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Article

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Healthcare Supply Chain Efficacy as a Mechanism to Contain Pandemic Flare-Ups:
A South Africa Case Study

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ABSTRACT

The resilience and reliability of healthcare supply chain models were put to the test by the Corona Virus Disease 2019 (COVID-19). This study investigated the application of supply chain systems in South African healthcare institutions during the COVID-19 pandemic. A systematic literature review (SLR) was employed to explore the performance of existing supply chain systems, followed by a case study that tested and compared the acquisition and distribution of COVID-19 resources. The SLR revealed that most of the flare-ups were exacerbated by the acquisition of insufficient resources and speculative shortages as the supply chain systems got overwhelmed by the unprecedented demand. The simulation of the real-world data of South Africa revealed gaps in the distribution of resources, allocation of medical staff to administer COVID-19 vaccines, and shortages of vaccines. The study recommends development of effective contextual (SA) healthcare supply chain systems to support the containment of pandemic flare-ups. The study was conducted in South Africa and only reported data was used.

KEYWORDS

Healthcare Supply Chain, Supply Chain Concepts, Supply Chain in Healthcare Institutions, Supply Chain Models, Supply Chain Systems

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INTRODUCTION

A supply chain system enables an organization to manage its resources efficiently and view various aspects of its operations, including its dependents, from a single system (Supply Chain Council, 2022). A supply chain is a network of entities collaborating to produce a service or product and deliver it to end users (Hasibuan et al., 2018). These entities include suppliers, manufacturers, distributors, and retailers (Akkucuk, 2020; Hasibuan et al., 2018). The purpose of a supply chain system is to enable organizations to manage and utilize their resources efficiently (Hasibuan et al., 2018).

The healthcare sector is a critical section of the economy and impacts human lives (Aldrighetti et al., 2019; Francis, 2020; Sanjoy et al., 2020; Sarkis, 2020). Studies conducted and compiled during the COVID-19 pandemic revealed shortcomings in existing supply chain systems (Alexander & Hendrik, 2021; Bhaskar et al., 2020; Guiyang et al., 2020). The shortage of COVID-19 vaccines, protective clothing, and equipment made it evident that existing supply chain systems could not accommodate the demand (Bhaskar et al., 2020; Guiyang et al., 2020; Park et al., 2020). Hence, the following research question guided this study: *How can the South African healthcare supply chain become more efficient and effective in combating pandemic flare-ups?* The study aimed to understand the application of supply chain systems used in healthcare institutions to equip them to mitigate and contain pandemics such as COVID-19. In addition, improving and optimizing supply chain systems and networks saves lives; for example, Harris (2021) states that masks saved an average of 20,000 lives in South Africa in 2020. Effective healthcare supply chain systems must enable federal governments to achieve the vaccination of 70% of the total population toward obtaining herd immunity (Tetteh & Hernandez-Vargas, 2021). The current study undertook a systematic literature review to provide a scientific dimension to the study. In addition, a case study was simulated using real-world data on COVID-19 in South Africa to establish gaps and alignment, and the simulated results were compared to actual values. The following section provides the background of the study.

BACKGROUND

Many healthcare institutions, particularly in developing countries, found it exceedingly difficult to manage the pandemic, mainly due to a shortage of human and health resources, such as ventilators and nebulizers (Bhaskar et al., 2020; Park et al., 2020). In addition, funding and sourcing the vaccines proved problematic, leading to delayed vaccination in most developing countries (Department of Co-Operative Governance and Traditional Affairs, 2020; Edholm et al., 2022; Statista, 2023). The existing healthcare supply chain systems proved inefficient due to an imbalance between supply and demand (Bhaskar et al., 2020; Singh et al., 2021). The following sections elaborate on three essential concepts—the supply chain overview, supply chain operation reference (SCOR) model, and healthcare supply chain—to facilitate an understanding of the application and effectiveness of the healthcare supply chain systems implemented by the South African government.

Supply Chain Overview

A healthcare supply chain consists of several stakeholders, such as pharmaceutical drug, medical device, and vaccine manufacturers, suppliers, and distributors; care providers, such as hospitals; and patients (Queiroz et al., 2022; Rehman & Ali, 2022; Skowron-Grabowska et al., 2022). All supply chain components must be in harmony to be efficient (Queiroz et al., 2022; Supply Chain Council, 2022). The components of a supply chain vary depending on the nature of the business it services. Porter’s value chain describes the basic components of the supply chain as its primary activities: inbound logistics, operations, outbound logistics, marketing and sales, and services (Barnes, 2001). In a supply chain, these activities, along with their associated businesses and individuals, are integrated to transfer products from one place to another to the customers’ satisfaction (Bvuchete et al., 2020). Those who play a role in a supply chain include suppliers, manufacturers, distributors,

Table 1. Supply chain role-players (Supply Chain Council, 2022)

Player	Activity	Summary
Suppliers	Inbound logistics	Involves activities related to raw materials required for the manufacturing of the products. The storage and inventory management in various warehouses is also part of the inbound logistics activities.
Manufacturers	Operations	Entails the transformation of raw materials into products. During this transformation process, processes associated with manufacturing, packaging, assembling, testing, and labeling the final products must also be managed.
Distributors	Outbound logistics	The process of getting the products to wholesalers and retailers also entails temporary storage.
Retailers/wholesalers	Marketing and sales	Creating product awareness and selling the product.
Customer	Services	The end users of the products expect satisfaction with the product.

retailers/wholesalers, and customers (Supply Chain Council, 2022). Table 1 details these entities, their activities, and a summary of their descriptions.

Table 1 presents the fundamental stakeholders in a standard supply chain model; additional aspects can be added to enrich the model and increase the efficacy of the business. The following section discusses the supply chain operations reference model established by the Supply Chain Council.

Supply Chain Operations Reference Model

The supply chain operation reference model (SCOR) is a widely used supply chain model developed by the Supply Chain Council (Akkucuk, 2020; Anas et al., 2018; Pulansari & Putri, 2020). The SCOR model comprises a framework joining supply chain performance metrics, processes, practices, and people into a unified structure that is easy to monitor and manage (Akkucuk, 2020; Supply Chain Council, 2022). The SCOR model consists of four process levels, as summarized in Table 2, which depicts the levels, applications, and related processes.

Level 1 presents the scope description of the five fundamental processes: plan, source, make, deliver, and return. Level 2 defines the strategies required to ensure the realization of the aspects in Level 1. Level 3 provides and prescribes the processes necessary to meet and support the strategies defined in Level 2. Lastly, Level 4 describes the implementation of these processes. Organizations can develop personalized Level 4 processes based on their setups and requirements.

SCOR is a management tool designed to improve, communicate, and address supply chain management decisions with the organization’s customers and suppliers (Akkucuk, 2020). The SCOR model integrates customer needs and organizational processes throughout a product’s journey from manufacturing to the finished product (Pulansari & Putri, 2020). In summary, the SCOR model enables the processes within the supply chain and provides a basis for improving, enhancing, and ensuring efficient supply chain processes (Supply Chain Council, 2022). The following section discusses healthcare supply chain models.

