical supplies for dealing with public health crises requires a well coordinated national stockpiling program and procuring strategy under the overall governance of public health authorities. However, such a national stockpiling program and procuring strategy would fail in its objectives if not well coordinated and if it does not have a clear strategic framework. In such a case, the market signals could get distorted leading to artificial shortages and higher price volatility (Raj et al. 2022).

In addition to demand uncertainties, supply-side disruptions have to be taken into consideration when addressing the matter of inventory resilience in pharmaceuticals. Such disruptions may be caused by a variety of events including manufacturer's shutdowns, export bans and others leading to supply delays. In such circumstances, management of safety stocks has to be synchronized with risk assessment of respective suppliers and with measures aimed at ensuring the highest level of reliability of the upstream part of the supply chain. In other words, having safety stocks of medicines efficiently stored does not automatically

mean that the company has an efficient inventory resilience policy in place. A holistic approach is required here, which involves stock of safety stocks as well as measures to ensure the highest possible reliability of the supply of items further up the supply chain. The stock management in pharmaceuticals has been influenced significantly by the digital technologies that have been introduced in this field. Real time monitoring of the quantities of medicines stored as well as using management information systems, such as ERP systems and others as well as advanced analytical tools enable for efficient monitoring of the stock of medicines distributed through the various channels and for forecasting their demand, especially in the case of vaccines (Hu et al. 2023).

Maintaining stock of large safety stocks for health preparedness, poses additional challenges for the large number of medicines, many of which have a limited shelf life and must be stored under specific conditions. As reported by Queiroz and al. (2022), managing health stock to supply chain resilience without incurring additional cost, to hold an efficient excess stock, is challenging and hybrid approaches to manage stock of medicines considering number of factors are considered such as required safety stock for critical medicine(s) to cope with any unexpected spikes in demand, holding cost of stock, diversification of supply from number of sources to mitigate risk of failure by single supplier and by using digital technologies to improve accuracy of demand forecasting.

In terms of implementing Strategic Inventory Management (S.I.M.) practices within the pharmaceutical distribution system, holding safety stocks of critical inventory in times of increased uncertainty has the potential to deplete quickly during periods of high demand and ultimately result in stock shortages that can have serious health consequences. To that end, a key component of S.I.M. practices is to incorporate risk into traditional safety stock modeling practices (Pathy and Rahimian 2023). As Ivanov (2020) noted, in planning future supply chain designs, it is important to incorporate disruption modeling and related measures of uncertainty into the mainstream of basic operations management models and practices. A hybrid approach of holding strategic safety stocks of critical products, while using sophisticated supply chain analytics to support more effective and efficient sourcing of other inventory, holds considerable promise as an effective method for creating supply chain networks that deliver value while minimizing the associated risks and costs.

Research Methodology

3.1 Research Design and Methodological Approach

The present thesis is based exclusively on bibliographical sources, case studies of companies, which are exclusively reported by their own managers. All information that has structured every detail of this work, is based on standard literature review, as the theme is of high complexity in order to be approached rather bibliographically, within the limits of master's degree.

Instead of using statistical models and having to gather primary numerical data, this research relies heavily on reviewing and critically analyzing secondary literature, policy documents, industry publications/reports, and empirical data related to disruptions to pharmaceutical supply chains and mechanisms for transformation. The ultimate goal of this study is to develop a comprehensive understanding of how pharmaceutical organizations and healthcare systems adapted to unprecedented levels of disruption while attempting to maintain access to medicines and to continue their operations.

The methodology of this study is deductive and consists primarily of thematic analysis of secondary academic sources found on PubMed, Google scholar and Scopus scholar. These are databases for research that are used by the majority worldwide and are renowned for their abundance and easy accessibility. The qualitative methodology employed in this study will synthesize available evidence as presented in peer-reviewed articles, institutional papers, and recently published research regarding the pharmaceutical supply chain

3.2 Data Collection and Selection of Academic Sources

Data collection for this study was conducted solely through the use of secondary qualitative data, derived from academic literature, institutional reports, scientific journals and other recent/peripheral research efforts related to pharmaceutical supply chains and the impact of the COVID-19 pandemic on global healthcare logistics systems. Academic literature published in peer-reviewed journals made up the foundation of this analysis.

The selection of academic sources to be utilized within this study were subject to specific criteria. Firstly the articles were prioritized, recent publications (dating from 2020 – 2026) were prioritized because they reflected the most current developments related to pandemic-related disruptions to global pharmaceutical supply chains and post-pandemic transformation strategies. Secondly, publications from well-known, international journals specializing in supply chain management; healthcare logistics; pharmaceutical policy; operations management; and technological innovation were emphasized within this research project. On the above mentioned academic literature databases-tools the keywords used are: Global pharmaceutical distribution, shortages of active pharmaceutical ingredients, inventory resilience, crisis management technologies, and government intervention mechanisms. Studies providing empirical evidence, operational case studies or strategic assessments of the pharmaceutical systems existing during the COVID-19 period were of paramount importance.

3.3 Reliability, Validity, and Ethical Considerations of the Research Methodology

Reliability and validity were considered essential methodological elements throughout the development of this study in order to ensure the consistency, credibility, and academic quality of the research findings. Reliability was strengthened through the systematic use of peer-reviewed academic literature, institutional reports, and contemporary scientific studies directly related to pharmaceutical supply chains, healthcare logistics, and COVID-19 disruption management via the most used academic data bases and always considering the scientific impact of the journal that the relevant article is published. Also after reading thoroughly the extensive literature, the most relevant and recent one are chosen as sources of the present dissertation. Except of the scientific articles, was also used data published by formal international organizations, as OECD (Organisation for Economic Co-operation and Development).

The validity of the study was enhanced through the careful selection of academic sources that were directly relevant to the research objectives and provided valuable insights into the transformation of pharmaceutical supply chains during the COVID-19 pandemic. Journal

impact, date of publication and the methodology which is based on every article are the main criteria, in order to maintain the overall validity of the sources.

All academic articles, institutional reports, and other sources used in the analysis were cited using the APA Referencing System to ensure academic integrity and acknowledge the work of original authors. Furthermore, the research did not require the collection of personal information, medical records, confidential business data, or any other sensitive material. These are reported in order to ensure that the major ethical considerations are taken into account and are approached appropriately.

Analysis of Covid-19's Impact on Pharmaceutical Supply Chains

4.1 Global Distribution in Pharmaceutical Supply

The Global Distribution System (GDS) of the pharmaceutical supply chain has been one of the primary operational systems severely affected by the spread of the COVID-19 pandemic. The distribution of pharmaceutical products has become even more complex, since they are part of a highly interdependent global network of manufacturers, API suppliers, wholesalers, 3PLs, customs agencies and healthcare institutions. A typical strategy in place prior to the pandemic was one of centralized manufacturing, with long range sourcing to minimize costs and to leverage from economies of scale. In parallel, all systems for the transportation and export of products were disrupted on several continents, thus requiring not only an efficient production volume, but also an efficient, visible and above all a flexible system of distribution (logistics) that is able to absorb local shocks and above all deliver the required products, particularly those for use in intensive care units and for emergency healthcare, in due time.

