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# Last Mile Distribution of COVID-19 Vaccines: A Cold Chain Logistical Challenge

## A Case Study of Norway

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# Abstract

The COVID-19 pandemic is a global health and humanitarian crisis that has wreaked havoc on economies and industries around the world. This study aims to address the distribution of the COVID-19 vaccines at the last mile by evaluating the vaccine supply chain and how it can be effectively utilized to address the last mile distribution of the COVID-19 vaccines through simulation. The first part includes a systematic literature review and bibliometric study of vaccine supply chain and cold chain logistics studies conducted in the last decade. The second part examines the distribution of COVID-19 vaccines in Norway as a case study. The study develops a two-stage optimization simulation method to analyse and improve the logistical performance of the COVID-19 vaccine distribution in Inland County, Norway. The study analyses the impact of fleet size and the use of heterogeneous vehicles in the last mile distribution network on some key performance indicators. The findings from the study reveal that the service level, transportation costs and environmental performance of the vaccine logistics system are significantly influenced by routing decisions, fleet size, fleet composition and the types of heterogeneous vehicles used. Based on the findings from the study, some managerial insights are outlined to help logistics managers better understand the interactions between the key parameters of a cold chain vaccine distribution system.

**Keywords**: COVID-19 vaccine, vaccine distribution, vaccine supply chain, cold chain logistics, bibliometric analysis, simulation, optimization.

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# List of Common Acronyms

3PL – Third Party Logistics

CCL – Cold Chain Logistics

ELT- Expected Lead Time

LRP – Location Routing Problem

NIPH – Norwegian Institute of Public Health

SCND – Supply Chain Network Design

SIM - Simulation

TO – Transportation Optimization

VRP – Vehicle Routing Problem

VSC – Vaccine Supply Chain

WHO – World Health Organization

# 1 INTRODUCTION

## 1.1 Background

The catastrophic effects of the novel coronavirus disease (COVID -19) have swept the globe, drastically affecting the global health care system, economies, and many industries. As of May 9, 2021, over 150 million confirmed cases of COVID -19 have been recorded with more than 3.2 million associated deaths, according to the World Health Organization (WHO) [1]. This infectious disease was first detected in December 2019 in Wuhan, China, and was declared a global pandemic by WHO on January 30, 2020, causing a great stir worldwide. Given the severity of this pandemic, WHO, along with several industry-leading pharmaceutical companies, are hastily seeking means to contain the spread of this infectious disease. While control measures are being taken, several studies have been conducted to develop reliable vaccines that can potentially prevent the spread of the disease.

According to WHO, about 2-3 million deaths can be prevented by mass immunization and vaccination, therefore, the COVID-19 pandemic can be contained by making the disease vaccine-preventable[1]. To fulfil this important commitment, WHO has collaborated with various stakeholders through the Access to COVID -19 Tools (ACT) Accelerator to accelerate the global response to the pandemic. In addition to the ACT - Accelerator, another important program, COVAX, was launched to expedite the development of various COVID -19 vaccines candidates and ensure availability and equitable access around the world.

Currently, several COVID -19 vaccines like Pfizer/BioNtech, Moderna, AstraZeneca, Johnson & Johnson etc., have been approved for use in mass vaccination programs in several countries. While a lot of research efforts have been put into the development of reliable COVID -19 vaccines in several countries, the supply chain experts are also burdened with the task of ensuring that these potential vaccines reach the end-user population through the appropriate cold chain distribution channels from the manufacturing facilities to the administration sites [2].

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[1] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/covid-19-vaccines

The development of COVID -19 vaccines is the first step in eradicating the disease. Vaccine production and distribution are critical steps in mass vaccination and immunization programs, which require appropriate planning and implementation due to the enormity of the requirements. While the COVAX program ensures equitable allocation and distribution of large quantities of COVID -19 vaccines to affected countries, effective last-mile distribution is an even greater challenge. Many influencing factors, such as stringent temperature requirements and timeliness, pose significant challenges to a country's cold chain logistics network for effective vaccine distribution. For example, Pfizer-BioNTech's COVID -19 vaccine requires an ultra-low freezing temperature of -70 ℃ during transport and storage to remain effective [3]. The primary goal of the COVID -19 vaccination program is to vaccinate enough of the entire world population as early as possible, therefore a higher and timely coverage is very important. It could be detrimental that COVID -19 vaccines reach all countries that need them, but end users do not have access to them due to poor cold chain logistics and practices.

This study presents a simulation-based analysis to improve cold chain logistics performance for effective COVID -19 vaccine distribution using a case study in Norway. Several scenarios with different fleet size configurations were tested and analyzed using anyLogistix, a professional optimization simulation software. This study demonstrates the applicability of dynamic simulation in real-life cases to help decision-makers effectively organize the distribution of COVID -19 vaccines. Based on the results of the simulation analysis, key management insights are proposed that can help logistics managers better understand the interactions between the key parameters of a cold chain vaccine distribution system.

## 1.2 Problem Statement

Immunization with vaccines is the most effective and convenient way to minimize the spread of infectious diseases. However, vaccines are temperature sensitive. This means they require special handling and transportation needs to maintain viability from the point of production to the point where they are administered.

With the spread of COVID-19, international health organizations like the World Health Organization (WHO) and Public Health institutions are constantly seeking out best efforts to ensure equitable allocation and efficient distribution of the COVID-19 vaccines worldwide.

These efforts to combat the prevailing COVID-19 pandemic have increasingly put the resilience of the global vaccine supply chain to the test.

However, a more imminent challenge that has presented itself is the last mile distribution of these vaccines within countries with different economic status. Parameters such as temperature requirements for the different types of vaccines from different manufacturers would require that a country's vaccine supply chain (VSC) should be able to accommodate them. As some vaccines need to be stored in frozen temperatures, others require storage in the liquid state. The COVID-19 immunization program aims to have enough of the entire world population vaccinated as early as possible as such, higher immunization coverage is expected. It would be catastrophic if end-users are unable to access COVID-19 vaccines allocated to the countries due to inadequate cold chain practices.

## 1.3 Research Aim

This research focuses on the challenge of the last mile distribution of COVID-19 vaccines. The main aim is to evaluate the vaccine supply chain and how it can be effectively utilized to address the last mile distribution of the COVID-19 vaccines through simulation.

## 1.4 Research Objectives

With the aim of the research in mind, the following objectives were developed:

1. Conduct an extensive literature review on the current state of COVID-19 vaccines.
2. Conduct a systematic literature review on the vaccine supply chain and vaccine cold chain logistics.
3. Perform a comprehensive literature analysis with VOSviewer and identify the literature gaps.
4. Conduct a case study by examining Norway’s COVID-19 vaccine distribution strategies.
5. Analyse Norway’s vaccine distribution network through simulation using anyLogistix software.

## 1.5 Research Questions

Five research questions were formulated to guide the realization of the objectives of this research:

1. What are the trends and gaps in the literature on vaccine supply chain and cold chain logistics?
2. What methods are used in vaccine supply chain analysis?
3. What are the challenges of the last mile distribution of COVID-19 vaccines?
4. How can the cold chain logistics for the COVID-19 distribution be improved?
5. What contributes to the effective distribution of the COVID-19 vaccines at the last mile?

## 1.6 Thesis Outline

This report is structured in seven main chapters, with each chapter consisting of different sections. The activity timelines and milestones are captured in a Gantt chart which is presented in Appendix D. An overview outline of the chapters is as follows.

**Chapter 1: Introduction –** This chapter gives a general outlook of the scope and background of the research and discusses the aim, objectives, and research questions guiding the study.

**Chapter 2: Research Methodology –** The systematic approach and choice of research methods used in this research are described in this chapter.

**Chapter 3: Literature Review –** This chapter gives a general overview of the related topics and literature associated with this thesis. Firstly, it presents the current development of the COVID-19 pandemic, followed by an in-depth content analysis of the existing literature on vaccine supply chain and cold chain logistics. Then, the result from a bibliometric analysis is also presented, to identify the current trends in the literature related to this research. The chapter also identifies the common methods applied in the vaccine supply chain and cold chain logistics. The first and second research questions are addressed in this chapter.

**Chapter 4: COVID-19 Vaccine Distribution in Norway –** This chapter introduces the case country and its COVID-19 vaccine distribution strategies. The case study methodology used in this research is outlined in this chapter. The third research question is addressed in this chapter.

**Chapter 5: Problem Description and Method Development -** The problem addressed by this study is defined in this chapter, followed by an in-depth description of the development of the simulation models. The fourth research question is answered in this chapter.

**Chapter 6: Results and Discussion –** This chapter answers the fifth research question and analyses the findings from the case study analysis. The implications of the findings are outlined and discussed.

**Chapter 7: Conclusion** – The summary of the key findings from this study and the limitations faced during the span of this thesis are presented. The contribution of this research and possible future research direction are also discussed.

# 2 RESEARCH METHODOLOGY

The research strategies and approaches used in addressing this thesis's objectives, including (1) a systematic literature review and (2) a case study, are outlined in this chapter.

## 2.1 Systematic Literature Review

A systematic review was conducted to understand the current development and identify the trends in vaccine supply chain and cold chain logistics research. This review consists of bibliometric analysis and comprehensive content analysis. The bibliometric analysis embedded in the systematic literature review helps to visualise the relationship amongst the literature in vaccine supply chain and cold chain logistics. The review protocol used is shown in Figure 1.

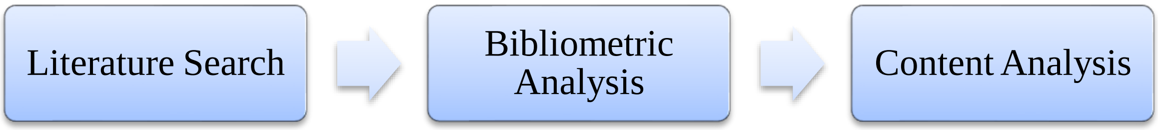

*Figure 1 Systematic Review Protocol*

### 2.1.1 Literature Search

A comprehensive literature search was conducted using the Scopus database on the 20th of November 2020. The literature search was performed on a single day to avoid daily updates on the Scopus database. Two separate searches were conducted on (1) Vaccine Supply Chain and (2) Cold Chain Logistics (CCL), and the results were combined after several search refinement and eligibility test. The search strategy is detailed in Figure 2.

Two logical keyword chains were developed for the search, as shown in Figure 2. The initial search results for both logical keyword chains yielded a total of 2362 records, with 1470 related to the vaccine supply chain and 892 on cold chain logistics. These records were limited to research articles with sources from journals to ensure the quality of the literature. The records were refined to show recent publications from the last decade (2020-2021) published in English.