Healthcare Supply Chain Models

According to the World Health Organization (WHO), the total amount of money spent on healthcare as a percentage of global domestic product (GDP) has reached an average of 10% of the GDP (World Health Organization, 2019). This represents a 3.9% annual increase from 2000 to 2017, compared to a 3.0% increase in economic growth. Several factors drive healthcare costs, including a high incidence of chronic diseases, such as cardiovascular disease, diabetes, and cancers (Lopes de Sousa et al., 2020; World Health Organization, 2019), as well as inefficient supply chains in the health sector

Table 2. SCOR model overview (adapted from Supply Chain Council, 2022)

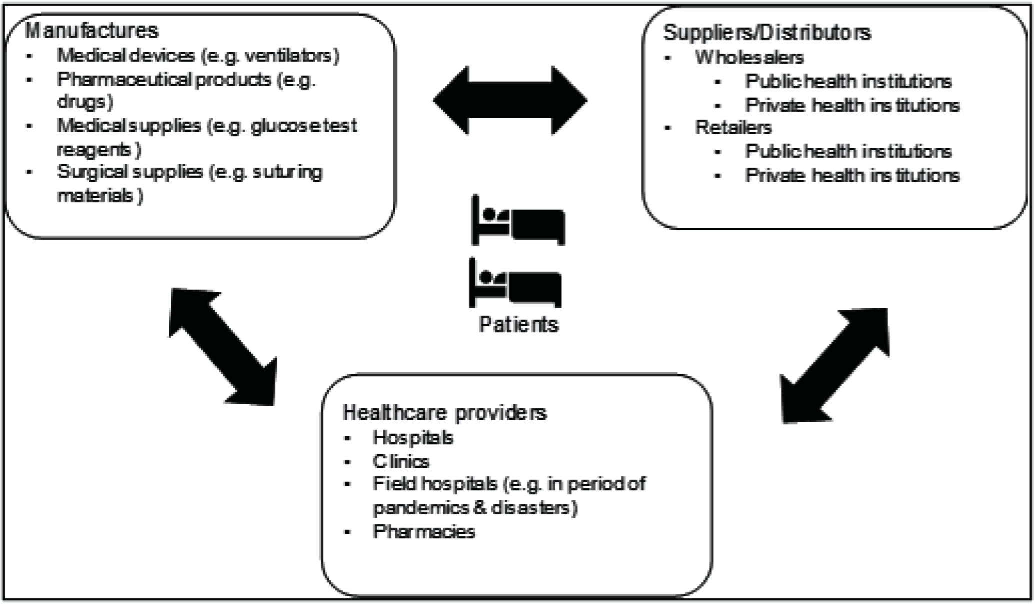
Level	Application	Processes
1	Level 1 provides the scope description and high-level outline of the supply chain comprising five processes.	• Plan • Source • Make • Delivery • Return
2	Level 2 presents strategies for the Level 1 processes. The SCOR Level 2 processes position and determine the supply chain strategy the organization should adopt. There are twenty-six processes in SCOR Level 2.	Examples • Make to stock • Make to order • Engineer to order
3	Level 3 describes the steps for executing the Level 2 processes. The sequence of execution influences the performance and overall supply chain. This level contains 185 processes.	Examples • Schedule production activities • Issue product • Produce and test • Package • Stage • Dispose of waste • Release product
4	Level 4 describes industry-specific activities essential to performing the Level 3 processes. In addition, Level 4 describes how to implement a process. SCOR does not provide a Level 4 process; the organization would have to develop its own.	Examples • Print pick list • Pick items • Deliver bin

(World Health Organization, 2021). The COVID-19 pandemic recently exacerbated already-spiraling healthcare costs because of the increased demand for personal protective equipment (PPE), specialized medical equipment, hand sanitizers, and vaccines (Kaye et al., 2021). Effective and efficient healthcare supply chain management (HSCM) could reduce overall healthcare costs and improve the quality of healthcare services provided to patients (Mathur et al., 2018). The main components of the healthcare supply chain (HSC) include the manufacturers of healthcare products, purchasers or distributors, and healthcare providers, while patients are the primary recipients of healthcare services at the center of the supply chain (International Monetary Fund, 2022; World Health Organization, 2019). Figure 1 illustrates the HSC components.

The delivery of safe, quality healthcare services by healthcare professionals relies on the effectiveness and efficiency of HSCM (Mathur et al., 2018). Healthcare professionals are constrained in performing their duties due to a lack of adequate resources, particularly in developing countries (Malakoane et al., 2020). The lack of healthcare resourcing has contributed to many people dying of treatable diseases (Mathur et al., 2018), while other patients have become permanently disabled (Polater & Demirdogen, 2018). An effective HSC is essential to the public healthcare sector, which is often the only way for the vast majority of citizens to access healthcare services, particularly in developing countries like South Africa (Malakoane et al., 2020). According to Bvuchete et al. (2020), HSCM can be approached from one of two strategic perspectives, namely the "push" and "pull" strategies:

- A push HSCM strategy is primarily driven by demand forecasts. One shortcoming of a forecast-driven HSCM is poor accuracy, which can lead to "stock-outs." Manufacturers often compensate for inaccurate demand forecasts by increasing their "safety stock" levels. This practice can drive increases in overall supply chain costs.
- A pull HSCM strategy is driven by actual customers, such as healthcare professionals, or by patients' demands. This strategy enables manufacturers to monitor the true consumption of

Figure 1. Components of the healthcare supply chain (adapted from Smith et al., 2012)



medical supplies. A pull strategy relies on the timely flow of demand information from the customer to other stakeholders in the HSC.

Bvuchete et al. (2020) hold that adopting a pull HSCM strategy could enable the public health sector in particular to deliver on its mandate of providing effective and efficient healthcare services to most of the population. The pull strategy ensures flexibility in the HSCM process so that medical supplies can be rerouted to areas of high demand. This strategy is ideal in periods of pandemics or disasters (Polater & Demirdogen, 2018), during which demand can vary from one region to another. Chronic disease conditions often require the use of drugs as part of a holistic treatment plan; the HSCM process must be efficient to reduce overall healthcare costs. The next section discusses the methodology employed in this study.

METHODOLOGY

The study was conducted in two phases. The first phase entailed the execution of a systematic literature review (SLR); the second phase involved a case study of a supply chain simulation for South Africa. In the following sections, we present an overview of the research strategies.

Systematic Literature Review

In the first step of this research project, we executed an SLR, which aims to consolidate existing knowledge related to phenomenon of interest (Siddaway et al., 2019). An SLR supports the identification and assessment of relevant primary studies in the extant literature that might address a specific research question. This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2015) and the SLR process outlined by Kitchenham (2004).

The search string "supply chain" AND "transport planning" OR "logistics" was used to execute searches on three electronic databases, namely ProQuest, Springer, and ScienceDirect, to identify the relevant primary studies. We selected these electronic databases because they have a high impact factor and are accessible from our institutional repository. The search yielded 544 papers, as presented in Table 3.

We filtered the papers by date, extracting those published between 2015 and 2021. Due to advances in supply chain models, we limited the period to recently published papers, in particular those published in the past five years. Only peer-reviewed papers published in English were eligible for consideration. Additionally, we removed duplicates, resulting in a total of 477 articles. We reviewed the article titles and abstracts to evaluate whether a paper was indeed related to the research objectives.

This review resulted in a total of 131 papers considered for the quality assessment, informed by the following questions:

- To what extent does the paper explain the nodes, role-players, entities, and flows in the SCM?
- To what extent is the paper focused on SCM in emergencies?
- Is the methodology of the paper clearly described and justified?

A scoring system ranging between 0 (not at all), 0.5 (partially), and 1 (fully) was applied based on the quality assessment questions against which we evaluated the papers. Papers scoring a total of 1.5 or more were included for full analysis. Figure 2 presents the applied SLR study selection process.

Figure 2 presents the PRISMA summary of the SLR study selection adopted for this study, resulting in a final corpus of 70 articles analyzed using Leximancer software, version 4.51. Leximancer is a software solution that applies unsupervised Bayesian decision theory and machine learning to analyze and visualize a corpus of work (Smith & Humphreys, 2006). Leximancer analysis and visualization are based on semantic and relational information extraction (Smith & Humphreys, 2006). The following section discusses the case study undertaken to support this research.