The global pharmaceutical distribution system has not been designed or configured to deal with a number of disruptions occurring all over the world at the same time. The impact on

‘business as usual’ stocks of so-called ‘normal medicines’ used in Intensive Care Units and other Emergency Healthcare situations has been largely as a result of a number of ‘bottlenecks’ occurring in the international supply chain of pharmaceuticals. These have been caused by a variety of factors including, but not limited to, travel restrictions, port closures and other measures that governments around the world have implemented in an attempt to contain the spread of the virus. The ‘grounding’ of the world’s passenger aircraft has had a particularly significant effect on airfreight capacity, a major component of global cargo movements, with resulting delays in the distribution of vaccines, biologics and other temperature sensitive products requiring rapid international distribution.

However, the lack of adequate global pharmaceutical distribution system exposed the world to serious shortage of medicines and the inability to distribute the available ones to patients in need in a timely manner. Several negative impacts on the distribution of medicines across the globe have been experienced during the pandemic. These impacts are particularly severe in countries that rely heavily on imports of medicines distributed through long distance logistics (Chowdhury et al., 2021). Moreover, the lag time for distribution of vaccines, biologics and temperature sensitive medicines has been significantly affected and increased during the pandemic. In addition, the global supply chain of maritime containers has been negatively affected. There is a severe shortage of empty containers to return to manufacturers of medicines across the globe. The waiting days to unload these medicines at ports around the world have significantly increased due to congestion at several ports. This would create uncertainties in the distribution of medicines through the logistics systems. Thus, to deal with the current global health crisis and to ensure the availability and distribution of medicines to patients in need, there are several strategies that could be adopted by stakeholders. These strategies include:

- increasing the diversity of available means of transportation and
- regionalizing the preparedness of logistics of pharmaceutical distribution.

The pharmaceutical manufacturing networks are highly concentrated geographically. This concentration of manufacturing sites, for Active Pharmaceutical Ingredients (APIs) and their intermediates as well as finished dose forms, creates imbalances in pharmaceutical product distribution during a global public health crisis, such as the current COVID-19 pandemic.

Many of the API and intermediate manufacturers are based in several countries in Asia, and are shipped as raw materials to finished dose form manufacturers in other parts of the world as part of complex global pharmaceutical product distribution networks. Lockdowns in single regions of the world can therefore very quickly affect downstream manufacturers in other parts of the globe, leading to shortages of critical drugs for importers (Miller, et al., 2021).

From the perspective of health care systems that rely on imports of products from external sources, the shortages revealed quickly that their own stock levels of products were not up to par. Even if the manufacturing sites had been able to keep to their schedules, the health care systems would have been unable to cope with the increased numbers of products required. In other words, establishing a globally distributed production network which can deal with a single point of failure is not an easy task and there are many organizations that are currently unable to cope. For the pharmacy and hospital-based distribution of products, the initial peak in demand for COVID-19 products followed by a drop in demand for non-COVID-19 products created a number of problems that national distributors were not able to cope with in terms of imbalances in cross country distribution (Tirivangani et al; 2021). In many developing countries, the lack of stock of critical medicines to be distributed in distribution in health care facilities in emergency situations is further compounded by the lack of a well-developed central and local government logistics infrastructure and funds to manage, stock, and distribute a wide array of products on an on going basis.

In low-income countries lack of distribution structure and financial means to purchase essential medicines in time created major problems in the distribution of these products. The production of sufficient quantities of the drugs is important to manage supplies of medicines. However, the coordination and flexibility of the logistics structures and measures play a major role when distributing medicines in times of crisis.

Modern digital technologies are increasingly used to create transparency and to coordinate the distribution of medicines. By using blockchain, digital supply chain monitoring, the Internet of Things (IoT) companies can better manage their supplies and their international supply chains by tracking shipments and stock items. The use of intelligent supply chains and tracking systems will be more effective than traditional tracking methods. All

stakeholders involved can be updated in real time on various factors such as the shipping company, the location where the shipment is, the customs clearance process, performance of the delivery, and products that require to be kept at certain temperatures. Studies into the distribution of vaccines using technology have found that in emergency situations the use of digital technologies greatly improved the visibility into the operations of logistics and enabled these to respond in a more operational manner. Through the sharing of accurate and real time data between stakeholders including the manufacturers, distributors and health care providers those involved in the distribution of pharmaceutical products were able to respond to any failures in the supply chain and increasing demands of medicines during emergency situations.

Similarly, research into the use of technologies within global supply chains has identified the ways in which organizations are utilizing intelligent supply chains to track shipments in real time and to locate where problems may be occurring in the distribution chain, such as customs clearance delays. Monitoring of shipments can highlight a number of areas, including where a shipment is currently located, the performance of the shipment, details of the storage of temperature sensitive products, etc. The research found that the use of digital solutions had ‘improved the visibility and operational responsiveness of pharmaceutical logistics’.

Current supply strategies for central type medicines are mainly based on transport chains and are usually not equipped with a sufficient safety stock to deal with disruptions in several regions. Experiences with current shortages of medicines due to the COVID-19 pandemic give reason to develop distribution strategies for future public health crises to avoid similar failures. The most important strategies could be: (1) the installation of regional stock points, (2) the establishment of alternative distribution channels, (3) the monitoring of the logistics chains by digital means and (4) the coordination of the governance of the distribution networks to secure healthcare in case of a crisis. Below a scheme is provided that shows some policies should be followed in order to avoid incidents in such crisis, according to OECD (2024).

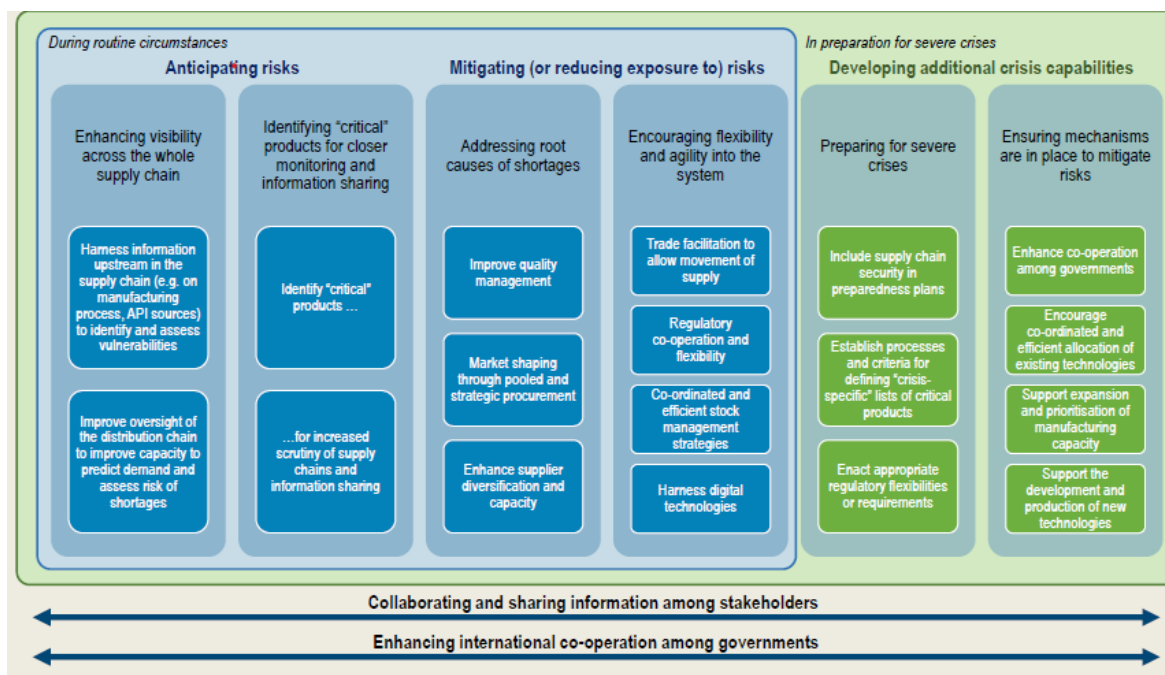


Figure 5 Analytical framing of policies to improve medical supply chain security. OECD, 2024)

4.2 Case Studies

The experiences of the US pharmaceutical supply chain during the COVID-19 crisis offer a rich source of primary material. Most of the pharmaceuticals that are consumed in the US are produced by companies located around the world and, prior to the COVID-19 pandemic, a large proportion of the active pharmaceutical ingredients (APIs) and generic medicines were imported. The lockdowns and export restrictions in key production locations for generic medicines, such as India and China, caused serious shortages of critical medicines, such as sedatives and anesthetics, as well as other intensive care medicines. Health care providers and their associated hospitals and health systems were left struggling to manage their inventories of required medicines as the failed to arrive as expected imports were not replaced by domestic production (Socal, Sharfstein and Greene, 2021).