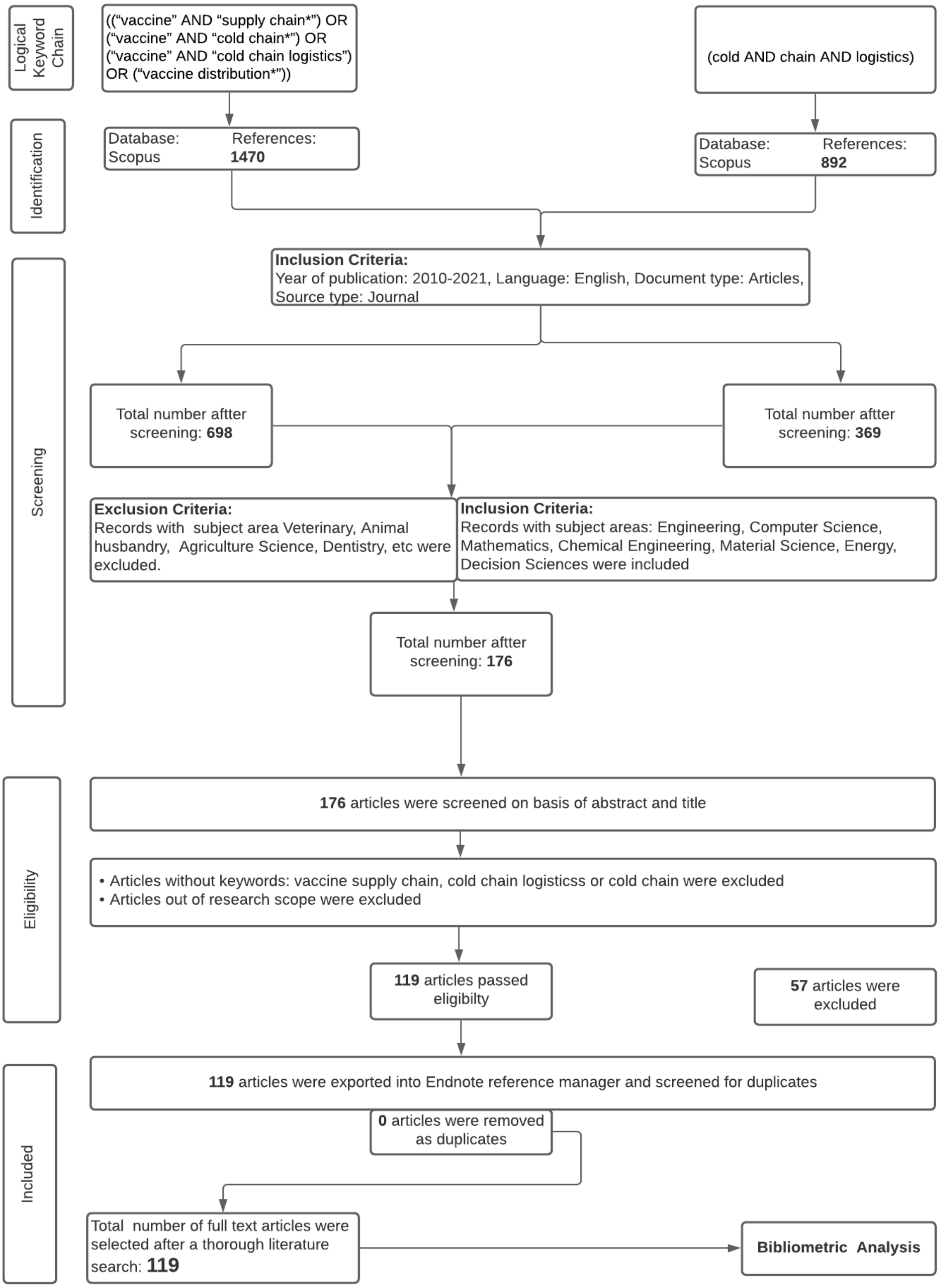

*Figure 2 Flowchart of Systematic Literature Review*

A total of 1067 records remained after this initial refinement. These records were then subjected to an inclusion and exclusion criterion filter in the subject area. Publications in Engineering, Computer Science, Mathematics, Decision Sciences, Energy, Material Sciences were included. Veterinary, Animal Sciences, Food Sciences, Agriculture Sciences, Dentistry, Immunology, Social Sciences, Neuroscience records were excluded.

176 records were left after this stage and were screened by titles and reading of abstracts. In this stage, keywords were defined to include "cold chain" and "vaccine supply chain". Articles that had none of these keywords in the abstracts, after careful reading, were excluded. Also, topics focused on vaccine development, vaccination and immunisation, risk assessment, fresh foods cold chain, aquaculture cold chain were excluded. Only articles that had to do with the vaccine cold chain logistics and supply chain were kept. A total of 57 articles were eliminated, leaving 119 articles. There were no duplicate articles found when the 119 articles were exported into the Endnote reference manager for duplicate checks; therefore, a total number of 119 articles remained for bibliometric analysis and review.

## 2.2 Case Study

The second research methodology used to support this thesis is a case study. Establishing that most of the methodologies adopted in operations management and supply chain management research use mathematical and statistical modelling approaches, an essential point to note is that, the processes involved in these fields are mostly related to real-world businesses and industries. Case study research is widely used as an inquiry tool in social sciences and medical research and in reviewing works in political sciences and economics [4, 5]. Thomas [4] defines case studies as an analysis of events, decisions, policies, or other systems studied holistically by one or more methods. The author further defines the case as the 'subject' of the inquiry and the analytical frame within which the study is conducted as an 'object'. In their study, Crowe, et al. [5] define a case study as a research approach used to obtain an in-depth and diverse understanding of a complex problem in a real-life context. The authors state that the case study approach can be used to implement strategic decisions and identify gaps in the chosen area of study.

There are three types of case study: intrinsic, instrumental and collective [5]. The type of case study used in this research is a combination of an intrinsic case study; to learn about the

COVID-19 vaccine distribution at the last mile and an instrumental case study; to gain a broader understanding of the strategies used by Norway in its vaccine distribution through simulation analyses. The case study methodology used in this thesis has been chosen based on Crowe, et al. [5] process of conducting a case study depicted in Figure 3.

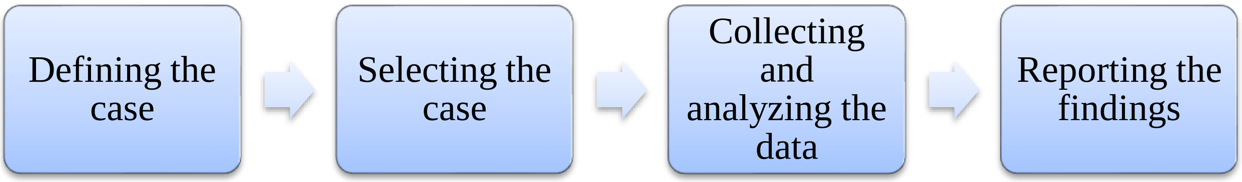

*Figure 3 The case study process* [5]

### 2.2.1 Defining the Case

The case defined for the study was based on the objectives of this thesis, the extensive literature review, and the formulated research questions.

*Case: The effective distribution of COVID-19 vaccines at the last mile*

### 2.2.2 Selecting the Case

Selecting the case study site included choosing a case that could allow easy access to data and information, the processes and resources that make up the preferred unit of analysis (the case). Norway was therefore selected as the case study site based on the considerations mentioned above and the possible low ethical implications and risks. Through careful evaluation of the distribution of the COVID-19 vaccines in Norway, the case site was scaled down to Inland county based on the vaccine distribution stakeholders' decision strategies.

*Case Site: Inland County, Norway*

### 2.2.3 Collecting and Analysing the Data

According to Crowe, et al. [5], using a range of multiple sources of data, including quantitative and qualitative techniques, provides an exhaustive understanding of the case. This data gathering approach can be used to validate the study and is popularly known as data triangulation. In this case study, the primary data sources are semi-structured interviews through emails and phone calls, stakeholders' documentation, news items from both national and local websites, and extensive web searches.

*Analysis: Dynamic simulation* (see chapter 5)

### 2.2.4 Reporting the findings

After the data is analyzed and conclusions are drawn, it is critical to document the findings from the study for transparency. This is achieved by providing a detailed contextual report which lays out the processes that were followed, data collected, and how the results and deductions were made.

# 3 LITERATURE REVIEW

This chapter presents an in-depth content analysis of research and literature relative to this thesis to identify the research gaps. A general overview of the current state of the COVID-19 pandemic and the vaccine candidates are first presented, followed by a comprehensive review of the vaccine supply chain. The chapter also investigates the current research landscape through a bibliometric analysis of the research published in VSC and CCL literature in the past decade. The common methods applied in the vaccine supply chain literature are presented in the later sections

## 3.1 COVID-19

The catastrophic effect of the novel Coronavirus disease (COVID-19) has bedevilled the entire globe, affecting global economies and industries. With over 150 million confirmed cases, the COVID-19 disease's mortality rate has been fatal, with associated deaths of about 3.1 million, according to the World Health Organisation (WHO)[2]. The COVID-19 disease originated from Wuhan, China, and was declared a global pandemic by WHO on the 30th of January, causing a significant stir. The illness is caused by severe acute respiratory syndrome coronavirus (SARS-CoV-2) with respiratory symptoms such as general fever, cough, fatigue, shortness of breath, etc., and spread through person to person contact in proximity[3]. Given the severity of this pandemic, WHO and industry-leading pharmaceutical companies are in haste to find means to curb the widespread of this infectious disease. Several studies are being conducted to find a potent vaccine that could prevent the spread whilst control measures are put in place.

### 3.1.1 The Role of WHO in COVID-19 Vaccine Development

The World Health Organization is a global health governing body responsible for setting international standards and implementing global health policies and practices. It is therefore incumbent that WHO fully participates in combating the novel COVID-19 disease. Immunization has been a standard used by the WHO to eradicate infectious diseases using vaccines. According to WHO, 2-3 million deaths are prevented with immunization and therefore attempts to expunge the recent COVID-19 disease by making it a vaccine-preventable

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[2] https://covid19.who.int/

[3] https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html

illness[4]. To achieve this significant obligation, WHO has collaborated with several stakeholders through The Access to COVID-19 Tools (ACT) Accelerator to expedite the response to the pandemic. The ACT-Accelerator provides a platform to bring together various scientists, researchers, governments, and global health organizations in the quest to find a solution to eradicate the COVID-19 disease. Along with the ACT- Accelerator, another important scheme that has been put in place to facilitate the search for a viable COVID-19 vaccine is COVAX[5]. COVAX is led by GAVI (The Vaccine Alliance) and Coalition for Epidemic Preparedness Innovations (CEPI) in collaboration with WHO, with the sole purpose of accelerating the development of COVID-19 potential vaccines and ensuring the availability and equitable access across the globe once the vaccines are available.

### 3.1.2 Current Studies and Research into a Potential Vaccine

Just as all novel pathogenic diseases receive attention in the academic research field, there are currently several studies and research on the SARS-CoV-2 virus and its associated characteristics.

To be able to develop a viable vaccine for the COVID-19 disease, there is a need to understand the causative organism and the types of vaccine categories [6-9]. The need to expedite the process of developing the COVID-19 vaccine is of great importance as there is a large demand from various countries. As a result, scientists and vaccine developers are exploiting different resources to push out a potent vaccine in the shortest possible time [6, 10, 11]. Krammer [11], in her paper, inferred that the development of the COVID-19 vaccine is being hastened. The traditional vaccine development process takes several years of up to about 15 years, but in the COVID-19 vaccine development, an accelerated pipeline of fewer than 2 years is to be expected [9-11]. The accelerated development of the potential COVID-19 vaccine is possible because there is pre-existing knowledge from the vaccines developed for SARS-CoV and MERS-CoV [8, 12, 13]. Dong, et al. [14] present an overview of the current SARS-CoV-2 vaccines in trials and highlight safety issues that must be considered in the race for the COVID-19 vaccine development.