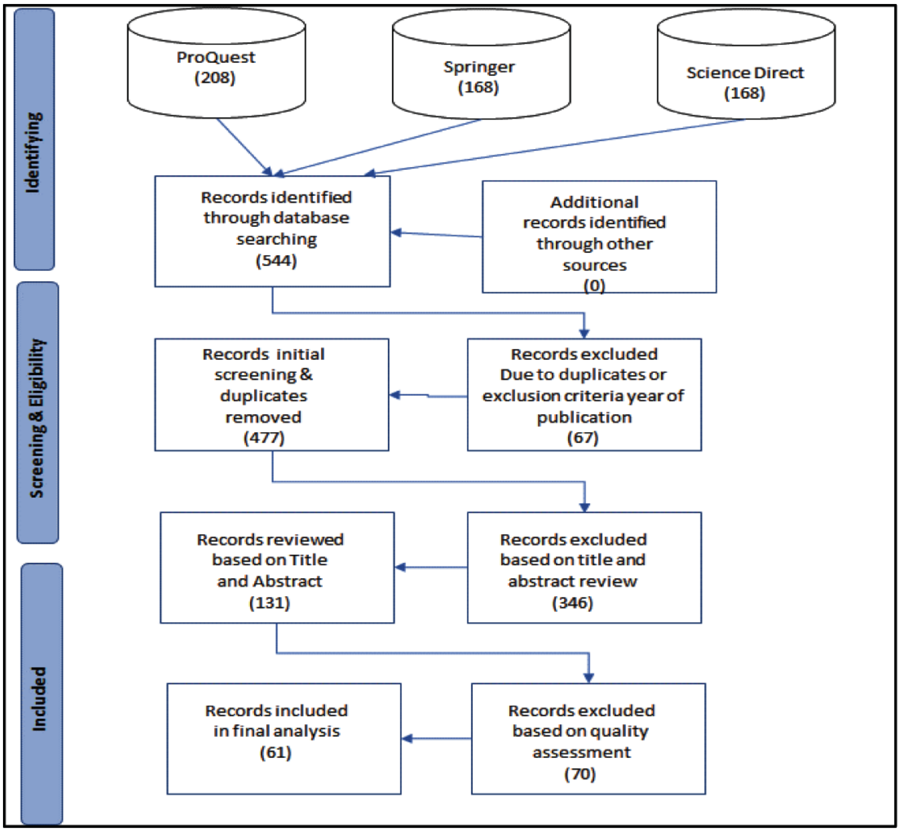
The Case Study: South Africa

The case study, representing the second step of the research approach, was conducted in South Africa (SA), an African country with a population of 60.6 million (Statista, 2022). South Africa has nine provinces: Eastern Cape, Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, Northern Cape, Western Cape, and North West. The country has an established private and public healthcare supply chain serving the population. Private healthcare institutions are owned and managed by private institutions, while state entities manage public healthcare institutions. Around 80% of the population relies on the public healthcare system, while about 20% access private healthcare. When the World Health Organization (WHO[1]) declared COVID-19 a pandemic, South Africa reacted promptly by imposing a countrywide lockdown and formulating a comprehensive public health response. The South African president declared a state of disaster under the Disaster Management Act, authorizing extraordinary statutory actions to contain the impact of the pandemic in SA.

Table 3. SLR search results

Database	Number of Articles
ProQuest	208
Springer	168
ScienceDirect	168
Total	**544**

Figure 2. Identification of primary studies for analysis



This study utilized the Software Advice website [2] to select a supply chain system. This website is a business database engine designed for evaluating enterprise software applications (Maramba et al., 2023). We applied the search phrase "supply chain system in healthcare" to the search, returning 91 applications, from which we chose the top five. We then assessed the top five applications by testing the trial versions. The costs associated with the software were also considered since the team needed to purchase a complete software suite to conduct a comprehensive evaluation. We opted for the *AnyLogistix* supply chain system software from the AnyLogic [3]Company. This software offers an affordable license model, ideal for an academic institution.

The three datasets described in Table 4 were imported into AnyLogistix software to perform a real-world simulation. Table 4 summarizes the data types and sources.

Table 4. Data sources and types

Data Source	Data Type	Summary
Statistics South Africa [https://www.statssa.gov.za/]	Population distribution data of South Africa	The SA population in June 2021
Healthcare wholesalers	Healthcare supplies distribution data in quantities and costs	Data provided by an international healthcare data provider for 2021
The Department of Health	COVID-19, tests, positives, recoveries, deaths in statistics	COVID-19 data statistics for 2021

The obtained healthcare data were anonymized and summarized to remove personal and organizational identity-revealing data, adhere to South African data regulations, and conform to the Protection of Personal Information (POPI) Act of 2013 (https://popia.co.za/). In the context of such research, the POPI Act strives "to promote the protection of personal information processed by public and private bodies." The following section discusses the findings from the SLR and the case study.

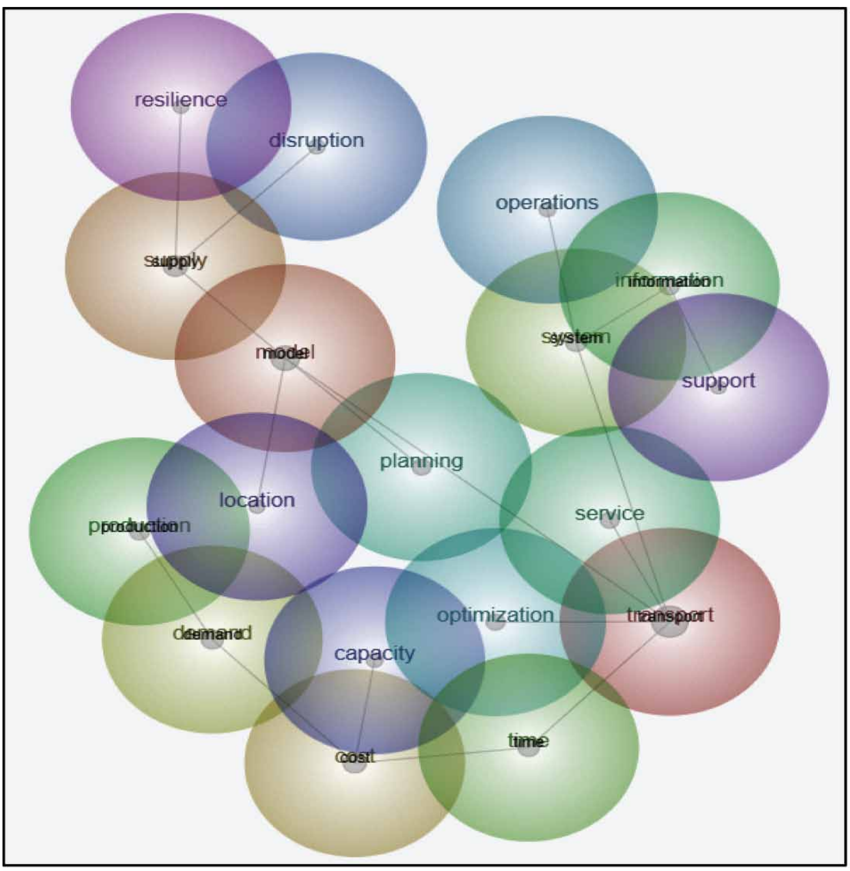
RESULTS

The first part of this section discusses the findings derived from the SLR, while the second part discusses the findings of the SA case study.

Systematic Literature Review Findings

The findings obtained from Step 1 of the research study, the SLR, were based on content analysis of the 70 selected studies analyzed with Leximancer software. The analysis of the studies resulted in a high-level summary of themes and concepts related to the supply chain concept map presented in Figure 3.

Figure 3. Overview of themes and concepts of supply chain map based on SLR corpus (Source: Leximancer visualization)



The theme and concept map in Figure 3 portrays a single connection network map. Figure 3 presents the major concepts and themes from the 70 selected and analyzed studies. The concept map presents the critical aspects of a supply chain: production, demand, cost, capacity, time, optimization, transport, service, location, planning, network/model, supply resilience, disruption, operations, systems, information, and support. Through text analysis of each theme presented, the concept map highlights the need for a supply chain to be resilient to sustain disruptions. Transport requires optimization, time management, and properly defined networks and routes. The concept map reveals that production requires demand, cost, and capacity to operate effectively. It further reveals that adopting data and information has become vital in modern supply chain models.