However, also the European pharmaceutical system has come under scrutiny. The problems of drug shortages that have been faced in the years before the pandemic, such as delays in the distribution of medicines, the lack of a strategic procurement policy and an unequal

distribution of available stockpiles between the EU Member States, have in many cases not been solved. Even in times of a pandemic, some Member States competed with each other for the purchase of medicines, putting excessive pressure on suppliers and on the distribution networks. The lack of a fully coordinated system of joint procurement and of stockpiles of reserve medicines that can be distributed in times of a crisis has strongly affected the distribution of medicines within the EU. Since then, European policy makers increasingly speak of strategic autonomy of the European pharmaceutical system. A key element of this strategy would be to promote the manufacturing of medicines within the region. In addition, mechanisms of cross-border cooperation should be developed in order to avoid a dependence on external suppliers of essential medicines.

4.2.1 The COVID 19 vaccines case.

The distribution of COVID-19 vaccines throughout the world presented a number of unprecedented challenges in the pharmaceutical logistics of a global health crisis. Initially, the pharmaceutical manufacturer had to increase production and put together a new global distribution network using for example air transport and other forms of logistics. Furthermore, a cold-chain had to be set up, which would be able to keep the contents of the vaccine at the required temperature throughout the distribution process and also during handling by health care workers. The distribution of the mRNA vaccines in particular has proven to be a great challenge for the pharmaceutical supply chains. mRNA vaccines are highly sensitive and must be kept at temperatures of down to -70°C . This places a very great burden on the distribution process of these vaccines, also with regards to the lack of a cold-chain as well as of digital tracking systems for the distribution of shipments, in many cases.

Challenges faced by health care systems worldwide in ensuring the distribution of essential health commodities (EHCs) are multifaceted. In the first place, most of the products classified as EHCs have complex distribution systems and multiple stakeholders involved in the distribution process from the manufacturer to the final consumer. In many cases, the production of EHCs occurs in industrialized countries while the majority of the consumption takes place in low- and middle-income countries. Moreover, the EHCs are procured from the global market. The restrictions on exports of medicines due to the COVID-19-related lockdowns and closed borders experienced by countries worldwide led to a dramatic decline

in the availability of life-saving medicines for the treatment of patients suffering from various diseases. In order to better understand the distribution challenges of essential health commodities faced by health care systems, a case study was conducted in Dar es Salaam, the largest city in Tanzania, which serves as the distribution hub for a variety of EHCs. The distribution system for essential health commodities studied by Ipagala and his coauthors (2023) experienced a number of problems that were largely attributed to the breakdown in the process of procuring commodities from the global market of essential health commodities. Specifically, the authors reported that the distribution system for EHCs in Dar es Salaam faced

Stockholding for health is typically conducted by health care providers and distributors and they have operated in an efficient and lean manner to keep costs down. However, stockholding for health has been found to be less than adequate during health crises as the systems have not been able to maintain health commodities during increased periods of demand. There are some models which attempt to forecast the amount of stock that will be required during a public health event. However, such an event is difficult to predict and can have an unexpected nature and timing. In the research into making health care inventory more resilient the limitations of current systems and the consequences of health care organizations running near empty during a time of high demand has been exposed. In particular, there is a need for health care organizations to hold a safety stock of essential respiratory medications and intensive care medications as they have been found to be rapidly depleted within a short time period.

There are many lessons to be learned from Pharmaceutical Companies who made use of digital technologies in the distribution of their Vaccines and Medicines during the pandemic. An example of this are intelligent tracking systems. Such tracking systems, which make use of blockchain, the Internet of Things and machine learning for example, are increasingly being put into practice in the Pharmaceutical Supply Chains of all over the world. Research showed that in the Vaccine Supply Chains which made use of such tracking systems transparency was increased and the tracking and monitoring of the distribution of Vaccines was facilitated. Moreover, such systems enabled the rapid coordination of the different logistics parties in the chain (Hu et al., 2023). As a result of the use of such systems the companies which made use of them were able to respond to changes in the demand for

their products more quickly and distribute their products more accurately than companies which did not use such advanced digital technologies.

Research analyzing strategies for dealing with the disruptions in the pharmaceutical supply chain caused by the COVID-19 pandemic found that companies that had adopted a diversified sourcing strategy and had integrated risk management into their business had been able to maintain their normal business activities. Many studies have examined different strategies for dealing with the spread of the pandemic. These studies found that companies that had adopted strategies such as switching to alternative suppliers, or altering their shipping plan, were able to continue to operate and to supply their customers to a greater extent than those companies using more traditional global sourcing strategies. The lessons from these studies are being used to drive changes in the pharmaceutical supply chain, including the development of regionalization strategies, the increased use of digital technology to manage the supply chain, the establishment of emergency stockpiles of key medicines, and the development of collaborative international logistics strategies to handle future crises.

4.2.2 The CVS case

CVS Caremark (Ochonogor et al., 2022) is a pharmaceutical and prescription management enterprise rapidly grown into a major corporation and coming second in the United States. CVS has more than 100 million customers and 10,000 stores and must ensure that the medication supplies are not interrupted in any way as their patients need to have access to medication needed to manage their health and avoid costly implications.

CVS uses predictive analytics to monitor prescription drug usage and adopt supplies of medications as needed. These models were not only used to ascertain the demand and supply trends but also to manage the distribution and logistics associated with their supply chain.

The big issues that CVS faced during the pandemic are the following, as CVS' actions are mentioned.

1) Common drugs

One of the symptoms seen in patients with COVID-19 was pneumonia. The treatment in early 2020 for this was to use off-label drugs that are also used to treat the chronic condition

in patients that do not have COVID-19 (CVS Health, 2020). To treat both types of patients, CVS devised a plan to limit the number of units of off-label medicine for patients with COVID-19 pneumonia, whereas they exempted the patients from any limit rule who have been using this medicine for the treatment of chronic illnesses.

2) Volume of calls to the pharmacy and in-person visits

Due to extreme shortages of medicines in the market, there was an extremely high number of calls and in-person visits to the pharmacy. In addition to that, CVS was losing staff due to various issues related to work stress and the possibility of COVID-19 infection. CVS mitigated this issue by extending previously approved prior authorizations for medicines set to expire before June 30, 2020 (CVS Health, 2020). This reduced the number of calls and customers who used to come to extend their medications.

3) High procurement cost

The analytics team of CVS was monitoring the changing trend of medicine consumption and identified new patterns in the prescription of medicines (CVS Health, 2020). This helped them to gain a head start in combating the upcoming supply chain crisis. CVS also helped its suppliers and the market by not stockpiling medicines since it would have increased the prices of the medicines even further.