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[4] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/covid-19-vaccines

[5] https://www.gavi.org/vaccineswork/covax-explained

### 3.1.3 COVID-19 Vaccines

Data from the World Health Organization's "Draft Landscape of COVID-19 candidate vaccines" highlights the current vaccine candidates, associated vaccine developers, and their stage in clinical evaluation. As of the 3rd of November 2020, there were 47 COVID-19 vaccine candidates in clinical and 155 in pre-clinical evaluation (see Appendix A) [15]. The draft landscape of the COVID-19 vaccine candidates in Appendix A is updated weekly with corresponding changes in the various phases of development. With ten potential COVID-19 vaccine candidates in Phase 3 of clinical trials, it is highly hopeful that a viable vaccine could soon be released for public administration.

On December 2nd, 2020, the vaccine from Pfizer/BioNTech was first approved in the UK for emergency use to flatten the sharp increase of COVID-19 infections. Shortly after, it was approved in the US, the EU, and many other countries. Currently, COVID-19 vaccines from several manufacturers, including Moderna, AstraZeneca, Johnson & Johnson, Serum Institute of India, etc., have been approved in several countries.

### 3.1.4 Potential Challenges in COVID-19 Vaccine Development

The development of a rapid vaccine comes with several immunological challenges [13]. In their study, Flanagan, et al. [26] outlined some significant challenges associated with the SARS-CoV-2 vaccine development. The authors discussed that if an effective vaccine is developed, there is a need to assess the safety of the vaccines to determine the efficacy in humans. In a similar study conducted by Dutta [9], the author inferred that the potential vaccine's safety could only be accounted for when a large population of subjects in distinct geographical locations with different ethnic backgrounds is studied.

[9, 13] in both their studies highlight another pressing challenge associated with developing the COVID-19 vaccine; the availability and mass deployment of a successful vaccine. The logistical and supply chain challenge of fairly distributing large quantities of the successful vaccines across the globe from the point of production to the end of the administration whilst maintaining the required temperature is a significant concern. As discussed in the early sections, through the COVAX initiative, WHO facilitates the fair distribution of the COVID-19 vaccines. It is also crucial to address the measures being put in place to ensure that the vaccines are kept viable at the community levels in developing countries where vaccination

takes place. Do all countries have the necessary cold chain facilities and equipment to store the COVID-19 vaccines upon receipt?

According to the Draft Landscape of the COVID-19 vaccine candidates [15], most of the vaccine candidates in Phase 3 of the clinical trials require two doses, except for one, which requires only a single dose. Most of these vaccines' double dose requirements imply that the vaccine manufacturers need to scale up productions to facilitate the enormous global demand. Dutta [9] and Krammer [11] discussed the characteristics of some potential vaccine candidates in advanced stages of clinical trials. The various types of vaccine candidates have different characteristics and trade-offs, with some needing frozen storage, such as mRNA vaccines. The need for different temperature requirements of the various types of COVID-19 vaccine candidates poses a major cold chain logistical challenge, especially in countries with poor cold chain storage and maintenance facilities.

## 3.2 Vaccine Supply Chain

Lee, et al. [16] defines the vaccine supply chain as a complex system consisting of locations, storage equipment, vehicles, transport routes, and personnel that handle these vaccines to the administration point. The uncertainty, risks, and disruptions associated with the vaccine supply chain make it delicate and complex and, as such, require thorough planning and implementation [17]. Duijzer, et al. [18], in their literature review, inferred that the vaccine supply chain is distinctively different from other supply chains due to unique attributes such as decentralized decision making, the influence of political decisions on allocation, the importance of making decisions and acting on time.

Global distribution of vaccines ensures that there is a fair allocation of vaccines to the targeted populations. When new vaccines like COVID-19 vaccines are to be introduced into the Expanded Programme on Immunization (EPI), they go through various stages in the supply chain. Rastegar, et al. [19] defines the four main stages of the vaccine supply chain as follows;

- Product – (what type of vaccine is needed?)
- Production – (how many vaccines should be produced and when)
- Allocation – (who should receive the vaccines)
- Distribution – (how should the vaccines be distributed?)

To ensure the viability of the vaccines at the point of administration, it is crucial to maintain effective and efficient cold chain logistics. A vaccine supply chain is effective if it can meet the full schedule by ensuring that the number of vaccines needed for the target population is available in good conditions at an affordable cost [20]. Therefore, vaccine distribution, although the last stage of the vaccine supply chain, is the most important if greater immunization coverage is expected. To achieve timely distribution of vaccines across the globe during the COVID-19 pandemic, it is necessary to implement a resilient and responsive supply chain that can bridge the gap in demand and supply uncertainties.

Several extensive studies on emergency and epidemic control supply chains have been conducted by researchers [21-24]. Other studies on the vaccine supply chain address the associated challenges [25-28] and the need for collaboration amongst stakeholders of the vaccine supply chain [18, 27, 29]. Duijzer, et al. [18] added to the existing literature on vaccine logistics by connecting the logistical components to create a coalesced vaccine supply chain. By viewing vaccine logistics from a supply chain perspective, the authors inferred that decisions made in each category of the vaccine supply chain affected the downstream components hence a need for integration.

Privett and Gonsalvez [25] suggested that with an increasing number of vaccine production, the vaccine supply chain could be faced with a lack of capacity to handle such demand. Given this, the possible way forward is to consider integrating other pharmaceutical products' supply chains with the vaccine supply chain. The authors believed that this strategy is theoretically efficient as it cuts down fixed and operational costs associated with transportation, warehousing, and distribution. Although this is beneficial to the upstream stakeholders in the supply chain, the authors argued that considering the specific requirements with the storage and distribution of vaccines, integrating the vaccine supply chain with other health products could be ineffective in managing product variety and customer requirements. The authors propose that if there is a need to integrate the vaccine supply chain with other medical products, it should be done cautiously with selected products at certain stages of the supply chain. This approach is more effective at the supply chain's downstream stages, such as warehousing and transportation [25]. Similarly, Duijzer, et al. [18] deduced in their study that the distribution of vaccines needed to be integrated with other medical supplies.

Highlighting the importance of stakeholder involvement in decisions affecting vaccine supply chain's design, many studies present the need for collaboration amongst decision-makers. Lee and Haidari [29] identified some vaccine supply chain stakeholders and the implications of their actions on the vaccine supply chain. The authors emphasized the need to educate and enhance communication between vaccine decision-makers and vaccine supply chain experts. De Boeck, et al. [30], in their review, implied that, although real-life data are used in modelling uncertainties and characteristics of the vaccine supply chain, real-life applicability is low because of lack of stakeholder involvement. A similar study conducted by Brison and LeTallec [20] also suggests that strong coordination and accountability amongst various stakeholders in the cold chain and logistics systems would improve fair and timely access to vaccines for immunization.

Although stakeholders of the vaccine supply chain need to be involved with decisions concerning the design of the VSC, some studies prove that a significant cause of freezing and other challenges in VSC is caused by human interference. Ashok, et al. [31] examined the various challenges faced by the Global Health Pharmaceutical Delivery (GHPD) supply chains and devised a dependency model which interlinked the challenges. Their study showed that the key factor that influences the GHPD supply chain is human resource dependency. As such, it is important to adequately train all stakeholders of the VSC. To buttress this, [32] studied the prevailing issues associated with the exposure of vaccines to temperatures below-recommended ranges within the cold chain. The study's findings show a lack of adequate knowledge of health workers regarding the effect of freeze damage on vaccines and temperature monitoring. Therefore, key players and staff involved in vaccination and cold chain must be adequately trained to improve temperature maintenance and supply chain management.

### 3.2.1 Cold Chain Logistics and Systems

As discussed in section 3.2, getting vaccines to the end-user requires adherence to specific temperature requirements. This can be achieved with effective cold chain logistics (CCL) and systems. WHO defines the vaccine cold chain as a system for storing and transporting vaccines in the recommended temperature from manufacturing to the administration [33]. Li [34], in his paper on cold chain transportation systems with 5G and IoT, discussed that, for vaccines to be kept viable at the end of the chain, it is crucial to make sure that there is enough capacity to store the vaccines and to maintain constant temperature monitoring during transportation. Cold logistics and systems, therefore, include vehicles, equipment, storage facilities, human resource and decisions that affect the maintenance of vaccines at the required temperature.

Most research on CCL focus on technologies that can improve temperature monitoring, transportation decisions, location of cold warehouses etc. The biggest challenge in VSC is temperature monitoring and control, which is consistent in all the stages of vaccine distribution. Various technological tools and strategies have been proposed to mitigate this challenge. Packaging used in vaccine CCL is an essential contributor in maintaining the viability of vaccines. Phase change materials (PCMs) have been studied by many researchers for use in cold chain storage equipment [35, 36]. Another possible outlook into eliminating the need for vaccine cold chain is making vaccines thermostable [37, 38].

Temperature monitoring and control is essential during the transportation and storage of vaccines. Yu, et al. [39] developed a safe, stable and energy-saving monitoring system with an accurate and rapid data collection module for transportation monitoring in vaccine cold chains. Similarly, [40, 41] studied the use of Radio Frequency Identification (RFID) which have become increasingly valuable for monitoring individual vaccine packs. In their study, Monteleone, et al. [51] presented a conceptual model of an innovative cold chain temperature monitoring model in healthcare industries using IoT systems. Their model utilizes RFID technology integrated with Wireless Sensor Networks (WSN), which will automatically record temperature changes in products – ensuring the quality of the products throughout the supply chain.

Internet of Things (IoT) has been recently adopted across several industries as part of the industrial revolution. As part of industry 4.0, IoT is a worldwide internet architecture that can facilitate the link between goods and services [42]. Tang, et al. [42] studied the use of IoT as a supervisory system to ensure that stakeholders of the cold chain adhere to regulations in maintaining the quality of perishable products like vaccines. Mohsin and Yellampalli [43] also researched how IoT can help improve the cold chain logistics system in food and vaccine distribution.

An interesting research avenue in CCL is focusing on sustainability by reducing the amount of carbon emissions during transportation. Recent studies on Location Routing Problem (LRP) and Vehicle Routing Problem (VRP) have been channelled to address carbon emissions and energy conservation and not only economic performance [22, 44, 45].

## 3.3 Bibliometric Analysis

Using VOSviewer, a professional literature analysis software, four primary classification analysis were performed, including: (1) journal co-citation analysis, (2) keyword co-occurrence analysis, (3) analysis of collaborations between countries and (4) document co-citation analysis. This analysis helps to identify publication trends in VSC and CCL, the most popular journals in the field, and the key areas that receive the most attention.

### 3.3.1 Publication Trend

The annual publication of papers in VSC and CCL from 2010 to 2021 is shown in Figure 4. As can be seen from the graph, a total of 119 papers were published during this period, with the highest number of publications in 2020. The trend shows that there has not been a steady growth in the number of articles published each year from 2010 to the present. In 2014, a peak of 14 articles was published in VSC and CCL research, which decreased for three consecutive years until 2018 with twice as many publications as the previous year. From 2018 to 2020, a total of 66 articles were published, representing 55% of the total publications in the last decade. This increase in publications on vaccine supply chain and cold chain logistics proves that more attention is being paid to this research area.