Figure 4 presents a zoomed-in theme and concept map demonstrating the critical aspects required for effective optimization to enable institutions to achieve the real benefits of an efficient supply chain model. This represents an essential aspect, particularly during a pandemic or disaster.

The initial analysis extracted from the theme and concept map produced 100 themes. An analysis of these 100 themes found that thirty-one were general words not sufficiently relevant to be considered themes, such as views, use, apply, and research. A further review was undertaken with the remaining 69 themes; themes such as transport and transportation were combined or merged, resulting in a final list of 27 themes, as presented in Figure 4. Table 5 presents the top 10 detailed themes and concepts, depicting themes, hits (number of times a concept occurs), and concepts.

The reviewed studies exhibit consensus on the importance of themes such as networks, transport, information, optimization, system, production, model, cost, and data in formulating a supply chain.

Figure 4. Supply chain optimization themes and concepts for healthcare (Source: Leximancer visualization)

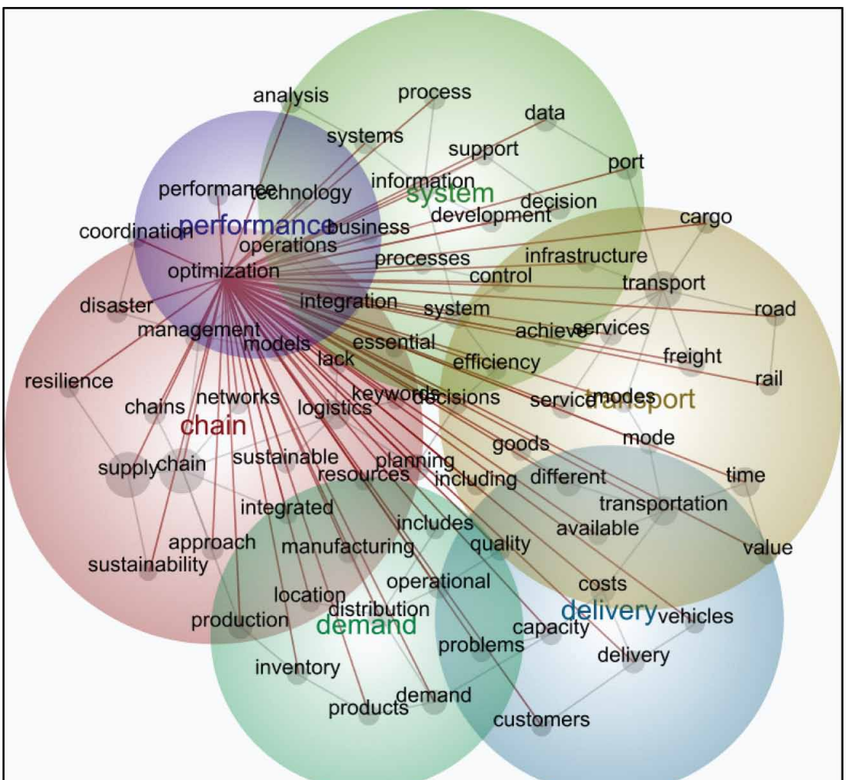


Table 5. Supply chain concepts used in healthcare services (Source: Themes and concepts generated from Leximancer software)

Themes	Hits	Concepts
Networks	8318	network, system, logistics, planning, based, information, delivery, decision
Transport	6813	transportation, services, freight, intermodal, order, optimization, time
Model	6751	model, distribution, approach, production, risk, design
Cost	5494	cost, demand, production, capacity, location
Chain	4418	chain, supply, management, capacity, delivery
System	4018	systems, information, operations, support
Information	1909	data, operations
Vehicle	1593	vehicle, deliver, return
Delivery	1223	delivery, distribution
Optimization	1186	transport, cost, system, supply chain
Production	1005	products, inventory, location, demand, create

The results in Table 5 reveal that networks (8318) are at the top of the list of themes, followed by transport (6813), model (6751), cost (5494), chain (4418), information (1909), vehicle (1593), and delivery (1223). Notably, the networks' theme enables various concepts and models used in healthcare services because the supply chain for manufactured medical suppliers could be harnessed to deliver supplies to the various healthcare systems.

Systematic Literature Review: Findings for South Africa

We reviewed the research papers in the corpus from studies that were specifically conducted in South Africa. These studies indicated that the healthcare sector does not fully utilize the complete supply chain management systems, which their authors attribute to high costs and the mismanagement of resources (Anas et al., 2018; Bvuchete et al., 2018). The current supply chain in the SA healthcare sector uses a traditional approach in which manufacturers of drugs and medical consumables dispense to approved suppliers, who then provide the products to retailers, such as private and public pharmacies and hospitals (Bvuchete et al., 2018). An overview of the current supply chain in the SA healthcare industry is depicted in Figure 5.

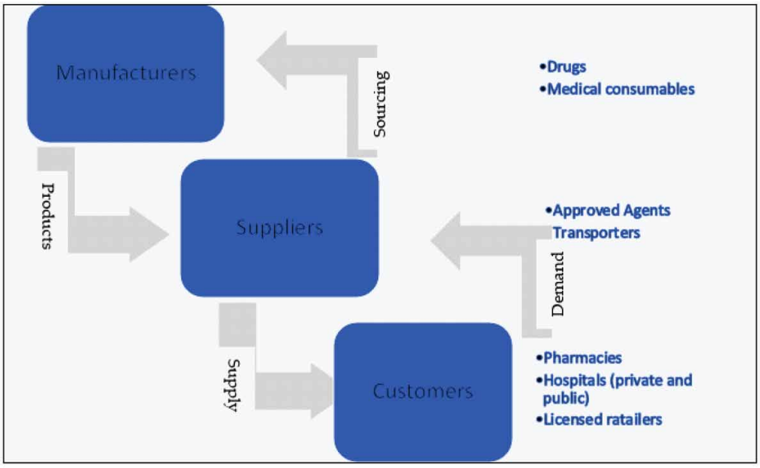
Figure 5 depicts the supply chain initiated by customer demand, which triggers suppliers to source the products from manufacturers. The manufacturers respond by producing and providing the products to suppliers, who stock them in their warehouses at distribution centers. The products are then transported to designated collection and delivery points from which customers and retailers can collect them.

Supply and demand processes are prone to congestion (Bvuchete et al., 2018; Mathur et al., 2018), including the delay and shortage of particular drugs. Treating known diseases does not require the fast manufacturing of necessary drugs (Schellack et al., 2011). The procedure to approve, source, and obtain licenses for manufacturing drugs is laborious (Liu et al., 2020), which can be disastrous when nations are confronted with pandemics. We simulated the existing South African healthcare supply chain using AnyLogistix simulation and application software to conceptualize the themes and concepts identified in Table 5. The next section discusses the case study's findings based on the use of AnyLogistix software.

Case Study Findings: AnyLogistix

The South African case study was conducted based on simulation data obtained from multiple role-players (see Table 4). Pandemics pose a complex challenge to federal governments; therefore, it is

Figure 5. Overview of South African healthcare supply chain



prudent to ensure that critical institutions are equipped with a resilient, robust, well-integrated supply chain (Arafatur et al., 2020). We used the AnyLogistix software to simulate a real-world scenario, starting with loading the population distribution of South Africa by province. Table 6 depicts the provincial population loaded onto the application by province and population.

The healthcare dataset imported into the AnyLogistix application comprised all healthcare products, including drugs, vaccines, protective clothing, equipment, and detergents. We selected the transactional data that contained COVID-19 vaccines, exploring this option to gain insights into the distribution of the COVID-19 vaccines. The acquired data included SA postal codes, enabling the geographical positioning of pharmacies nationwide. In addition, the postal codes were mapped to geographical positioning system (GPS) coordinates to perform real-life simulations.