4.2.3 Pfizer's case - COVID-19 vaccine cold supply chain modeling

Simulation modeling of a COVID-19 vaccine supply chain provides insights into its dynamics and trade-offs. These insights help manufacturers understand the structural complexity of the overall system and predict the quantity and the timing of deliveries.

In this case study, anyLogistix supply chain design and simulation software was used to test different scenarios and determine maximum productivity under specific constraints. The consultancy team modeled a global supply chain with facilities located in different geographical locations:

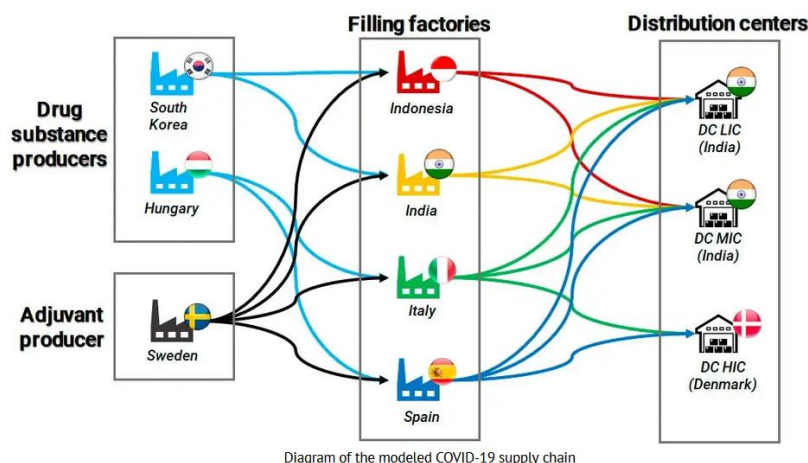


Figure 6 Diagram of the modeled COVID-19 supply chain- anyLostix. (<https://www.anylogistix.com/resources/blog/vaccine-cold-supply-chain-detailed-case-study/#p5>)

With the use of the software and supply chain modeling and simulation helped identify improvements that could accelerate the entire process of vaccine production. This is case study that relied on technology and software solutions, in order to overcome the extreme demands of the COVID19 vaccines.

4.3 Logistics and Transportation Challenges

Another very important element within the pharmaceutical supply chain are the logistics and transport of the products stocked within the chain. In terms of global distribution of medicines there is a high level of international mobility of people and goods. Therefore synchronization of freighting and other activities is critical. The impacts of COVID-19 on pharmaceutical logistics were extreme and the impacts were extreme with border closures and measures to contain the virus, including quarantines, and the collapse of the commercial airfreighting market creating extreme delay to the movement of all types of products through the pharmaceutical supply chain, including finished medicines, vaccines and biologics, active pharmaceutical ingredients, and medical and packaging supplies (Ivanov, 2020).

Delays in the logistics transport of products requiring special temperatures for storage, are additionally affected by the unstable and unpredictable nature of their storage. In attempt to maintain the appropriate temperature for these products throughout their entire transport route, additional complexities are introduced to an already disrupted distribution center (Hu

et al., 2023). Moreover, as a result of shortages in the supply chain of critical medicines to be distributed by pharmaceutical distribution companies, delays in the companies' logistics processes have generated a sharp increase in distribution costs, as well as in times for customs clearance that are unpredictable, and difficulties in reserving alternative routes and means of transportation through all the world's ports and airports (Badreldin and Atallah, 2021; Chowdhury et al., 2021; Queiroz et al., 2022).

Even the distribution of vaccines has challenges. The distribution of COVID-19 vaccines worldwide is the largest pharmaceutical distribution endeavor in the world. The distribution of such sensitive products requires a cool chain and the transporter must move these products as quickly as possible (Bown and Bollyky, 2022). Some of the approved vaccines are stored at ultra-low temperatures, which puts a lot of pressure on the cold chain and logistics systems (Hu et al., 2023). In many countries, there are not enough refrigeration systems, warehouses, and monitoring tools to maintain the specified temperatures during distribution (Ipagala et al., 2023). However, the use of monitoring and tracking technologies that are integrated into the pharmaceutical distribution system can help to monitor the distribution of temperature-sensitive products in real time and can identify any temperature excursions before they become serious problems that could affect the safety and efficacy of the product (Rajak, Khanal and Ansari, 2026).

In many countries, the distribution of the doses of vaccine that were allocated to them was not sufficient and lacked the temperature-controlled storage facilities as well as the monitoring systems required to keep the vaccine at the right temperature (Ipagala et al., 2023). Thus, the intelligent logistics of pharmaceuticals, which use digital tracking as well as monitoring in real time of the shipment, are critical to guarantee the just-in-time distribution of medicines and to prevent temperature excursions during their transportation (Rajak, Khanal and Ansari, 2026). Intermittent suspensions of transportation services due to shortages of staff, health measures, as well as arbitrary and ad-hoc customs inspections at borders around the world created serious challenges to the distribution of vaccines via several of the international logistics distribution channels (Raj et al., 2022).

However, even in the area of transportation, or rather in the various modes of it, such as maritime and ground, there were also various inefficiencies which affected the

pharmaceuticals' logistics throughout the pandemic. The congestion at the ports caused by the various means of transport, the lack of available containers, and the collapse of the international trucking, all resulted in scheduling problems with the medicines' transport as well as with the timely restocking of the various inventory locations (Chowdhury et al., 2021). Moreover, as already mentioned, the companies that adopted a long-distance sourcing policy were the ones that suffered the most as far as the time required to receive the various goods and raw materials, such as active pharmaceutical ingredients and packaging materials, was concerned (Adak, 2024).

In addition, during the pandemic's peak, the irregularity of supply-replenishment cycles and the fluctuating lead times for transportation to customers created temporary shortages of various products and affected healthcare systems (Pathy and Rahimian, 2023). Assessments of the shortages of medicines in Europe revealed also the problems of uneven distribution of health services and the fragmentation of the coordination of the transport of medicines between Member States. As a result, although there were stocks of medicines available in one region of the EU, it was not always possible to redistribute them to another region in need of them (European Court of Auditors, 2025).

Recent developments within the pharmaceutical supply chain are related to increasing logistics resilience, as already occurring in other fields (Miozza, Brunetta and Appio, 2024). This can be achieved through the use of advanced analytics to predict possible shortages, through more accurate tracking and sharing of information (through for example blockchain systems) and through the implementation of new forms of organization that make use of cloud-based platforms for process coordination (Aivazi, Bursucc and Asikainen, 2024; Rajak, Khanal and Ansari, 2026; Papalexi, Sefo and Dimopoulou, 2026). Hence, a greater flexibility with respect to possible transport modes, a more decentralized storage system and the use of new forms of digital management of the freight are the core elements of the current logistics strategies.

4.4 Shortages of APIs and Critical Drugs

The COVID-19 crisis has created shortages of Active Pharmaceutical Ingredients (APIs) and of many critical drugs used to treat this new disease. Production and distribution of finished pharmaceuticals have been affected by several factors in the media, on the stock markets and within the companies' production systems. One of the main root causes of shortages of APIs and medicines for the treatment of COVID-19 is the excess of globalization in the production and distribution of APIs as well as of finished medicines. As a result of an excess of globalization, pharmaceutical manufacturers have moved production of APIs to low-cost countries in Asia. As a result, the production of APIs in many countries has been reduced and concentrated in the hands of only a few suppliers in a very small number of countries. This has created a very fragile international market for most of the drugs. As a result of national lockdowns, of closures of manufacturing sites and of export bans decided at national level, the supply of raw materials for drug production as well as the distribution of finished medicines have been seriously affected worldwide, leading to a very serious crisis in the supply of medicines within a few days from the beginning of the crisis (Ivanov).