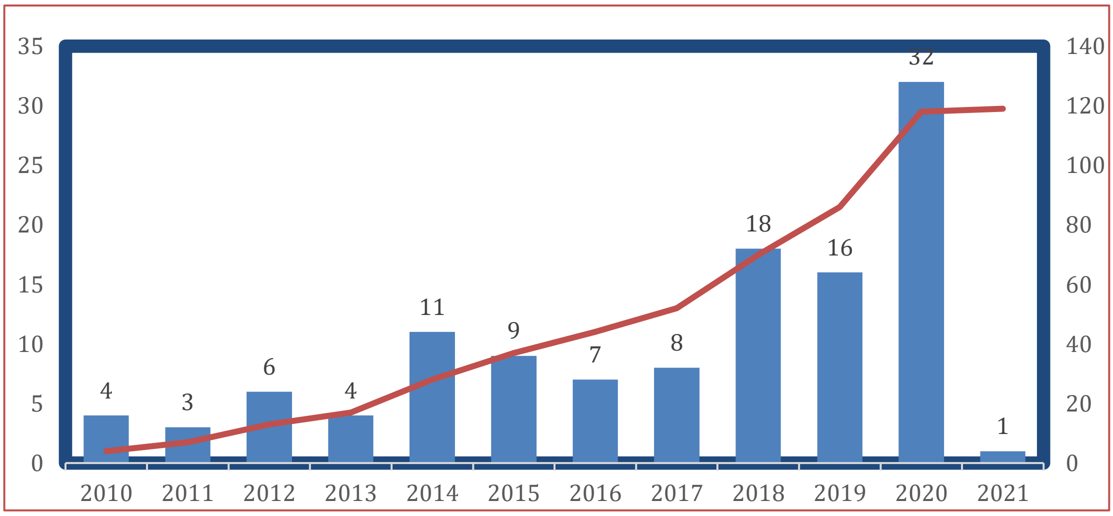


*Figure 4 Number of Publications Per Year*

### 3.3.2 Journal Allocation and Co-citation Analysis

#### 3.3.2.1 Journal Allocation

The 119 papers used in this study were published in 91 different journals. Table 1 shows the top 15 journals with two published papers. These 15 journals account for 40 papers, which makes up 34% of the total. As can be seen from the table, the Journal of Computers and Industrial Engineering has the highest number of published papers.

*Table 1 Summary of top 15 journals in VSC and CCL publications*

| **Journal** | **Documents** |
|---|---|
| Computers and Industrial Engineering | 6 |
| European Journal of Operational Research | 4 |
| Annals of Operations Research | 3 |
| Omega (United Kingdom) | 3 |
| Biologicals | 3 |
| Mathematical Problems in Engineering | 3 |
| Manufacturing and Service Operations Management | 2 |
| International Journal of Multimedia and Ubiquitous Engineering | 2 |
| International Journal of Information Management | 2 |
| Building and Environment | 2 |
| Journal of Biotechnology | 2 |
| Neural Computing and Applications | 2 |
| International Journal of Refrigeration | 2 |
| International Transactions in Operational Research | 2 |
| Open Cybernetics and Systemics Journal | 2 |

#### 3.3.2.2 Co-cited Journal Analysis

A co-citation analysis was performed to identify the most co-cited journals in the vaccine supply chain and cold chain logistics literature. A network of 12 elements with 66 links was created from journals with more than 20 citations. The network shows two clusters of interlinked journals (Figure 5). Cluster 1 consists of 5 journals, mainly in the field of operations research (OR), with the European Journal of operations research having the most citations and the highest total link strength. Cluster 2 consists of 7 journals representing several research areas of Management Science (MS) and Operations Research, with the journal of Management Science having 69 citations and a total link strength of 1449. Although Operations Research and Management Science are often used interchangeably, the journals in Cluster 1 have papers that focus on the development of mathematical models and computational algorithms. The journals in Cluster 2, on the other hand, have publications that focus on the managerial implications from the application of the models. Looking at all the journals in this category, the *European Journal of Operations Research* and *Management Science* are the most frequently co-cited journals. The co-cited journals are grouped under each cluster as shown in Table 2.

*Table 2 Cluster groupings of interconnected journals in VSC and CCL research*

| Clusters | Journal | Citations | Total Link Strength |
|---|---|---|---|
| Cluster 1 | European Journal of Operational Research | 91 | 1861 |
| | International Journal of Production Economics | 38 | 688 |
| | Computers & Industrial Engineering Journal | 32 | 366 |
| | Computers & Operations Research Journal | 25 | 800 |
| | Annals of Operations Research Journal | 24 | 201 |
| Cluster 2 | Management Science | 69 | 1449 |
| | Operations Research | 66 | 1526 |
| | Omega – International Journal of Management Science | 34 | 455 |
| | Plos One | 25 | 527 |
| | Production and Operations Research | 23 | 965 |
| | Mathematical Biosciences | 22 | 585 |
| | Interface Journal | 20 | 972 |

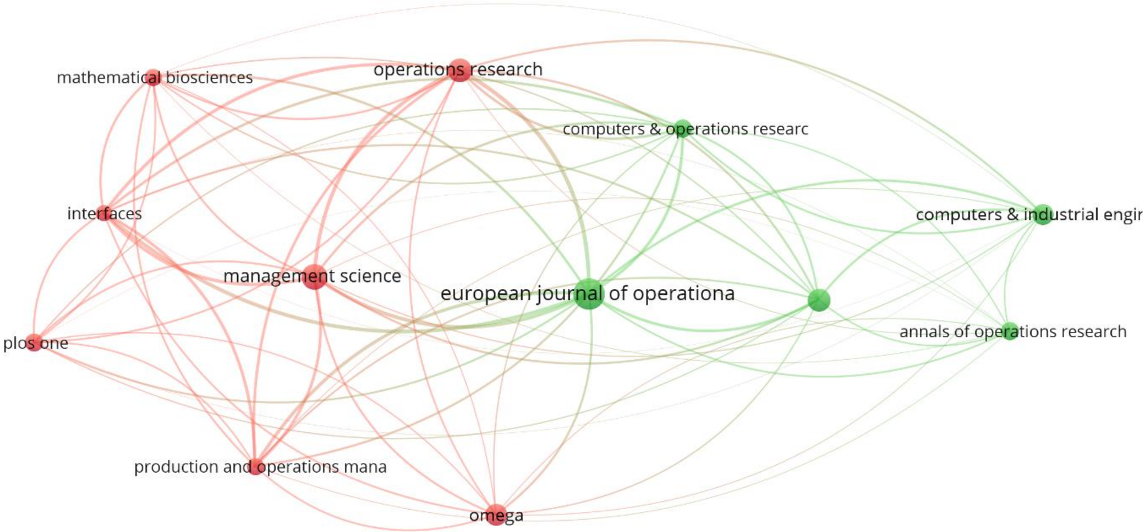


*Figure 5 Mapping of co-cited journals*

### 3.3.3 Countries Collaboration Analysis

To identify the countries actively involved in the study of vaccine supply chain/cold chain logistics, a co-authorship of collaborating countries network map is created using VOSviewer as presented in Figure 6. The minimum number of documents was set to 2, with each country having a minimum citation of 2. This yielded a total of 14 interconnected countries actively collaborating to VSC/CCL research. Table 3 presents the list of countries involved in VSC/CCL research. The average citation was calculated by dividing the number of citations of each journal by the number of documents.

From the table, it is seen that VSC/CCL research is widely spread across the regions of Europe and Asia. China is observed to have the most published documents, followed by the United States. Although China has more publications than the United States, the United States has twice as many citations as China which implies their publications may have a more substantial influence at the time of this study. In the table, the average year column represents the average year in which the documents are published. It means that when comparing China and the United States, the latter has documents published from 2015 as opposed to 2017 in the case of China. This may account for the reason why the publications from the United States have received more citations than publications from China.

Countries like South Korea, the United Kingdom, and Italy have very few publications that seem to have higher average citations, indicating their strong influence in the research field. It can also be deduced from Table 3 that research in VSC/CCL in these countries has been published more within the last seven years.

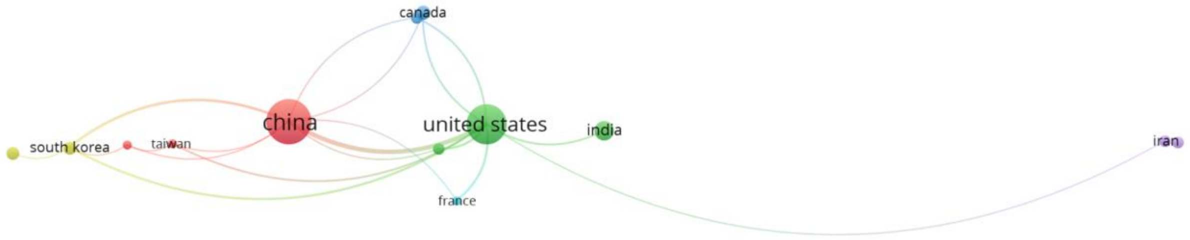


*Figure 6 Mapping of collaborating countries in VSC/CCL*

*Table 3 Active countries in VSC/CCL research*

| Country | Region | Documents | Citations | Avg Citations | TLS | Average Year |
|---|---|---|---|---|---|---|
| **China** | Asia | 47 | 182 | 3.87 | 11 | 2017 |
| **United States** | America | 36 | 385 | 10.69 | 14 | 2015 |
| **India** | Asia | 9 | 36 | 4.00 | 1 | 2018 |
| **Canada** | America | 5 | 17 | 3.40 | 2 | 2017 |
| **South Korea** | Asia | 4 | 41 | 10.25 | 1 | 2016 |
| **United Kingdom** | Europe | 4 | 48 | 12.00 | 2 | 2018 |
| **Australia** | Australia | 3 | 29 | 9.67 | 4 | 2016 |
| **Hong Kong** | Asia | 3 | 15 | 5.00 | 2 | 2018 |
| **Spain** | Europe | 3 | 15 | 5.00 | 2 | 2014 |
| **Switzerland** | Europe | 3 | 26 | 8.67 | 4 | 2017 |
| **France** | Europe | 2 | 14 | 7.00 | 1 | 2013 |
| **Italy** | Europe | 2 | 76 | 38.00 | 1 | 2013 |
| **Saudi Arabia** | Asia | 2 | 19 | 9.50 | 2 | 2019 |
| **South Africa** | Africa | 2 | 15 | 7.50 | 1 | 2018 |

### 3.3.4 Co-occurrence Analysis of Keywords

The keyword co-occurrence analysis is a necessary assessment as it often depicts the main theme of articles in a particular field. In this analysis, the co-occurrence of all keywords with a minimum number of occurrences as 3 was the focal point. Of the 1407 keywords found in all publications under this study, 67 keywords met this criterion forming 7 clusters with their co-occurrence relationships, as shown in Figure 7. The top 10 keywords in VSC/CCL with the highest frequency of occurrence and inter-connections includes Vaccines (Freq = 50), Cold Chain Logistics (Freq = 32), Cold Chain (Freq = 17), Optimization (Freq = 15), Supply Chains (Freq = 15), Vehicle Routing Problems (Freq = 12), Vehicle Routing (Freq = 11), Developing Countries (Freq = 10), Supply Chain Management (Freq = 10) and Chains (Freq = 10). From Figure 7, it can be deduced that keywords such as vaccines, cold chain logistics, optimisation, and supply chain are recurring the most and have very close relationships.