To effectively distribute the COVID-19 vaccines to all parts of the country, we conducted a series of simulations using the available data to create a digital supply chain. The simulation enabled us to determine the following: the number of vehicles required to distribute the vaccines, the ideal number of vaccination sites, the number of distribution centers and warehouses, the distance vehicles would need

Table 6. South African population by province (Source: Statistics South Africa, 2021)

Province	Population
KwaZulu-Natal	11,538,325
North West	4,186,984
Northern Cape	1,308,734
Western Cape	7,212,142
Eastern Cape	6,676,691
Limpopo	5,941,439
Gauteng	16,098,571
Mpumalanga	4,720,497
Free State	2,921,611
Total	**60,604,994**

to travel, the demand for the vaccines in figures, the costs of purchasing and transporting vaccines, the number of staff required to vaccinate the whole country, prediction analytics, and accurate reporting.

COVID-19 vaccines must be stored at specific and continuously maintained temperature levels. Hence, the vaccines must be transported safely and securely; long road trips are not ideal. In South Africa, each province has an airport; as such, vaccines could be delivered to each province by cargo airliners before distribution to their final destinations using the road network.

We chose to use pharmacies as vaccination sites since they were already equipped to store COVID-19 vaccines safely and securely. We identified the number of licensed and authorized pharmacies possessing facilities for temporarily storing COVID-19 vaccines from the healthcare data. Table 7 outlines the distribution of pharmacies by province, showing the province, its population, and the number of pharmacies.

The COVID-19 infection data were loaded as a percentage of the population because the data did not include GPS coordinates. The COVID-19 infection data contained the number of tests conducted, the number of positive tests, the number of recoveries, the number of deaths, and the number of admissions per week and province. This dataset and the population data were loaded to create a digital twin representation.

After all required data had been loaded into the AnyLogistix supply chain software, the following parameters were set:

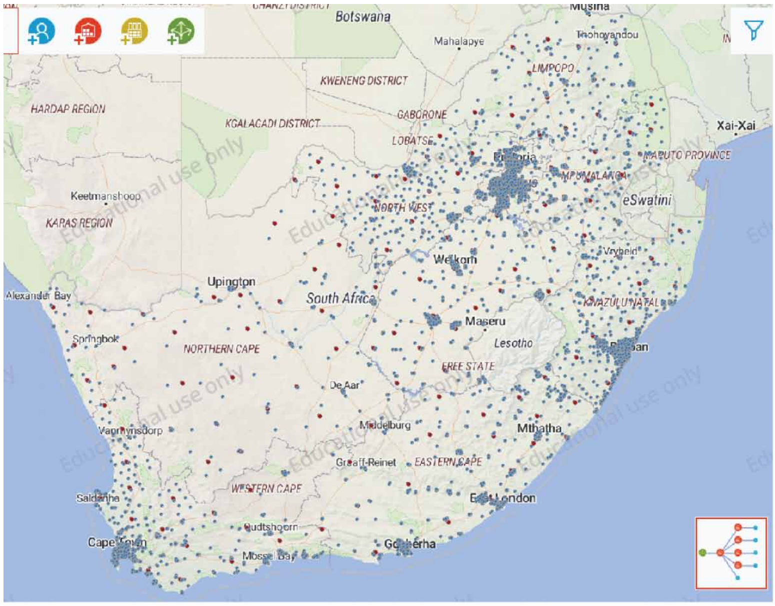
- Each vehicle should travel no more than 80 kilometers when transporting COVID-19 vaccines from warehouses to distribution centers.
- Each vehicle should travel no more than 50 kilometers when transporting COVID-19 vaccines from distribution centers to pharmacies (vaccination sites).
- Each vehicle should carry a maximum of 300 vaccines per trip.
- All 1,150 pharmacies provided through the data were loaded to provide a visual map.
- Each pharmacy/vaccination site used a maximum of 150 vaccines every day.
- Each vaccination site should have an average of six staff, including security personnel.

Figure 6 depicts the distribution of pharmacies (blue dots) and distribution centers (red dots) required to service the SA population using the current pharmacies as vaccination sites to manage the COVID-19 pandemic.

Table 7. Province, population, and pharmacies distribution in South Africa (Source: Statistical South Africa, Healthcare Wholesalers Data)

Province	Population	Number of Pharmacies
KwaZulu-Natal	11,538,325	121
North West	4,186,984	66
Northern Cape	1,308,734	272
Western Cape	7,212,142	119
Eastern Cape	6,676,691	53
Limpopo	5,941,439	72
Gauteng	16,098,571	266
Mpumalanga	4,720,497	42
Free State	2,921,611	139
Total	**60,604,994**	**1,150**

Figure 6. COVID-19 vaccination sites and distribution centers (Source: Authors' *AnyLogistix* visualization)



South Africa mainly sourced COVID-19 vaccines from four countries: the United States of America, the United Kingdom, India, and China. Figure 7 shows the distribution of the supplying countries mapped to each province.

The simulation was run to model a supply chain for twelve months. Using the data in Table 7, the simulation produced COVID-19 vaccines that would enable vaccinating the whole population and the cargo airline trips required to bring those vaccines to SA. Figure 8 shows the predicted requisite COVID-19 vaccines and cargo airline trips per month.

Figure 7. COVID-19 vaccine sourcing (Source: Authors' *AnyLogistix* visualization)

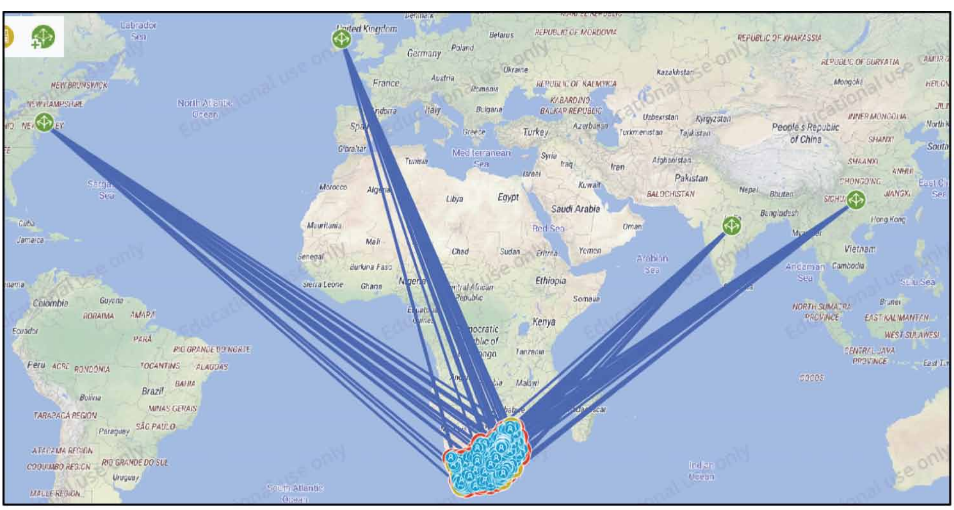


Figure 8. Vaccines and cargo airliner trips per month

Covid 19 Vaccines per month

	Statistics name	Period	Value	Unit
1	Demand Recei...	Month 01	4,554,000	pcs
2	Demand Recei...	Month 02	3,726,000	pcs
3	Demand Recei...	Month 03	4,140,000	pcs
4	Demand Recei...	Month 04	4,140,000	pcs
5	Demand Recei...	Month 05	4,554,000	pcs
6	Demand Recei...	Month 06	4,140,000	pcs
7	Demand Recei...	Month 07	4,140,000	pcs
8	Demand Recei...	Month 08	4,140,000	pcs
9	Demand Recei...	Month 09	4,140,000	pcs
10	Demand Recei...	Month 10	4,554,000	pcs
11	Demand Recei...	Month 11	4,140,000	pcs
12	Demand Recei...	Month 12	4,140,000	pcs

Covid-19 Vaccines required per month

Cargo Airliner (Number of Trips)

	Statistics name	Period	Value	Unit
1	Max Number o...	Month 01	68	Vehicle
2	Max Number o...	Month 02	68	Vehicle
3	Max Number o...	Month 03	68	Vehicle
4	Max Number o...	Month 04	68	Vehicle
5	Max Number o...	Month 05	68	Vehicle
6	Max Number o...	Month 06	68	Vehicle
7	Max Number o...	Month 07	68	Vehicle
8	Max Number o...	Month 08	68	Vehicle
9	Max Number o...	Month 09	68	Vehicle
10	Max Number o...	Month 10	68	Vehicle
11	Max Number o...	Month 11	68	Vehicle
12	Max Number o...	Month 12	68	Vehicle

Cargo Airliner Trips per month

Sixty-eight cargo airliner trips would be required monthly to meet the demand and deliver the requisite single doses of COVID-19 vaccines. This measure allowed for utilizing sources to ensure a continuous supply of COVID-19 vaccines.