The supply chains for pharmaceuticals showed signs of stress and were relatively resilient during the COVID-19 pandemic. While there were instances of stock outs in local markets due to a dramatic upsurge in demand for critical products used in the acute care of patients with COVID-19 such as anesthetics, two key products, propofol and azithromycin, are analyzed in detail below. (OECD,2023)

- Propofol: As with other anesthetics that are used for procedural sedation, the propofol supply chains experienced extreme stress early on in the pandemic and some countries reported a lack of this intravenous anesthetic and had to import it from companies without a marketing authorization in the importing country. In the US there have been several years of shortages of propofol and the current ones are attributed to increased demand for other anesthetics as well as extreme shipping delays, according to the American Society of Health-System Pharmacists' (ASHP) shortage tracker.

- Azithromycin (macrolide antibiotics for various types of bacterial infections, mainly for respiratory tract infections) – The producers tried to keep up with the increased demand and almost ran out of stock. The lead time for these items increased from typical 45-90 days to 6 months. In many countries there are restrictions for the export of these types of

antibiotics (bans or by license for the local market). The exporters of these essential medicines face additional challenges to clear their export stock. They are facing approval procedures for the export and controls at the borders. These additional challenges create additional delays and additional costs for the exporters. In some countries like Canada even essential medicines are struggling to be supplied to the local market, since there is no local production and due to export restrictions.

In order to better manage the risks of the pharmaceutical supply chain, researchers and practitioners around the world studied the supply chains of manufacturers of medicines during the COVID-19 pandemic, the production processes of Active Pharmaceutical Ingredients (APIs), the transfers of these APIs to the manufacturing of finished medicines as well as the distribution of the finished medicines to the health care systems of the world and the resulting disruptions or shortages of critical drugs in hospitals, in ICUs and in other health care facilities around the world (Aivazi et al.). They studied the extremely globalized production and distribution networks of the manufacturers of medicines and they found out that also the production and distribution networks of the extremely concentrated manufacturers of medicines are not robust enough. They identified an extremely reduced number of manufacturers of APIs and a highly centralized geographical distribution of their manufacturing plants (almost exclusively outside of the countries where the finished medicines are distributed to the patients). The study of the research group of Aivazi et al. proved that even minor interruptions of the production processes of APIs may have a huge impact on the supply of finished medicines to the health care systems of the world. This results in a very fast consumption of a reduced number of critical drugs for respiratory treatments as well as for sedation, for the intensive care of patients as well as for the treatment of infectious diseases.

The majority of the available information focuses on the shortage and instability experienced by companies providing healthcare. One of the biggest challenges that almost all health care providers faced during the time of highest demand was lack of visibility into suppliers' inventory levels and production delays. The lack of visibility into key components of the health care supply chain made it very difficult for organizations to develop an effective purchasing plan and respond to an unscheduled event by locating an adequate alternative product in a timely manner. Vogler and colleagues described three common practices that

were used by organizations to cope with stock-outs during the pandemic: (1) treatment substitution; (2) stock ‘rationing’; and (3) the postponement of non-urgent (elective) surgery in the hope that required products would become available in time. The challenge of coping with stockouts during a Public Health Emergency highlights the importance of having a stock of medicines that is maintained by a stock of resilient manufacturers within the pharmaceutical manufacturing sector.

The stock management and holding inventory of the pharmaceutical products during the Covid-19 health crisis have become another critical element in the pharmaceutical supply chain. The majority of the healthcare organizations around the world and also most of the retail pharmacies were managing their stock by means of a lean inventory management and a just-in-time replenishment strategy (Pathy and Rahimian, 2023). By adopting such models, the organizations could hold minimum stocks of products and thus reduce their holding inventory costs and increase their profit margin (Queiroz et al., 2022). However, in the case of health crises that affect the entire world and also cause serious disruptions to the supply chain, such strategies fail to guarantee the organizations the stability they require to continue their ‘business as usual’ (BenAmor et al., 2022). In such cases, the organizations are left to their own devices to deal with stock shortages of critical products and to find the best alternative ways and means to manage to acquire the stocks of the other necessary health products (BenAmor et al., 2022).

Although as yet unquantified, a number of risks have been identified for health care organizations (BenAmor et al.). These include an organization’s lack of inventory reserve in the face of supply chain interruptions in manufacturing or global transportation. Once a global crisis has started, countries and health care organizations have been known to start stockpiling, which can create additional instability in the supply of critical pharmaceuticals of interest, while ‘panic buying’ by countries and health care organizations of limited supplies of the same pharmaceuticals of interest can put even greater pressure on the manufacturers of these products, who are already struggling to maintain production because of shortages of work force, transportation and of supplies of key raw and/or intermediate materials.

Technologies, tools, and strategies are being explored by pharmaceutical manufacturers, and

by governments around the world and their health-care paying agents, to minimize future shortages of medicines containing critical active pharmaceutical ingredients (APIs) that are in short supply. These strategies include: (1) the use of digital systems for real-time monitoring of supply-chain events; (2) advanced predictive analytics; and (3) integrated supply-chain visibility systems. Diversification of the supply of critical medicines is also viewed by government, manufacturers, and their regulators as necessary to reduce the risk of ‘single-source’ failure of a manufacturer — whether caused by natural disaster, civil unrest, bankruptcy or other reasons — of medicines produced in geographically distant locations (Duke-Margolis Center for Health Policy 2024).

Indeed, studies conducted during and after the COVID-19 pandemic have identified that in addition to increased regionalization of API manufacturing, increased use of APIs in finished dosage forms, stockpiling of critical medicines, greater collaboration of pharmaceutical manufacturers’ procurement activities on a global basis (within their own supply chains as well as across said supply chains), increased manufacturing flexibility in the pharmaceutical manufacturing sector, greater supply chain transparency in pharmaceuticals, stockpiling of critical medicines, and the use of buffers of inventory and of cooperative arrangements to secure supply of medicines essential for treatment and/or prevention of illness and/or injury in a globally uncertain environment, are required to increase the level of resilience in the global pharmaceutical supply chain.

4.5 Role of Digital Technologies in Crisis Management

In the context of the ongoing large number of disruptions to the flow of goods and services worldwide caused by the measures for containing the spread of the coronavirus as well as by volatile demand and supplier failures, digital technologies are becoming essential for the production and distribution of medicines of pharmaceutical companies. In the crisis management of the supply chains of these companies, blockchain, cloud computing, the Internet of Things, artificial intelligence and big data analytics increase visibility and support the visibility as well as the coordination and the forecasting capability of the companies. They also support the companies’ operations with a fast and flexible reaction. Most

pharmaceutical supply chains are still operating with the inadequate information systems which in the pre-pandemic period did not allow for a fast identification and for corresponding stock-keeping-type countermeasures of disruptions as well as for an adequate coordination of measures in a crisis (Queiroz et al., 2022).