To further analyse and understand the recurrence of the keywords, a density map was generated using VOSviewer, as shown in Figure 8. The density map helps to visualise the most critical areas on the map. Points on the map are represented by a colour that indicates the density of the item. The default colour coding used in VOSviewer ranges from red to blue, with red indicating the highest density and blue the lowest density. Vaccines, Cold Chain Logistics fall in the red zone, with the highest density, whereas Supply Chains, Vehicle Routing, and Optimisation fall in an orange zone with a higher density than keywords in the green zones. However, fewer keywords in the red-orange spot indicate that these keywords have received more focus and are more mature study areas forming the core of the Vaccine Supply Chain and Cold Chain Logistics research. Keywords in the green zone suggest that more studies are being conducted in new areas within the research field.

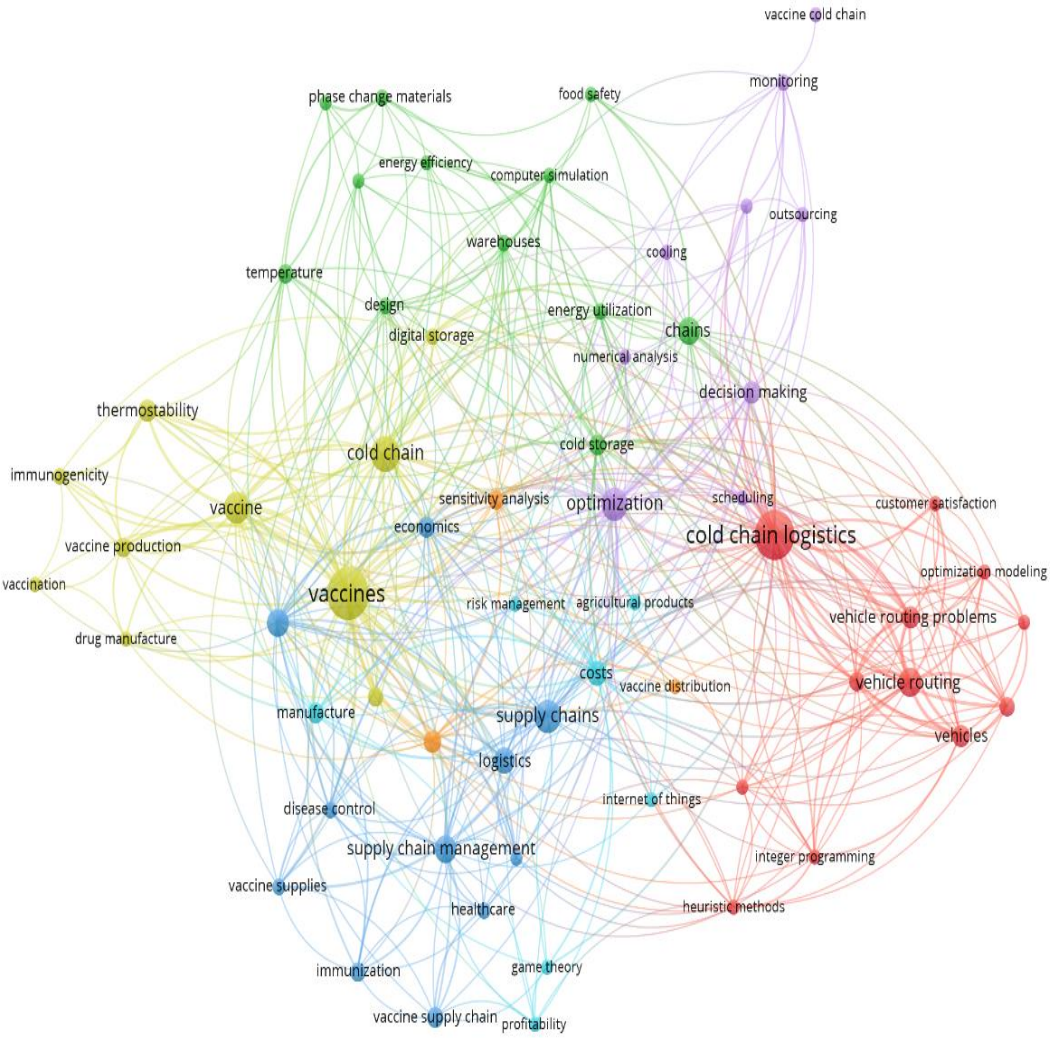


*Figure 7 Mapping of co-occurred keywords*

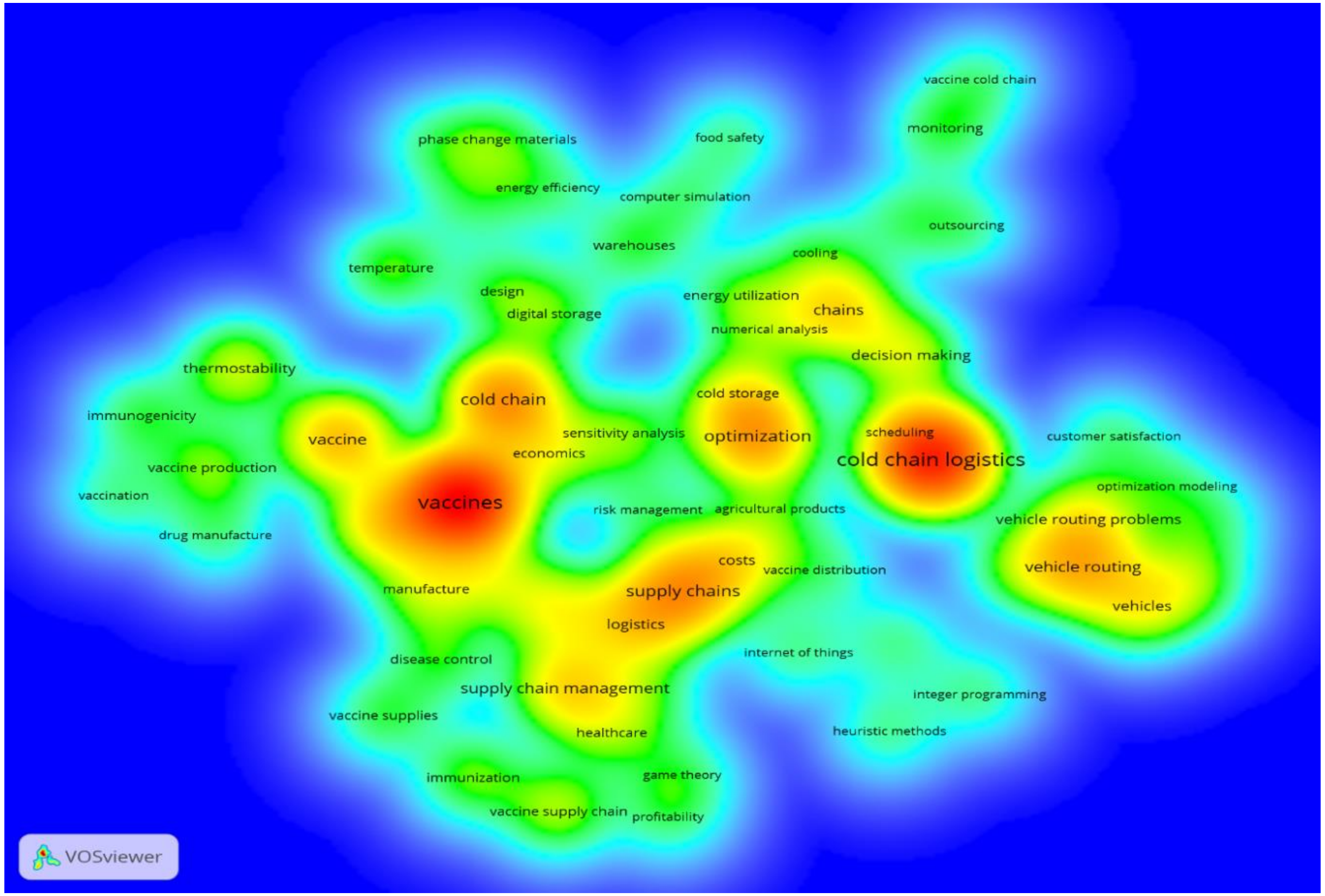


*Figure 8 Density map visualisation of keywords*

### 3.3.5 Document Co-citation Analysis

The document co-citation analysis is performed to identify the most influential documents in the VSC and CCL research. The result from the co-citation analyses of all 119 records with VOSviewer is shown in Figure 9.

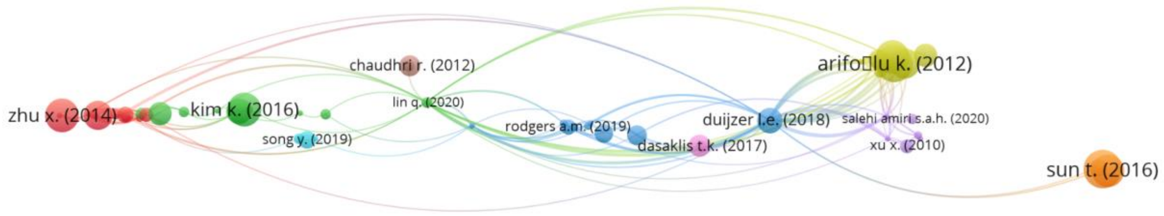


*Figure 9 Mapping of co-cited documents in VSC and CCL study*

The top 15 documents with the most impact in VSC and CCL literature along with the year of publication, title and area of research are presented in Table 4. It can be seen that Arifoğlu, et al. [46] study on the influenza vaccine supply chain, with a focus on demand and supply, has received the most citations in this classification as such ranks first in the list of the most influential documents in this study. Melone, et al. [47] research on materials for cold storage of perishable products follows in second place. It is observed that literature on VSC and CCL is a holistic study with areas from management science, operations research, production engineering, applied energy etc.

*Table 4 Document list with the most impact in VSC and CCL research*

| **Document** | **Year** | **Tittle** | **Area of Research** |
|---|---|---|---|
| **Arifoğlu, et al. [46]** | 2012 | Consumption externality and yield uncertainty in the influenza vaccine supply chain: Intervention in demand and supply | Management Science |
| **Melone, et al. [47]** | 2012 | Phase change material cellulosic composites for the cold storage of perishable products: From material preparation to computational evaluation | Applied Energy |
| **Kraiselburd and Yadav [48]** | 2013 | Supply Chains and global health: An imperative for bringing operations management scholarship into action | Production and operations management |
| **Kim, et al. [49]** | 2016 | I-RM: An intelligent risk management framework for context-aware ubiquitous cold chain logistics | Expert Systems with applications |

| | | | |
|---|---|---|---|
| **Dai, et al. [50]** | 2016 | Contracting for on-time delivery in the US Influenza vaccine supply chain | Manufacturing and service operations management |
| **Zhu, et al. [51]** | 2014 | A flexism-based optimisation for the operation process of cold-chain logistics distribution centre | Applied research and technology |
| **Lütjen, et al. [52]** | 2013 | Quality driven distribution of intelligent containers in cold chain logistics networks | Production engineering |
| **Li, et al. [53]** | 2012 | Cold chain logistics system based on cloud computing | Concurrency Computation Practice and Experience |
| **Miller Neilan and Lenhart [54]** | 2011 | Optimal vaccine distribution in a spatiotemporal epidemic model with an application to rabies and raccoons | Journal of Mathematical Analysis and Applications |
| **Duijzer, et al. [18]** | 2018 | Literature review: The vaccine supply chain | European journal of operations research |
| **Mejjaouli and Babiceanu [55]** | 2018 | Cold supply chain logistics: System optimisation for real-time rerouting transportation solutions | Computers in industries |
| **Liu, et al. [56]** | 2018 | Optimisation of cold chain logistics distribution network terminal | Wireless communication and networking |
| **Samii, et al. [57]** | 2012 | Reservation and allocation policies for influenza vaccines | European Journal of operations research |
| **Ding, et al. [58]** | 2016 | Numerical study and design of a two-stage ejector for sub-zero refrigeration | Applied thermal engineering |
| **Hasan, et al. [59]** | 2019 | Smart contract-based approach for efficient shipment management | Computers and industrial engineering |

## 3.4 Common Methods in Literature

While addressing the problems associated with the design of supply chain networks under uncertainty, several studies have been conducted in Operations Research (OR), which makes use of two common techniques; (1) analytical optimization and (2) simulation approaches.