Once the vaccines have been delivered from overseas suppliers, they would be transported to provincial warehouses, where they would be stored at the appropriate temperatures while awaiting further distribution. The vaccines would then be transported using refrigerated vehicles to maintain the vaccines under the recommended conditions. Vaccines would be collected from provincial warehouses for dissemination to local distribution centers and from distribution centers to vaccination sites (pharmacies) using smaller and faster vehicles (for example, a Nissan NP 300) fitted with refrigerators. Nationwide, 1,005 vehicles would be required monthly to meet this demand. Figure 9 details the required number of vehicles and the total distance to be traveled.

The delivery distance traveled per month enables fuel procurement, budgeting, and planning. This focus is critical as it involves human resources planning, which is also susceptible during a pandemic.

The model simulated that achieving an equal distribution of vaccines for South Africa would require 12,727 vaccination points. Table 8 below details the breakdown provided by the simulation. Using the (then) current pharmacies as vaccination sites was ideal; however, more vaccination sites would be required to meet the demand in the shortest possible timeframe. Table 8 compares the current number of pharmacies to the ideal number needed to contain future pandemics.

Figure 9. Delivery vehicles and distance traveled per month (Source: Authors' *AnyLogistix* data)

Number of Delivery Vehicles (Nissan NP 300)

	Statistics name	Period	Value	Unit
1	Max Number o...	Month 01	1,005	Vehicle
2	Max Number o...	Month 02	1,005	Vehicle
3	Max Number o...	Month 03	1,005	Vehicle
4	Max Number o...	Month 04	1,005	Vehicle
5	Max Number o...	Month 05	1,005	Vehicle
6	Max Number o...	Month 06	1,005	Vehicle
7	Max Number o...	Month 07	1,005	Vehicle
8	Max Number o...	Month 08	1,005	Vehicle
9	Max Number o...	Month 09	1,005	Vehicle
10	Max Number o...	Month 10	1,005	Vehicle
11	Max Number o...	Month 11	1,005	Vehicle
12	Max Number o...	Month 12	1,005	Vehicle

Delivery vehicles required per month

Delivery Traveled Distance per Month

	Statistics name	Period	Value	Unit
1	Traveled Dista...	Month 01	607,462.505	km
2	Traveled Dista...	Month 02	497,014.777	km
3	Traveled Dista...	Month 03	552,238.641	km
4	Traveled Dista...	Month 04	552,238.641	km
5	Traveled Dista...	Month 05	607,462.505	km
6	Traveled Dista...	Month 06	552,238.641	km
7	Traveled Dista...	Month 07	552,238.641	km
8	Traveled Dista...	Month 08	552,238.641	km
9	Traveled Dista...	Month 09	552,238.641	km
10	Traveled Dista...	Month 10	607,462.505	km
11	Traveled Dista...	Month 11	552,238.641	km
12	Traveled Dista...	Month 12	552,238.641	km

Delivery distance travelled per month

Table 8. Vaccination sites: Current versus proposed (Source: Authors' *AnyLogistix* data)

Delivery Region	Population	Current Pharmacies	Proposed Pharmacies
KwaZulu-Natal	11,538,325	121	2,423
North West	4,186,984	66	879
Northern Cape	1,308,734	272	275
Western Cape	7,212,142	119	1,515
Eastern Cape	6,676,691	53	1,402
Limpopo	5,941,439	72	1,248
Gauteng	16,098,571	266	3,381
Mpumalanga	4,720,497	42	991
Free State	2,921,611	139	614
Total	**60,604,994**	**1,150**	**12,727**

The values representing current pharmacies presented in Table 8 are based on purchased data and were assumed to be accurate; hence, no further investigation or verification was undertaken. The country would need to increase the current number of pharmacies by at least a power of ten to contain a pandemic such as COVID-19.

Figure 10 indicates the ideal vaccination sites (blue), the distribution centers (red), and the road network SA could adopt in a future pandemic or disaster.

The red circles represent the distribution centers with storage facilities, while the blue circles represent the proposed vaccination sites, as reflected in Table 8.

Planning the human resources aspect is crucial during a pandemic since those same human resources might become infected. Healthcare staff shortages represent a global problem (Bhaskar et

Figure 10. Distribution network

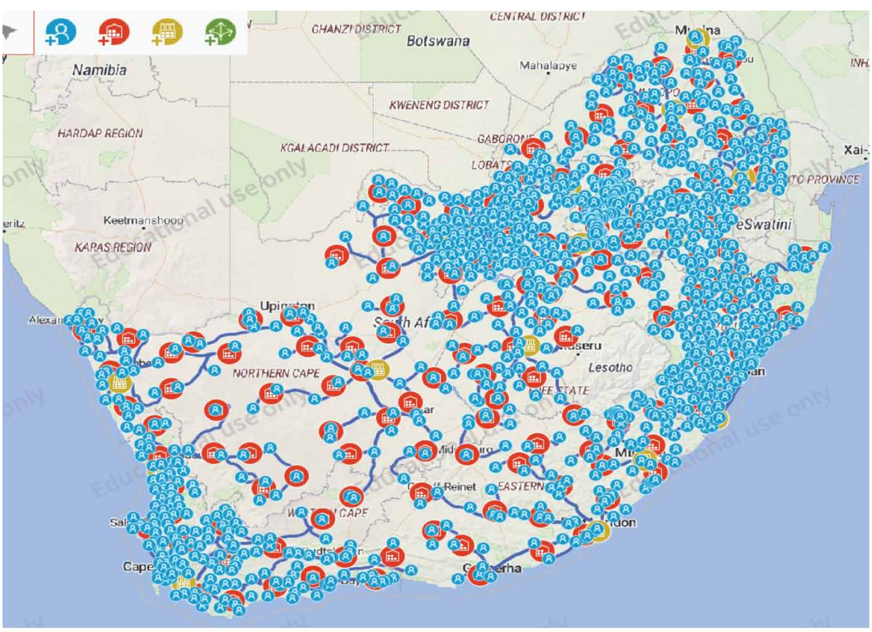


Table 9. Staff complement (Source: Authors' *AnyLogistix* data)