In terms of the supply chain operations of pharmaceutical companies, the digital systems support intelligent tracking and tracing. By means of the tracking and tracing of pharmaceutical products that are to be distributed within a cold chain (i.e. require a constant temperature) in real time during their distribution worldwide, intelligent tracking and tracing has become a central component of global distribution processes of vaccines and other pharmaceutical products (Rajak, Khanal and Ansari, 2026). Many studies have dealt with the digital transformation of the pharmaceutical industry. A number of these studies in particular analyzed the role of integrated digital systems for increasing the resilience of companies from the pharmaceutical sector (Tirivangani et al., 2021). Such integrated digital systems enable pharmaceutical companies, in the event of a supply shortage, to respond quickly and to reprogram their procurement and their logistics in real time. In addition, the digital systems created platforms for the coordination of supply chains of the pharmaceutical sector. These platforms are used by manufacturers and distributors as well as by health care providers and by government authorities (Tirivangani et al., 2021). The platforms created by means of the digital systems avoid delays, which could occur as a result of a lack of information exchange in a crisis.

Artificial intelligence (AI) and predictive analytics created huge value in managing a crisis. The existing forecasting models failed to predict the extraordinary demand for a large number of medicines as well as supply disruptions. However, pharmaceutical companies started to utilize machine learning methods for predicting trends of disease spread as well as supply chain, inventory, transportation and consumption data by regions during the pandemic (Hu et al., 2023). Digital twins or simulation models were also implemented for planning and testing of potential supply chain disruptions.

The ability of companies in the pharmaceutical sector to deal with a crisis has significantly increased with the use of digital technologies. The faster detection of risks in a shorter period of time, the planning of the allocation of resources, and the coordination of

all activities in the supply chain are crucial factors for increased flexibility in the pharmaceutical market (Papalexi et al., 2026). Blockchain technology can strengthen transparency and accountability in the pharmaceutical supply chain. It enables the creation of secure and traceable records of all transactions in the supply chain in order to prevent counterfeiting and to increase confidence in the distribution of medicines (Saeed et al., 2022). However, there are also a number of challenges that have to be overcome during the digital transformation process in the pharmaceutical sector. Cybersecurity risks, problems with integrating existing systems and processes, as well as high investment costs for new digital infrastructure and corresponding international requirements with respect to legislation and regulation are just a few of the challenges that need to be addressed (Raj et al., 2022). The experiences made during the COVID-19 pandemic, however, show that digital technologies are no longer just additional tools for dealing with a crisis. Instead, they are an integral part of pharmaceutical crisis management that supports continuity, transparency, and fast changes in the supply chain.

4.6 Regulatory and Government Interventions

Government intervention and the regulation of global pharmaceutical markets has enabled the healthcare system to cope with the extreme shortages of a variety of products, including vaccines, during the COVID-19 pandemic and the resulting extreme increase in demand for vaccination. Attempts have also been made to facilitate distribution of products around the world. Governments and their regulatory bodies have had to respond very quickly to the healthcare system's needs in order to allow the distribution of essential medicines to healthcare providers and patients in a timely manner, all the main aim being to safeguard public health and safety by the implementation of very fast acting emergency processes, designed specifically for public health crises (Raj et al., 2022).

The approval processes of new manufacturers as well as of their products typically require long timeframes for approval and a large set of requirements that have to be met by the manufacturers. However, in the context of the pandemic, the production as well as the

distribution capacity of manufacturers of vaccines as well as of other pharmaceuticals increased very fast. In order to be able to distribute vaccines as well as other medical products as fast as possible to health care systems and to administer them to patients as needed, so-called Emergency authorization (EA) regulations were introduced and quickly enacted by the regulatory bodies. By means of these Emergency authorization regulations, vaccines as well as antiviral therapies as well as diagnostic devices and other medical products were able to be allowed to be distributed immediately and to be administered to patients as needed.

Rules were implemented on an emergency basis to allow for the manufacturing of, for example, medical devices and the sourcing of alternative raw materials. Manufacturers, logistics providers and storage facilities were subject to rapid inspections in order to alleviate supply chain problems with the movement and storage of pharmaceutical products worldwide (Socal, Sharfstein, & Greene, 2021). As a result of these temporary measures, pharmaceutical manufacturers were able to increase their production and maintain distribution in times of high uncertainty for global supply chains.

Government intervention affected the pharmaceutical supply chain, in particular through procurement policies. Procurement of vaccines and other essential medicines was centrally coordinated in many countries in order to ensure health care systems were equipped for the crisis. Additionally, financing was provided to allow health care systems to purchase much needed medicines. Furthermore, through advance purchase agreements (APAs) governments were able to secure the future of their vaccine budget as manufacturers increased their production. Public-private partnerships (PPPs) between government agencies, manufacturers and logistics providers enabled the quick setup of necessary health care infrastructure and of corresponding processes and supply chains for the distribution of large amounts of products.

While many of the interventions by governments have had mainly very positive effects on the supply chains of the global pharmaceutical industry, there are some negative unintended effects. For instance, export restrictions and national preference rules for medicines of essential human needs, such as life saving or severely disease causing medicines, are currently blocking the supply flows between countries and, as a consequence,

even creating new shortages of already scarce medicines in countries with a large share of imported medicines (Queiroz et al., 2022).

Learnings from the COVID-19 health crisis point to the need for international regulation frameworks for the pharmaceutical supply chain, which are flexible and sustainable in the long term and guarantee fair access to medicines in times of crisis. Companies in the pharmaceutical industry also have to be able to cope with a health crisis of this kind in the long term.

Strategies for Transforming Supply

5.1 Building Resilience and Efficiency

The main goal of pharmaceutical companies before the pandemic was to develop extremely efficient supply chains to produce and distribute their products on a global scale as efficiently and cost-effective as possible, within highly optimized supply networks. Their purchasing policies were based on lean production processes and were mostly based on a small group of main suppliers that were sourced from a central point. Their safety stock of finished medicines was minimalistic (Queiroz et al., 2022). This type of set up exposes companies to risks, especially in times of a crisis. Disruptions to the manufacturing process or to transportation and trade can have severe consequences for a highly optimized global network, for example by causing a shortage of active pharmaceutical ingredients and other essential medicines, especially when the network of suppliers is very concentrated and the inventory is minimal (Socal, Sharfstein and Greene, 2021).

During COVID 19 pandemic the global flow of the healthcare sector showed that over-optimization for cost and efficiency can lead to systemic failures in times of crisis. Thus resilience-enhancing strategies can help mitigate the impact of such disruptions on healthcare logistics systems.

1. Inventory Buffering, is one of these strategies, holding extra stock of critical items to absorb demand shocks or supply delays as safety stocks provide a buffer against uncertainty and increase short-term system responsiveness. One disadvantage of this

strategy is the increased storage costs and wastage due to expiration.

2. Multi-sourcing, or diversifying the supplier base across multiple geographic regions. A strategy that reduces the dependency on a single supplier or region. The factors that should be considered is that multi-sourcing may lead to coordination complexity, contractual risks, and potential variability in product quality [\[14\]](#).
3. Local Manufacturing, in order to minimize reliance on international transportation reducing lead times. However, this strategy can be capital-intensive and time-consuming.
4. Digital simulation models and virtual test response strategies. Similarly, demand forecasting algorithms, in order to predict future surges and proactively adjust supply levels.

Pharmaceutical Supply Chain (PSC) refers to the sum of the components of Artificial Intelligence (AI), Blockchain (BC), Cloud Computing (CC) and Real-time monitoring and tracking (RTT) (Fornari et al. 2023). Increased transparency in the processes of the pharmaceutical supply chain can support improved coordination and cooperation between manufacturers, distributors, and healthcare organizations (Hu et al. 2023). Therefore, companies that are equipped with advanced digital systems can promptly respond to any possible disruptions or threats to the continuity of the supply chain, such as transportation delays, peak demand, supply shortages, etc. (Papalexi et al. 2026).