### 3.4.1 Analytical Optimization

Optimizing supply chain network design (SCND) using mathematical models has become an increasing area of interest to both researchers and practitioners, primarily due to the pursuit of highly effective and efficient supply chain operations. An optimized supply chain design network can provide various benefits such as reduced operating costs, improved customer experience, improved environmental impacts, efficient production and distribution. Using mathematical models can assist decision-making at both strategic and operational levels [60]. As supply chain costs are directly proportional to customer responsiveness, the vaccine supply network design must be modelled to achieve low operating costs. Simultaneously, it should be capable of rapidly distributing vaccines to end-users, especially during global pandemics. Research on SCND tends to use analytical optimization approaches when analyzing problems related to the strategic location and allocation decisions and tactical relocation decisions. The purpose is to find the optimal solution among a large set of alternatives [61]. To tackle these complex decision-making problems in vaccine SCND, the most extensively used modelling techniques are linear programming (LP), mixed integer programming (MIP), and multi-objective programming (MOP). Based on these techniques, several analytical optimization models have been formulated with focuses on reducing the total costs associated with vaccine supply chain design and operations [22, 45, 62-66], reducing the cargo damage [23, 64], minimizing the carbon emissions [23, 24, 44, 62], and improving the customer satisfaction [24, 66].

At the operational level of a cold chain logistic system for vaccine distribution, the vehicle routing problem (VRP) is one of the most important issues to determine the system's operational efficiency. Several VRP algorithms have been developed and tested to improve the operations of cold chain logistics. Song, *et al.* [45] modelled a canonical VRP, where the varied time windows, the types of vehicles, and the different levels of energy consumption were modelled as the main control parameters. An improved artificial swarm fish (IASF) algorithm was also proposed to solve this NP-hard problem. Al Theeb, et al. [67] proposed a generic mixed-integer optimization model to support the decisions related to inventory allocation problems, vehicle routing problems, and cold supply chain (IVRPCSC). Huai, et al. [63] formulated a multi-objective model to reduce the freight damage and the distribution costs of a cold chain logistics system.

Facility location and routing problems have received attention in vaccine supply chain management, where complex decision-making problems are usually tackled with analytical optimization approaches. Lim, et al. [68] developed a MIP model for planning a vaccine distribution network using intermediate distribution networks. Rastegar, et al. [19] investigated a novel mixed-integer linear program for a location-inventory problem to ensure the fair allocation of influenza vaccines in developing countries during the COVID-19 pandemic. PG Petroianu, et al. [69] developed a user-friendly excel spreadsheet with optimization tools for effective routing and scheduling of vaccine distribution in Mozambique. With an analytical optimization model, Lin, et al. [70] presented the impacts of different cold chain transportation policies in a vaccine supply chain. Yang, et al. [58] developed a MIP model to improve vaccine supply chains' network designs focusing on low and middle-income countries. The authors proposed a novel MIP-based disaggregation-and-merging algorithm to improve the model's computational efficiency for large-scale instances.

### 3.4.2 Simulation

Simulation methods have until recently gained momentum in supply chain analysis. One of the main challenges of a complex supply chain such as VSC is the uncertainty of the system. The volatility of demands, cost variability, and turbulence associated with supply chains are best addressed by utilizing simulation techniques [28]. Giacomo [28] defines simulation as a way of tackling a problem by building a model of the related system. Simulation models are virtual representations of the problem being studied, presenting a 'real world' outlook and allows experimenting with different VSC scenarios. Ricki G. Ingalls [71] argued that mathematical optimization models could not well address many real-world conditions. Hence, the use of simulation methods in modelling supply chain problems had more advantages than optimization methods in processes where demands and other parameters change with time.

There are various ways to use simulation techniques in supply chain management. Simulation models allow different scenarios of supply chain configurations and operational strategies to be assessed, whereas, in some instances, they are used to test and validate analytical optimization solutions [61, 72]. Moreover, for problems with a limited number of scenarios, the ability of simulation methods to incorporate high levels of complexity and mimic a supply chain network's real-life characteristic makes it advantageous than optimization methods [61]. Several studies with optimization models and methods use simulation to test their algorithms' applicability and validity [64, 73, 74]. Vieira, et al. [75] suggested that simulation tools should be used as data integration tools in solving the dynamics and uncertainties associated with supply chains. Dai, et al. [76] used a numerical simulation to test their decision-making time-delay model for vaccine transportation.

Vaccines from foreign sources arrive in a country by air or by sea and stored in a central warehouse before further transported to other parts of the country through intermediate distribution centres [68]. The vaccine supply chain at the country level can be broken down into four main stages: (1) the sourcing at the national level; (2) the storage of vaccines; (3) the transportation between different levels and (4) the administration of vaccines at administration points [61]. Decisions and problems associated with these stages of the vaccine supply chain can be effectively analyzed using computer-based simulation tools such as; HERMES, AnyLogic, etc. With the help of HERMES modelling software, Lee, *et al.* [16] developed a simulation model for evaluating Mozambique's vaccine supply chain's weaknesses and suggested improvements for supply chain operations. Usually, the researchers using HERMES software consider the entire vaccine supply chain [16, 29, 77]. Also, Shittu, et al. [78] addressed problems relating to vaccines storage facilities in Nigeria by applying a simulation model to analyze the effect of the vaccine supplies' fluctuations and demands on the storage capacity requirements.

### 3.4.3 Optimization Simulation

The recent advancement in computational science and its applications has caused a surge in the hybrid application of simulation and optimization methods, often referred to as SIM-OPT. The advantages of both methods can be combined to yield a better analysis and solution to complex decision-making problems in vaccine supply chains. A recent study shows that the simulation-optimization approach has gained a lot of attention in the industry and is a more appropriate method to solve SCND problems with uncertainties, time efficiency and to optimize preferred criteria [79]. Furthermore, this method's application also caters for operational risks that are prone to uncertainty in real-world problems [79]. For instance, Dillon and Colton [80] used a simulation-optimization based approach to determine the most economical design solution of vaccine warehouses in developing countries. Their experiments indicate that using the simulation-optimization method yields a more accurate analysis and makes the problem less computationally expensive.

## 3.5 Summary

Vaccine supply chain and cold chain logistics literature have received increasing attention in the past decade among various study fields. This study presents; (1) bibliometric analysis to determine the most popular publications and identify the trends in literature and (2) an in-depth content analysis to identify the research gaps.

In conducting this research, a total of 119 documents that have contributed to VSC and CCL within the past decade were reviewed. Using a network analysis tool, four classification analysis, including (1) journal co-citation analysis, (2) co-occurrence analysis of keywords, (3) analysis of collaborations between countries and (4) documents co-citation analysis, were made. The results indicate that there has been a tremendous increase in the number of publications in VSC from 2018 till date, with the Computers and Industrial Engineering journal having the most publications. This increase in VSC and CCL publications in OR/OM could be attributed to the fact that researchers are focused on making VSC more efficient in terms of cost and logistical challenges as this contributes to achieving an effective immunization scheme. Since logistics play a crucial role in the VSC, it becomes inherent that more studies are conducted towards improving the VSC. Some of the countries actively involved in VSC and CCL research mainly include China, the United States and India, with China having the most publications and collaborations with several countries across Europe.

Research on vaccine supply chain is relatively limited, and simulation-based approaches to logistical transportation problems have not been fully explored. There is a lack of research using two-level optimization-simulation methods in vaccine distribution. Most studies on vaccine distribution focus mainly on strategic and tactical issues and less on operational decisions at the last mile. Also, more real-world applications of developed methodologies developed in such studies are needed.

# 4 COVID-19 VACCINE DISTRIBUTION IN NORWAY

In this chapter, an overview of Norway's demographics, followed by the strategic distribution of the COVID-19 vaccines in Norway is presented. The case study methodology is discussed in the later sections.

## 4.1 Norway in a nutshell

Norway is a Scandinavian country located in Northern Europe and shares borders with Sweden, Finland and Russia, as shown in Figure 10. The country consists of the mainland, the archipelago of Svalbard and the island of Jan Mayen. The total population of the country sits at over 5.3 million (2020) [81], with the inhabitants spread over 385 207 square kilometres [82], making it one of the most sparsely populated countries in Europe. The country's landscape averages plains, coastal fjords, mountains with a temperate climate along the coast [83].

Norway has had a high growth over several decades following the discovery and production of oil in the early 1970s, making it one of the wealthiest countries per head in the world with a GDP, USD per capita of 81,697 (2018) [84]. The country is divided into 11 administrative regions called counties and 356 municipalities, with Oslo as the capital [85]. Norway is not an EU member, although it is a member of the European Economic Area (EEA) [83].

Founded on the principle of universal access, the Norwegian health care system is semi-decentralized. Health care policies, regulation and supervision of the entire health system are centrally controlled by the Directorate of Health and the Norwegian Medicines Agency under the Ministry of Health, whilst specialized health care is administered by the four Regional Health Authorities (RHAs). The local municipalities solely control primary health care, whereas public health services are delivered both at national and regional levels [86]. With good access to pharmaceuticals, Norway's population has a benefit of good health status, with a life expectancy of 84.2 years for women and 80.6 years for men, which is above the EU average of 80.14 years [87].