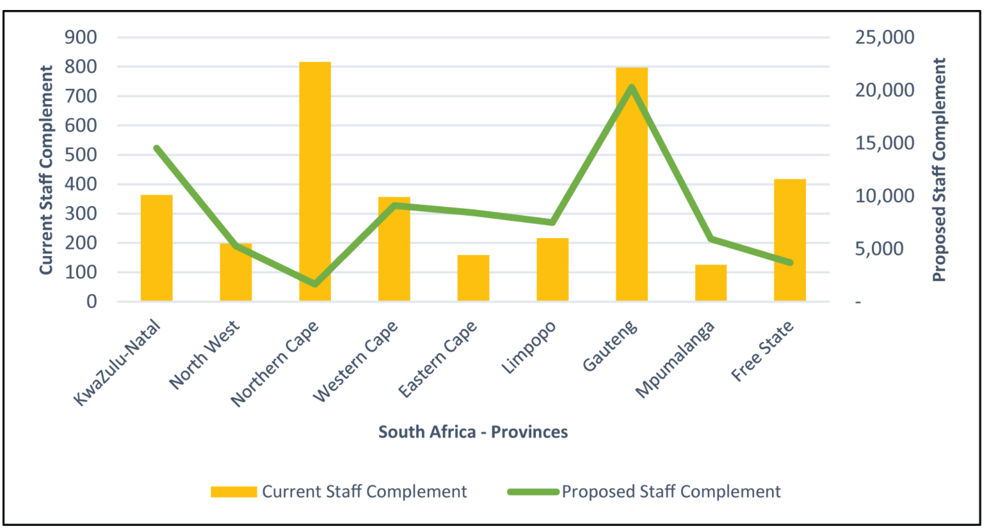
Province	Population	Current Vaccination Sites	Average—Staff Current Complement	Proposed Pharmacies	Proposed Staff Complement
KwaZulu-Natal	11,538,325	121	363	2,423	14,538
North West	4,186,984	66	198	879	5,274
Northern Cape	1,308,734	272	816	275	1,650
Western Cape	7,212,142	119	357	1,515	9,090
Eastern Cape	6,676,691	53	159	1,402	8,412
Limpopo	5,941,439	72	216	1,248	7,488
Gauteng	16,098,571	266	798	3,381	20,286
Mpumalanga	4,720,497	42	126	991	5,946
Free State	2,921,611	139	417	614	3,684
Total	**60,604,994**	**1,150**	**3,450**	**12,727**	**76,368**

al., 2020) that requires proper planning. Table 9 shows the staff complement per province, population, current vaccination sites, the average current staff complement, proposed vaccination sites, and the proposed staff complement.

The current staff distribution comprises three resources per vaccination site, which leaves staff exhausted and overworked (Bhaskar et al., 2020; Fathuse et al., 2023; Osman et al., 2021). The ideal staff complement in the future should be six resources per site to balance the workload and prevent staff from becoming overworked (Fathuse et al., 2023). A supply chain model that can predict all these aspects would enable informed decision-making during a pandemic. Figure 11 depicts the discrepancy between the current and proposed staff complement.

Supply chain models play a significant role in all sectors of the economy; however, the current resources, infrastructure, and systems showed they were neither resilient nor robust and were

Figure 11. Current and proposed staff complement



susceptible to disruptions caused by the COVID-19 pandemic (Akkucuk, 2020; World Health Organization, 2021). The supply chain system used in private and public healthcare institutions must be improved, integrated, and data-driven to be agile and flexible, especially when dealing with pandemics and disasters (Kamble & Gunasekaran, 2020). The next section presents the proposed ideal supply chain model for South African public and private healthcare institutions.

The Proposed Supply Chain Model

The healthcare supply chain in South Africa must be reviewed, enhanced, and optimized for a pandemic to effectively distribute the required medical supplies to all locations, particularly in COVID-19 flashpoints (Handfield et al., 2020). Based on integrating all datasets—the SLR findings, the visualization created by the Leximancer themes and concepts, and the simulation outcomes of real-world data—a conceptual view of the factors that impact an effective healthcare supply chain is proposed in Figure 12.

An analysis of the reviewed existing literature revealed current challenges in South African supply chain models (Edholm et al., 2022; Harris, 2021). These challenges hinder the sourcing, distribution, and production of COVID-19 vaccines (Bhaskar et al., 2020; Park et al., 2020). Figure 12 outlines supply chain problems or bottlenecks, such as delayed deliveries, difficulty accessing remote locations, the shortage of medical supplies, and poor distribution network supplies. A comprehensive supply chain can enable the administration of stakeholders such as drug manufacturers, suppliers, approved storage facilities, approved transporters, and end users (Harris, 2021).

A supply chain should enable the analysis of requirements, such as demand based on purchase real-time data, mode of transport based on logistics data, and simulations to determine turnaround times. Modeling and simulation have become critical business tools since they enable network optimization, the identification of potential challenges and drawbacks, supply chain factors, transport optimization, variables simulation, and predictions (İrkey & Tüfekci, 2021). The factors impacting the healthcare conceptual supply chain presented in Figure 12 can be used as a basis for an envisioned effective and efficient supply chain to contain a pandemic such as COVID-19. Figure 13 presents a

Figure 12. Factors impacting a healthcare sector supply chain (Source: Author's visualization—Leximancer)

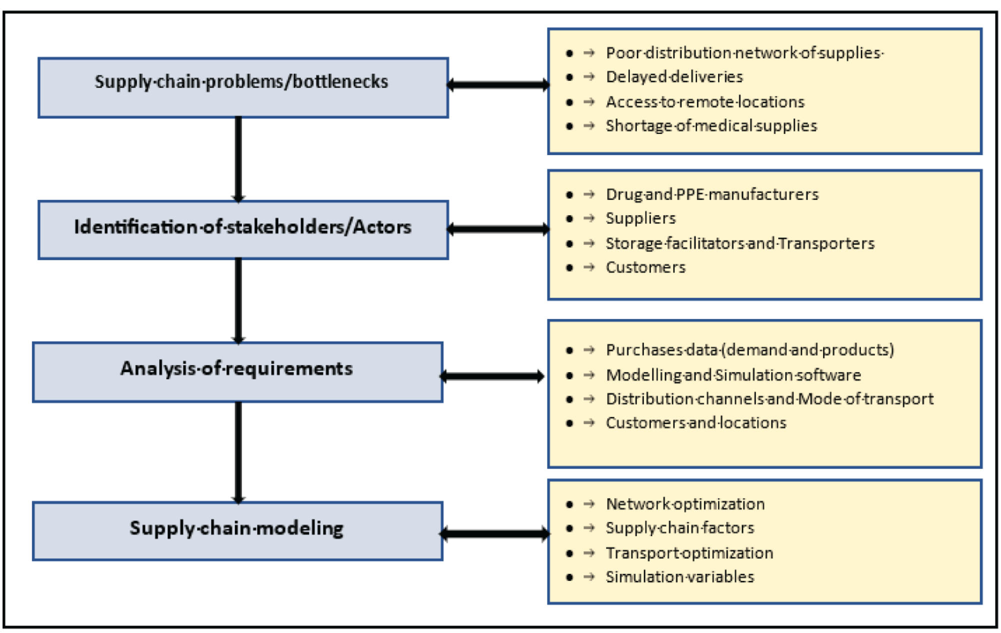
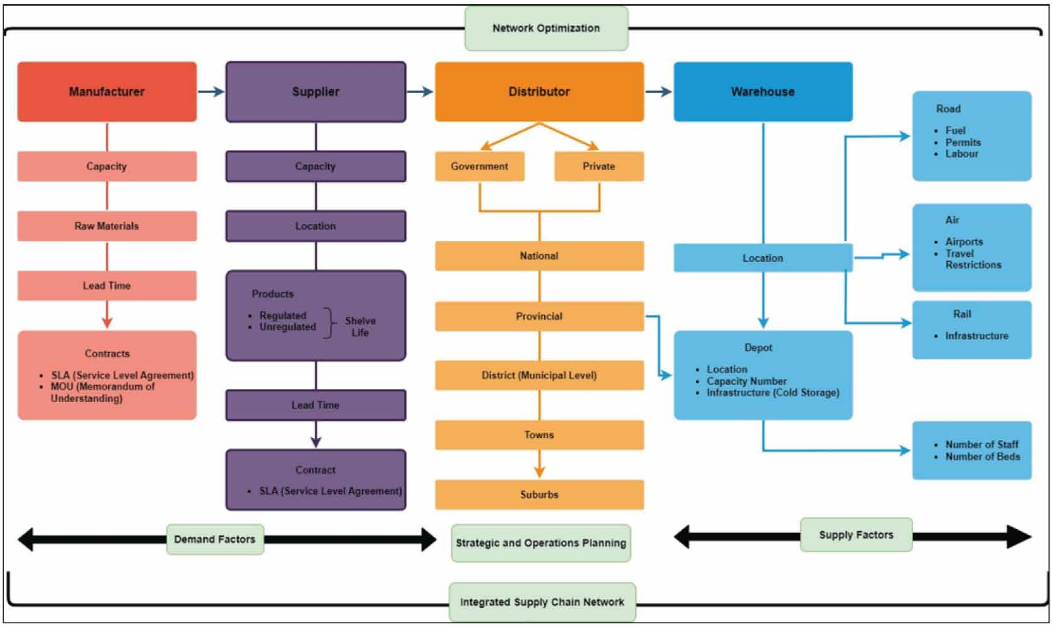


Figure 13. Proposed healthcare supply chain (Source: Authors' visualization – *AnyLogistix* and Leximancer)



visualization of the detailed supply model processes ideal for making products available where and when they are most needed.