Intelligent analytics currently supports more effective stock holding and production planning and, in doing so, prevents avoidable delays and, in general, supports better preparation for crises of all kinds (Miozza, Brunetta and Appio, 2024). As regards the resilience of pharmaceutical supply chains, the cooperation between governments and pharmaceutical organizations is gradually creating the preconditions required for improved procurement processes, for rapid changes to existing regulations and the establishment of emergency distribution structures in crisis situations.

5.2 Role of New Technologies

New technologies have recently come to the forefront of changes that are taking place within pharmaceutical supply chains around the world. The traditional model of pharmaceutical logistics has recently found itself unable to manage rapid increases in demand on an unprecedented scale, as well as managing through the normal fluctuations and uncertainties within supply chains, in relation to transportation, for example. Technologies such as artificial intelligence, blockchain, the Internet of Things (IoT), cloud computing, and predictive analytics have recently been rapidly implemented by pharmaceutical companies all over the world, in order to allow them to monitor stocks and shipments in real time around the world, in order to respond to a crisis or other developing situation as it unfolds. In order to monitor critical medicines, including vaccines, and temperature sensitive products, stock throughout the distribution network is now also being intelligently monitored, in order to be able to check the temperature of such products during their transport (Rajak, Khanal and Ansari, 2026). The research into the use of digital systems in the pharmaceutical industry, using Industry 4.0 technologies, was recently published (Papalexi et al., 2026). The findings from the research indicated that, by using digital systems, supply chains were able to quickly detect a disruption to supplies and coordinate with other parts of the supply chain, including with suppliers and customers, such as healthcare providers, in real time, thereby minimizing delay as a result of information sharing, which had not been the case in the recent COVID-19 crisis.

Intelligent monitoring systems have also been implemented by companies to monitor their distribution channels in real time. Such systems improve visibility and allow for better control over the distribution process, especially when dealing with temperature-sensitive products, such as vaccines, which require constant monitoring to maintain the cold chain during transportation (Papalexi et al., 2026). Implementing digital technologies and Industry 4.0 systems in the pharmaceutical market can facilitate the quick identification of any potential threats to the supply of medicines and allow for prompt response, as well as improved coordination between all stakeholders, i.e. suppliers, manufacturers, distributors, and healthcare providers. This, in turn, can minimize the risk of any potential delays or

information failures that may hinder a company's ability to function within the global pharmaceutical market.

Advanced technologies, such as AI and analytics, are enabling the pharmaceutical supply chain to become more resilient by improving forecasting accuracy and enabling a business to respond to rapidly changing market circumstances and make best use of available resources on an on-going basis. Historically, most pharmaceutical products have been forecasted using historical market data for that specific product, with such data typically being available for a relatively short period of time. The unprecedented increase in demand for a number of medicines, caused by the rapid spread of the COVID-19 pandemic, for example, resulted in conventional forecasting failing (Ivanov and Dolgui, 2021). Therefore, an increasing number of organizations are employing AI systems that are able to process a wide variety of data sets that could be relevant to forecasting such as for example, epidemiological data, as well as current inventory position and historical performance data for a number of processes including logistics. Such systems are able to make on-going production scheduling decisions and make best use of available resources (Hu et al., 2023). Meanwhile, Blockchain technologies are being increasingly used within the distribution chain of the pharmaceutical market in order to increase security and transparency. For example, a permanent digital record is created for each medicine that is distributed within the chain, which can subsequently be used to verify the authenticity of that medicine at any point in time. Therefore, the risk of there being distributed within the market counterfeit versions of legitimate medicines is significantly reduced and, should any instances of medicine fraud arise, those responsible will be easily identified (Saeed et al., 2022).

New technologies also support global coordination between companies which have in the past operated independently. Cloud-based platforms allow for cross-company coordination and real-time data exchange to improve supply chain management on a global scale. The goal is to better serve customers in emerging and other markets of the world (Miozza, Brunetta and Appio, 2024). In this way, digital technologies are no longer confined to optimizing processes within a company. Instead, they are a strategic tool to increase the efficiency and resilience of a company's supply chain also in times of crises and in the face of future global disruptions.

5.3 Inventory and Demand Forecasting Improvements

The disruption to consumption patterns in the healthcare market caused by the COVID-19 pandemic has recently prompted changes to the inventory management and demand forecasting systems used by the pharmaceutical companies. In the pre-pandemic period, most of the pharmaceutical companies adopted a lean inventory strategy and used a historical demand forecasting model for managing their inventory. These models were designed for managing the inventory in order to reduce the costs of storage and to make the best use of resources (Pathy and Rahimian, 2023).

On the other hand, an unexpected surge in demand for critical care drugs, such as antivirals, sedatives, vaccines and other ICU drugs that were not stocked before the pandemic, caused a rapid depletion of available stock at hospitals and the distribution centers of pharmaceutical companies around the world (Badreldin and Atallah, 2021). The lack of safety stock and the associated rigid processes for replenishing stock were found to be key factors that contributed to the resultant shortages of medicines during the pandemic. In addition, production- and distribution-related disruptions also had a significant impact on supply. To mitigate future healthcare-related supply disruptions, companies are turning to adaptive inventory management methods that consider indicators of potential supply disruptions, as well as the use of reserve stock policies that support a dynamic approach to inventory replenishment and depletion. In order to reduce their dependence on having to maintain stock of goods from around the world, companies are also turning to the use of strategic buffering and regional inventory reserves.

In the second half of the pandemic, the capabilities of pharmaceutical demand planning have significantly increased by employing more advanced forecasting technologies and digital analytics. The mentioned types of data allow for real-time monitoring of the epidemiological situation, consumption patterns in different regions of the world, as well as of the performance of logistics chains. Therefore, it is possible to apply the latest technologies such as Artificial Intelligence (AI), Predictive Analytics (PA), and digital monitoring systems integrated into a single platform for monitoring and forecasting (Hu et al., 2023). By ‘reading’ emerging peaks in demand, pharmaceutical companies are able to

adjust their production in time (Ivanov and Dolgui, 2021).

Pharmaceuticals companies have started to use new digitally integrated forecasting models to support their inventory allocation and manage the risks of stockouts in times of crisis (Papalexi et al., 2026). Many companies in the pharmaceuticals sector are also starting to use cloud-based solutions to coordinate their logistics and manage their supply chain. These new solutions can facilitate better cooperation between producers, distributors and users (e.g. hospital and clinics) and can also improve the information exchange concerning the availability of medicines and future requirements. Overall, the main strategies for managing the supply chains of companies in the pharmaceuticals industry are based on predictive models of inventory management that make maximum use of new technologies in order to achieve efficient management and be prepared to face any future health crises on a global scale.

5.4 Cost Efficiency and Risk Management

Cost efficiency and risk management in Pharmaceutical Supply Chains (PSCs) has become a highly relevant topic after the COVID-19 pandemic has revealed the risks of very cost-driven production, inventory holding and distribution. For many years, Pharmaceutical companies have operated their PSCs on the basis of lean production cost, inventory holding and distribution expenditure by means of centralized procurement, globally optimized manufacturing networks and management systems (e.g. Queiroz et al., 2022). These models lead to efficient PSCs with favorable expenditure under ‘business as usual’ conditions. However, the underlying structures and processes are not able to deliver the needed degree of resilience to deal with a wide variety of disruptions to production, logistics and trade (e.g. Ivanov, 2020).