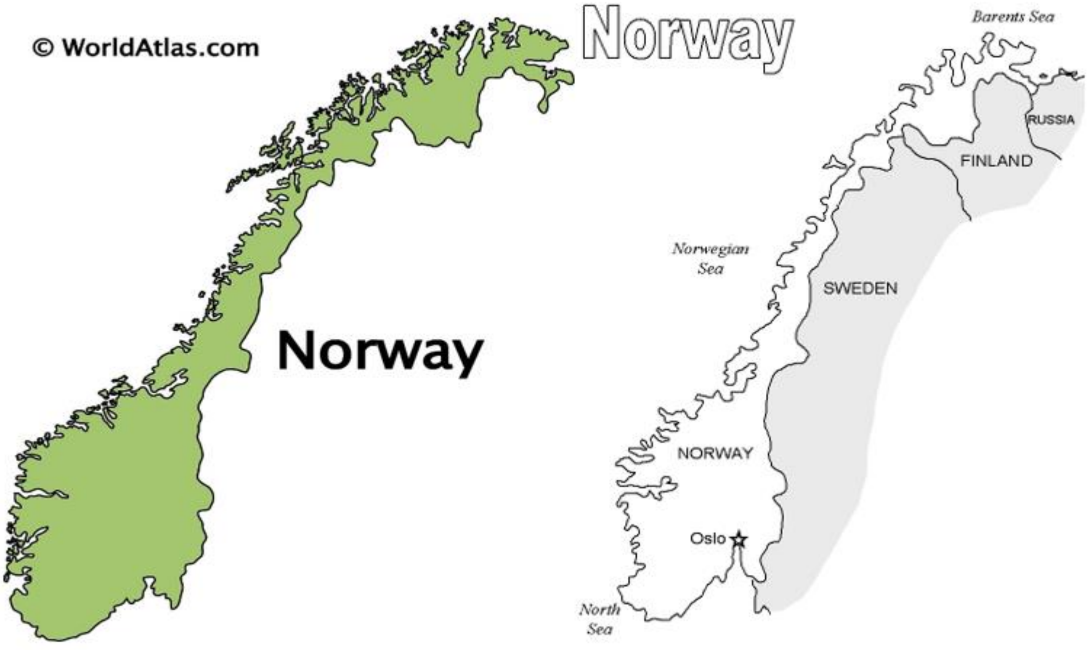


*Figure 10 Map of Norway* [88, 89]

### 4.1.1 COVID-19 Vaccine Distribution in Norway

Before vaccines are introduced into the Norwegian Immunization Program, they are approved by the Norwegian Medicines Agency (NMA) and procured by the Norwegian Institute of Public Health (NIPH). COVID-19 vaccines approved in Norway are first reviewed for use throughout Europe by the European Medicines Agency (EMA). The vaccine manufacturers send their research to the EMA for 'rolling review' before the vaccines are recommended [90]. In February 2020, Johnson & Johnson applied for approval of its COVID-19 vaccine candidate to the EMA [91]. The EMA's recommended vaccines are then approved by the European Union (EU) Commission for use across Europe. Through the European Economic Agreement (EEA) agreement, the Norwegian government approves the COVID-19 vaccines from the EU Commission to be used for vaccination [90].

Currently, four COVID-19 vaccines have been approved by the Norwegian government in its Coronavirus Immunization Program; (1) Pfizer/BioNTech, (2) Moderna and (3) Oxford/AstraZeneca, (4) Johnson & Johnson. The vaccines arrive in Norway by air and are received by the Norwegian Institute of Public Health (NIPH) and stored in its central warehouse before direct distribution to several reception centres in the various municipalities, as shown in Figure 10. The Pfizer/BioNTech vaccines are shipped directly from the factories to the regional health authorities and hospital pharmacies [92] to cater for the physical transportation of the vaccines to maintain their ultra-cold temperature requirements throughout the cold chain.  The NIPH controls the weekly distribution of the vaccines to the municipalities with real-time tracking. Direct distribution from the central warehouse to the various reception centres is done either by refrigerated trucks or cooling boxes within 0-8 hours in Eastern Norway and 24–36 hours to the other parts of Norway [93].

*Figure 11 Norway Vaccine Supply Chain adopted from VG-Coronavirus* [90]

The current COVID-19 vaccine distribution strategy used by NIPH is to allocate more vaccine doses to municipalities with high COVID-19 infection rates and the number of people over 18 in the various municipalities. The geographical redistribution based on areas with high infection rates allows for a 20% increase in vaccine doses to Oslo and four other municipalities. Additionally, the distribution will also depend on the number of inhabitants in a municipality over 18 years of age. This new distribution key follows a previous one where the distribution was solely based on the number of people over 65 years living in the municipalities. Since a significant number of the older generation have been vaccinated, the new distribution key is needed to prevent the spread of the more contagious variants of the COVID-19 virus in the larger urban municipalities [94]. The distribution of Norway's population according to the 11 Counties and age proportion is presented in Appendix B [81].

The Head of the Vaccine department at NIPH, in an interview, disclosed that the transportation of the COVID-19 vaccines to the various municipalities is carried out using third-party logistics companies [95]. Moderna and AstraZeneca vaccines are centrally stored in NIPH's central warehouse and then directly transported to different municipalities using AmerisourceBergen World Courier, a biopharmaceutical logistics company. The deliveries are done with 50 active cooling cubes fitted in small trucks (Figure 12) to all parts of Norway except the northern parts of Nordland, where passive cooling containers are used. Whereas Pfizer/BioNtech vaccines are transported directly from the manufacturing factory in Belgium to the hospital pharmacies using SLexpress refrigerated transport [95], Figure 13. Both 3PL companies use ThermoKing cooling containers and cubes [96] as shown in Figure 12.

This is what the vaccine car looks like. In the vehicle a huge freezer is installed.

PHOTO: STIG JAARVIK / NRK

VAKSINEBIL: I kjølebokser, montert i disse kjøretøyene, skal vaksinene oppbevares når de fraktes ut til kommunene.

FOTO: JOAKIM REIGSTAD / NRK

*Figure 12 Vaccine Trucks with active cooling cubes* [96]

*Slik ser bilene ut som skal frakte koronavaksinen ut til landets kommuner. (Foto: Pfizer Norge)*

VACCINE TRANSPORT: The car with the first corona vaccines arrived at Ullevål Hospital on Saturday morning. Photo: Terje Pedersen / NTB

*Figure 13 Pfizer/BioNtech vaccines truck* [97, 98]

Two types of cooling boxes are used within the municipalities for internal transportation or storage during vaccination; (1) Coldtainer coolers 22 litres and 32 litres capacities, and (2) Dometic CFX 32 litres [99]. The COVID-19 vaccines are distributed in the municipalities according to a prioritization scheme with target groups set by the NIPH. Table 5 shows the dosage per vial for the distribution of different COVID-19 vaccines in Norway.

*Table 5 COVID-19 Dosage/Number of Vials Distribution in Norway*

| Type of COVID-19 Vaccine | Doses/vial | Doses/pack |
|---|---|---|
| Pfizer/BioNTech | 6 doses/vial | 1170 doses/pack [100] |
| AstraZeneca | 10 doses/vial | 100 doses/pack [101] |
| Moderna | 10 doses/vial | 100 doses/pack [102] |

## 4.2 Challenges of the Last Mile Distribution of COVID-19 Vaccines

1. *Supply uncertainties:* Due to the high demand for COVID -19 vaccines around the world, there is a high degree of uncertainty regarding supply to various countries. Orders cannot be placed according to the number of infections; this leads to poor planning of vaccination in countries. Supply uncertainties also lead to delayed deliveries, which does not augur well for the last mile distribution of the vaccines.
2. *Time Constraints:* Since vaccines are temperature sensitive, they must be delivered on time to maintain the cold chain and avoid wastage. Timely delivery is very important in this case to also achieve higher vaccination coverage and contain the spread.
3. *High cost of last-mile distribution:* A major factor of COVID -19 vaccine distribution is on-time delivery. The associated costs of delivering vaccines on time at regular intervals are usually high.
4. *Route optimization:* Optimization of transportation routes in last-mile distribution is of key importance. This has an impact on the expected lead times of deliveries and the associated transport costs.
5. *Cold chain requirements:* To effectively store and transport the vaccines to the health facilities for vaccination, an effective cold chain needs to be ensured. Storage facilities and refrigerated trucks that adhere to the temperature requirements of the COVID-19

vaccines need to be in place to effectively ensure the viability of the vaccines at the point of administration.

6. *Environmental impact:* The increasing number of regular vaccine deliveries to health facilities (end customers) causes a trend of increased carbon gas emissions from refrigerated trucks. This is one of the major causes of environmental pollution in CCL and needs to be addressed. How can the VSC effectively achieve its goals with less environmental impact?

## 4.3 Methodology

### 4.3.1 Choosing the Case

Narrowing down on the distribution of COVID-19 vaccines in Norway, Inland County was chosen to evaluate its COVID-19 vaccine distribution network. Inland is the second-largest county located in the eastern part of Norway and is the only county with no coastline. It has a population of about 371,385 (2020), with 46 municipalities divided into ten regions [103]. Following the distribution strategy used by the NIPH for vaccine distribution as discussed in section 4.1.1, it was, therefore, crucial to choose an urban county with a high COVID-19 infection rate and a large population of inhabitants over 18 years old to evaluate its vaccine distribution network. It can be deduced from Appendix C that the proportion of the population in Inland over 18 years is 30,1975, which accounts for 81% of the entire population.

### 4.3.2 The simulation method used in this study

As discussed in section 3.4.2 of the Literature review, the ideal approach to solving the problem in this case study is the use of the simulation since it allows the overall picture of the distribution of the COVID-19 vaccines in Inland County to be mimicked and analyzed. Using the simulation method makes it easy to look at different scenarios under a more realistic environment; however, the models generated in the simulation experiments are simplified renditions, and as such, not all characteristics and attributes of the vaccine supply chain can be encapsulated [16].

The simulation software used in this study was "anyLogistix supply chain software". AnyLogistix uses a combination of analytical optimization techniques and innovative, dynamic simulation technologies to help in supply chain design and analytics as shown in Figure 14 [104]. Figure 15 shows how simulation and optimization variants are combined depending on the modelling objective [105]. With a powerful built-in CPLEX solver and supported VRP optimizer, the software allows users to optimize logistical challenges quickly. The generated optimal solutions could be tested and visualized under dynamic and stochastic conditions with the embedded GIS tools in anyLogistix's simulation technology.