DISCUSSION

This research focused on the South African healthcare sector to design the proposed supply chain presented in Figure 13. The model identifies four essential components: manufacturers, suppliers, distributors, and warehouses. The COVID-19 pandemic revealed these components to have been poorly designed, and they failed accordingly during the lockdown and travel restriction period (Harris, 2021). The manufacturer aspect in the model identifies production capacity, raw materials, lead time, and contracts with raw material suppliers and consumer bodies. Having these elements in a supply chain provides a holistic view, enabling the identification of possible supply chain bottlenecks. The second aspect comprises suppliers' capacity, location, products, lead time, and contracts. The location of suppliers and the types of products they supply are essential in determining the mode of transport, while lead time and contracts are critical elements in determining the ability of a supplier to provide the products on time, particularly during a disaster or pandemic.

The third aspect is distribution, which can be public or private at various levels, such as provincial or national levels, districts, towns, or suburbs. This component takes the product from the supplier for onward distribution to warehouses. Such warehouses provide temporary storage for finished goods, which retailers or consumers would then collect. Warehouses enable the visualization of locations that define the transport mode, such as road, air, rail, or water. In addition, depots, infrastructure, staff complement, and the type of product can enable timely planning and also take risks that have a direct impact on staff and operations into account, such as pandemics or disasters (Hendrickson & Rilett, 2020; İrkey & Tüfekci, 2021). The disruptions in the supply chain systems during the pandemic occurred in the public domain, which aligns with this finding. A supply chain model should be capable of being scaled up or down to sustain a national or international distribution without collapsing

(Bhaskar et al., 2020; Park et al., 2020). The results presented in Table 9 highlight the need for supply chain process optimization to contain a pandemic effectively.

The study recommends that South African healthcare institutions engage in workshops and seminars to share lessons learned on the supply chain during the COVID-19 pandemic. Running separate acquisition processes exacerbated the failure to source adequate vaccines, protective clothing, and equipment (Bhaskar et al., 2020; Park et al., 2020). To manage this better, South African healthcare institutions need integrated supply chain systems (Arafatur et al., 2020) that provide a single view of all required essentials. The integrated supply chain will provide a single view from a healthcare perspective, incorporating raw materials suppliers, drug manufacturers, transporters, distributors, and warehouses. This will provide a visualization of potential bottlenecks. South African healthcare institutions must modernize their supply chain systems to become data-driven through research and development (Bhaskar et al., 2020), enabling informed and timely decision-making during a pandemic such as COVID-19.

South Africa often experiences power cuts, which had an adverse impact during the COVID-19 pandemic; the envisioned supply chain systems must always be available and allow supply chain processes to run with or without electricity. Therefore, this study recommends that healthcare institutions operate supply chain systems from the cloud (Amine et al., 2021) with mirrored backups. In addition, the modernized supply chain systems need to allow the sourcing of medical essentials from multiple sources, such as drug manufacturers, suppliers, and cargo airliners. Finally, improved supply chain systems capable of simulating and performing analytics will be suitable when managing a fast-spreading pandemic. Healthcare institutions will need to prepare for disruptions that may be unprecedented and devise mechanisms to avert and keep supply chain systems and processes operating.

Healthcare institutions must adopt data-driven strategies to manage vaccine sourcing, distribution, and infection rates in response to the pandemic flare-ups. A predicting and forecasting strategy using data to identify hot spots entails running this data into simulators to make ideal decisions. Simulated infection rates should be used to plan and mobilize adequate resources such as hospital beds if there is an increase in infections.

Limitations and Future Research

This study does not conclusively encompass healthcare supply chain systems since several aspects require further investigation. The study only employed a single software application (AnyLogistix); consequently, the need exists to investigate additional healthcare supply chain systems and models used in other healthcare institutions and countries. We conducted the simulation using South African data for one year (2021); therefore, more data should be tested to see if the same results and conclusions will be obtained. The case study and data applied in this study were limited to South Africa; conducting simulations on a broader scale would be ideal. However, the findings of this study and recommendations—for example, the need for an agile supply chain systems (Morawiec & Sołtysik-Piorunkiewicz, 2021)—align with what other studies have identified.

CONCLUSION

The implementation of curfews and travel restrictions caused massive economic disruptions worldwide, resulting in the malfunctioning of most supply chains. The reviewed literature revealed challenges that could have been mitigated if the existing supply chain systems had been resilient and agile. This study identified the supply chain's lack of agility and resilience as significant concerns during the pandemic; therefore, more studies will add valuable insights. The case study highlighted aspects such as shortages of protective clothing and ventilators and the overpricing of face masks in South Africa due to supply chain instability. No universal healthcare supply chain exists, and the current systems are customized to fit their contexts, as dictated by the market, demand, supply, customers, and regulations. Furthermore, applying a proper and functioning supply chain is challenging to adopt and implement in healthcare due to its complexity and multi-dimensionality; therefore, diligence must be applied to ensure stability and continuity during the implementation phases.

The variance between proposed and allocated human resources (Table 9) and vaccination sites (Table 9) indicates the need to optimize supply chain processes and systems. Comprehensive supply chain systems will enable fair and equal distribution of resources, eradicating the perceived nepotism, bias, speculative shortages, and exorbitant prices. The study asserts that awareness of robust and agile supply chain systems and networks enables healthcare institutions to formulate strategies for combating pandemics, using elegant, practical solutions and proactive approaches during times of uncertainty. While the study was conducted using a single data set, the findings were compared to real statistics in South Africa. The simulation proved more effective when ordering vaccines based on infection rate and population distribution. The simulation highlighted trends, such as identifying hotspots using consumables demand. Additional studies on this subject must be conducted to equip institutions with strategies that will be effective in the event of another pandemic. The study recommends that South African healthcare institutions invest in research and development of resilient and robust supply chain systems that will be sustainable during a pandemic. Healthcare institutions need to adopt strategies that improve supply chain efficiency and optimization through best practices, as this will ensure stability, fewer flare-ups, and continuity during a pandemic.

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DATA AVAILABILITY STATEMENT

This study used three different data sets: population data, healthcare wholesalers, and COVID-19 statistical data. Population data were obtained from the official Statistics South Africa website: https://www.statssa.gov.za/, accessed on July 12, 2023. Healthcare wholesalers' data cannot be shared due to privacy and ethical restrictions. The COVID-19 statistical data were obtained from the National Institute of Communicable Diseases official site: https://www.nicd.ac.za/wp-content/uploads/2021/, accessed May 20, 2023, and the Department of Health's COVID_19 official site: https://sacoronavirus.co.za/covid-19-daily-cases/, accessed April 26, 2023.

COMPETING INTERESTS

The authors of this publication declare there are no competing interests. The funders had no role in the study's design, the collection, analyses, or interpretation of data, the writing of the manuscript, or the decision to publish the results.

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ENDNOTES

1 https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020
2 https://www.softwareadvice.com/
3 AnyLogic Company official site: https://www.anylogistix.com/

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