However, in focusing on cost while neglecting adequate risk management, the pharmaceutical industry encountered major problems in handling the challenges of the COVID-19 pandemic. While most companies relied on a few major suppliers, holding only minimum stock, the production of active pharmaceutical ingredients as well as of finished

medicines frequently failed to meet demand. Failures in the production of pharmaceuticals then propagated in the highly interconnected global supply networks. For a long time, the pharmaceutical industry pursued a production, inventory and distribution concept on the basis of lean management, low costs for production, inventory and distribution as well as a globally centered production network from a single location. In normal times, such a strategy creates a lot of value for the company as well as for the customers while keeping costs at a minimum level. However, in times of failures, such a strategy does not create any value and, therefore, is not resilient (Ivanov 2020). So far, many strategies for dealing with supply chain failures in the pharmaceutical industry have been analyzed by research (BenAmor et al. 2022; Socal, Sharfstein and Greene 2021). However, more strategies are needed which, on the one hand, balance cost efficiency with appropriate risk management measures and, on the other hand, protect the long-term value of a company.

Diversification, digital visibility, adaptive inventory management and predictive analytics, collectively referred to as strategic risk management, enable supply chains to become more resilient and still remain cost efficient. Minimizing the risk of geographic concentrations and their potential disruption through sourcing, procurement and transportation strategies is increasingly becoming an important aspect of pharmaceutical companies' supply chain strategies (Duke-Margolis Center for Health Policy, 2024). Inventory management with digital visibility into the supply chain using advanced technology, such as AI, and predictive analytics (on-time forecasting) also can increase supply chain efficiency, enhance decision making under uncertainty and, therefore, deliver value to customers (Hu et al., 2023).

There are several practices that are used by organizations for managing their stock in uncertainty including stock holding locations, stock optimization, customer and supplier collaboration. For ensuring stock resilient production and cost-efficient distribution, the pharmaceutical inventory systems can be managed using adaptive stock management practices along with best practices for forecasting in real time. For addressing disruptions in supply chains, the supply chain practices need to be made resilient. For this, the various practices have been identified by researchers including that of supply chain resilience and stock resilient practices. The resilient practices in supply chain include practices for making governance structure of supply chain resilient by involving governments, manufacturers and

logistics providers. The collaborative governance is very important as it enables a quick response to a crisis and also effective utilization of resources during crisis. Thus, presently, pharmaceutical supply chain strategies are being developed to achieve efficient production and distribution by integrating practices of preparedness, risk, flexibility for long term.

Discussion and Conclusion

The study analyzes pharmaceutical supply chains and their development in the COVID-19 health crisis. During the health crisis, strategic priorities for supply chain management of pharmaceuticals changed fundamentally from a focus of operation of efficient pharmaceutical supply chains to a focus on a resilient health care system. Prior to the COVID-19 pandemic, most pharmaceutical companies pursued an efficient operation of their pharmaceutical supply chain by implementing a range of strategies, such as the use of a lean inventory management system, a focus on a central manufacturing location and a global sourcing of raw materials and excipients. In addition, most companies had adopted cost-orientated logistics structures in their supply chains. While these strategies enabled a pharmaceutical company to generate good profit margins and to keep its effective costs of operation low, they exposed the pharmaceutical supply chain of a company to a high risk of failure in a crisis, when several elements of the supply chain fail at more or less the same time (production, logistics, distribution and market demand).

The COVID-19 pandemic therefore has been a turning point for Governments, Pharmaceutical Companies and Healthcare Institutions alike to re-think the balance between efficiency and resilience in their Pharmaceutical operations. The findings of this research project have largely confirmed what already was common knowledge: having Resilient Supply Chains is no longer a desirable strategic option but has become a necessity to protect Public Health and the sustainability of Pharmaceutical operations in a world full of uncertainty and volatility.

The findings of the current study also indicate that heavy reliance of the global healthcare system on a few countries for the production of Active Pharmaceutical Ingredients (APIs), essential medicines and finished dosages has the potential to expose the system to global

supply disruptions. Production stoppages, export restrictions and lack of transportation caused by local events in different parts of the world can rapidly affect hospitals and patients all over the globe. The current study reveals that future pharmaceutical systems have to be set up in a way to reduce excessive reliance on single suppliers, i.e. countries, as well as on a few central production locations around the world.

Inventory management was another crucial component within pharmaceutical supply chains that needed a change in emphasis in order to create supply chains that were capable of coping in health crises. Just in time management and keeping minimal stock in order to reduce warehousing and storage costs for pharmaceuticals had its limitations. By keeping strategic reserves of key products for emergency health situations healthcare organizations would be able to deal with a health crisis such as the current COVID-19 pandemic whilst at the same time trying to maintain financial sustainability. By developing a range of adaptive inventory management strategies the pharmaceuticals companies and healthcare organizations can develop strategic safety stocks of key products, create regional stocks of medicines and use dynamic and replenishment stock management systems.

A number of lessons were learned by the pharmaceutical supply chain during the COVID-19 pandemic. First, a number of different digital technologies have the potential to create significant amounts of value in pharmaceutical supply chains, by increasing visibility, improving coordination, supporting forecasting and enabling a faster and more effective response to any change in demand that may occur on an extremely frequent basis. Technologies have been used across the pharmaceutical supply chain to support monitoring of potential supply chain disruptions and to manage the resultant effects on logistics and to make alterations to production and distribution, as required. Thus, technology-driven supply chain management is set to become an increasingly important area for pharmaceutical organizations.

Effective pharmaceuticals supply chains operate through collaboration and collective action by stakeholders involved in the supply chain and that mechanisms and structures need to be put in place to facilitate effective co-ordination and collective action. Such supply chains are inherently fragile so are sensitive to any disruption. Therefore, a pharmaceuticals supply chain is deemed to be resilient if it is able to function effectively through the collaboration

of stakeholders and through the use of mechanisms and structures that facilitate co-ordination and collective action in order to deal with a crisis. The study established the critical role of governments and other regulatory bodies to approve vaccines and other essential medicines during health crises, to allow for modifications to products and manufacturing processes by pharmaceutical manufacturers in order to respond to health crises in the market place. Public-private partnerships play important roles in ensuring access to health care through the supply of medicines during health crises. Strong institutional structures are needed to facilitate co-ordination and collective action between stakeholders. Such structures would also facilitate adaptive behavior by stakeholders in order to respond to a crisis. Therefore, it is highly recommended that pharmaceutical companies, governments and other stakeholders in healthcare invest in the logistics resilience of their supply chain. This can be achieved by developing flexible distribution networks that include regional warehousing, creating alternative transportation routes to minimize exposure to single modes of transportation and utilizing the latest technologies to monitor in real time all aspects of the shipment.

In summary, future pharmaceutical supply chains are likely to become more regionalized, more technologically integrated, and more risk aware. This development will not be a direct result of the lessons learned during the COVID-19 pandemic, but it will enhance the pharmaceutical system's potential in protecting global public health during a large-scale health crisis. Investment in preparedness and in digital solutions for monitoring, tracking, and sharing of information as well as in improved mechanisms of collaborative governance and in strategies for dealing with uncertainty will be needed to make the pharmaceutical supply chain future proof. The changes in the pharmaceutical supply chain are not only a result of the events during the COVID-19 pandemic, but rather part of a long-term strategic transition towards the development of more adaptive, transparent, and resilient health care distribution systems.

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