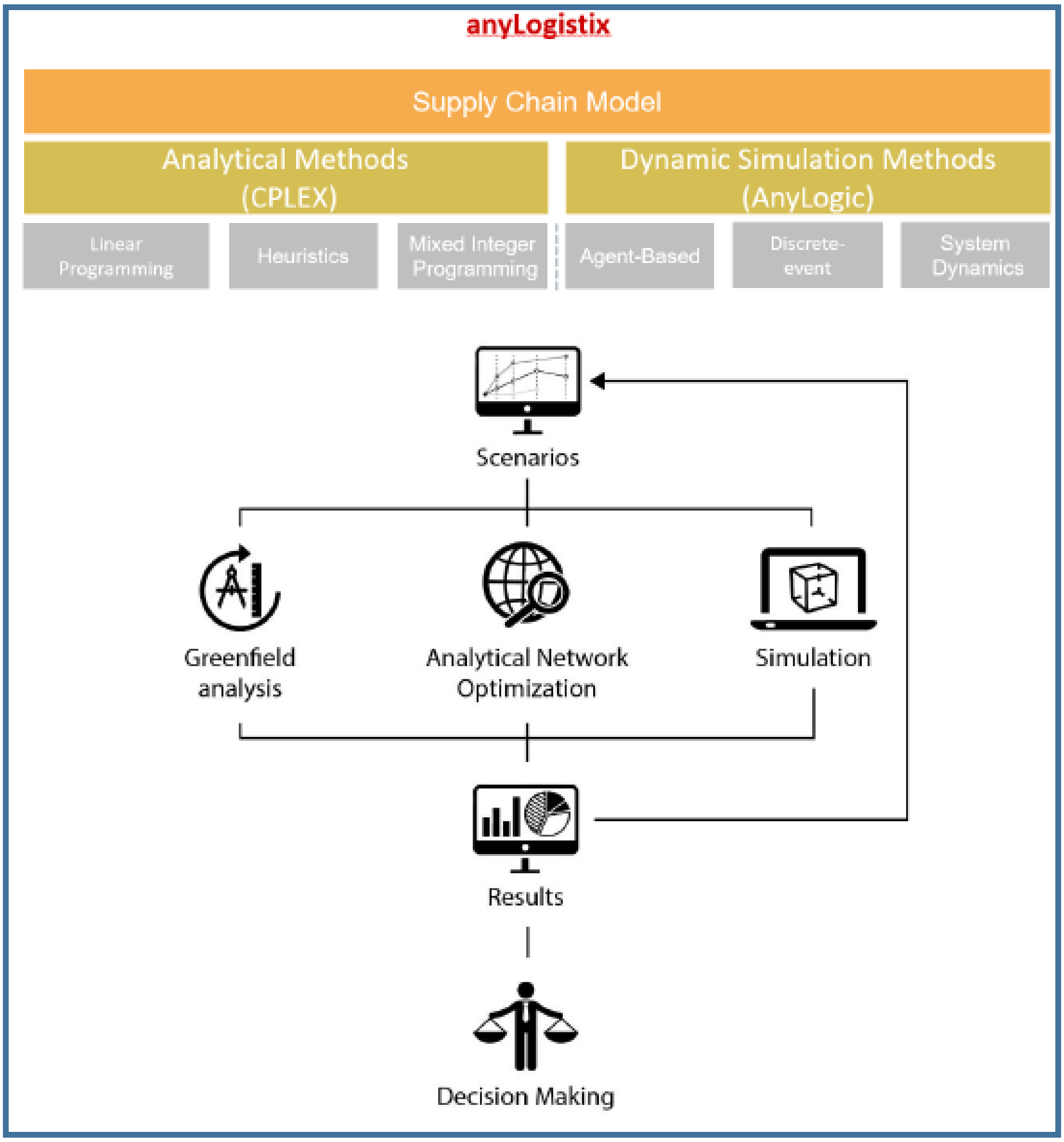


*Figure 14 Analytical and Simulation methods in anyLogistix* [105]

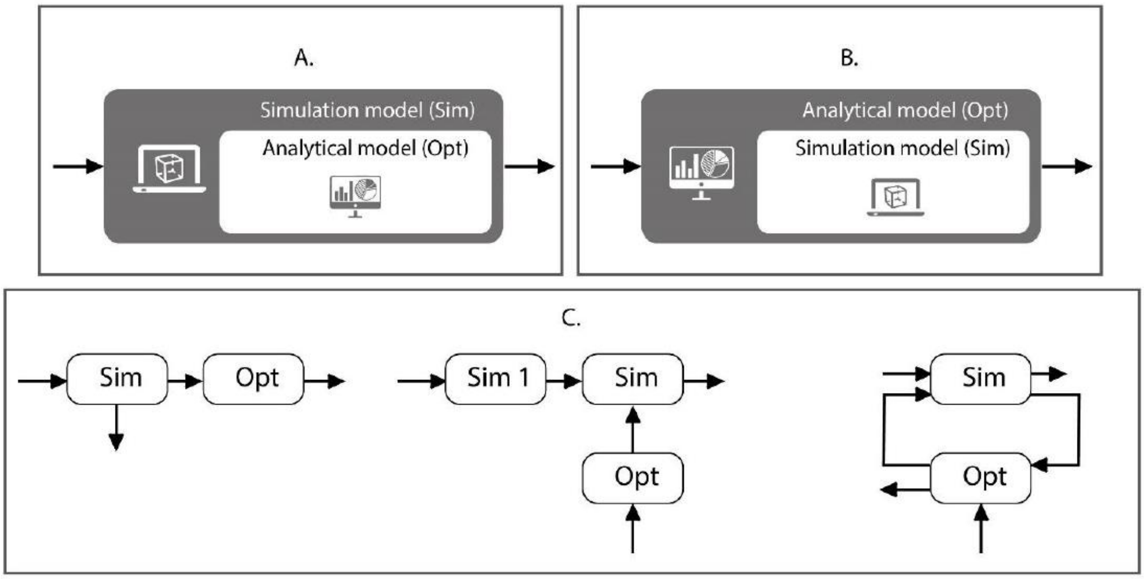


*Figure 15 Optimization and simulation combination variants* [105]

### 4.3.3 Data Collection

To fully simulate and analyze the last mile distribution of the COVID-19 vaccines in Norway, it was essential to narrow the distribution down to a regional level to avoid complexities. Therefore, Inland County's vaccine distribution network was chosen as a case study. The data curated for this study were classified into supply data and demand data.

The supply data mainly included the structure of the current vaccine distribution flow network, operational strategies, geographical location of the FHI warehouse and health centres where the vaccines are received in the municipalities, transportation modes, vehicle types used for transportation and their capacities. The demand data used in the study were the types of COVID-19 vaccines distributed to Inland county, their corresponding quantities and the time windows for receiving the vaccines.

Through several web research, most of the secondary and statistical data were acquired and some raw data captured through email interviews and phone calls. The director and Head of the vaccine supply department of NIPH were accommodating as they provided information concerning the transportation modes, vehicle fleet size and some operational strategies. Most data curated for this study were mainly derived from NIPH' website, VG.no Coronavirus live update feed and news items from both national and local websites. It is important to note that not all required data were available for this study; some assumptions and estimation had to be made.

### 4.3.4 Experimental Settings

This experiment is a two-stage optimization simulation as shown in Figure 16. Using anyLogistix software, the vaccine distribution to the municipalities is modelled in a transportation optimization experiment to find the optimal vehicle routes and associated decisions. The optimal decisions are then tested under dynamic simulation conditions to determine the decisions that maximize the expected lead time (ELT) service responsiveness and minimize transportation costs and associated environmental impact ($CO_2$ emissions). The analysis of the case study is done in two settings;

1. Transportation Optimization (TO)
2. Simulation (SIM)

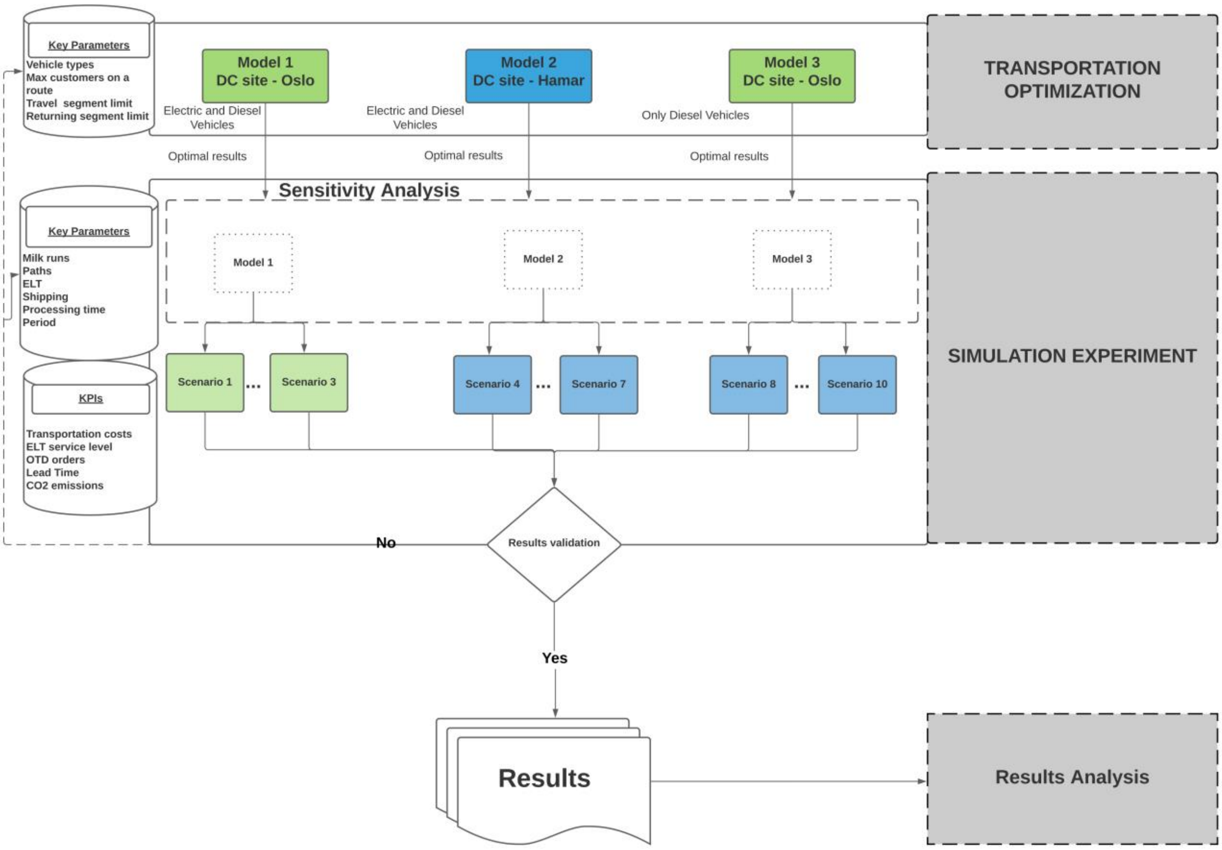


*Figure 16 Experimental settings framework*

A mimic model of the vaccine supply chain is built with anylogistix software, and a transportation optimization experiment is performed with its' built-in CPLEX to obtain optimal transportation routes. Models created in TO are exported to SIM and are run over the results obtained in the TO experiments as 'Milk Runs'. Building the model in TO to obtain optimal results helps to *validate* the structure of the simulation model created. In SIM, a sensitivity analysis is performed to test the behaviour of several KPIs in the models. Different scenarios are created and simulated from the results obtained in the sensitivity analysis. The simulation experiment provides a visual representation of the supply chain, and with additional parameters such as paths, shipping, processing time, period, etc., several performance indicators can be analysed. For *verification*, simulation runs are monitored closely, and the results generated are analysed, hinging on deterministic data such as the lead time.

# 5 PROBLEM DESCRIPTION AND DEVELOPMENT OF METHOD

This chapter defines the problem to be solved in this study, followed by an in-depth description of the development of the simulation models.

### 5.1.1 Problem definition

The problem discussed in the early sections of this thesis aims to find an effective way of distributing COVID-19 vaccines in Norway to curb the widespread Coronavirus disease. The current COVID-19 vaccine supply chain in Norway is a demand-pull system heavily constrained by uncertainties in vaccine supplies and deliveries. Municipalities cannot place orders for the vaccines but must wait for the weekly allocated vaccines by the NIPH; as a result, affecting the planning of the vaccination program. The fourth research question is addressed in this section.

The supply chain under study is considered a two-stage SC consisting of one distribution centre shipping out COVID-19 vaccines to 46 customers. The generic representation (Figure 17) of the SC shows that the vaccines from the factory are received into FHI's central warehouse in Oslo before transporting them to the municipalities' health facilities using small trucks fitted with active cooling cubes. Based on available data, the study period is from Week 53, 2020 to Week 10, 2021. The weekly distribution of the vaccine doses curated from the NIPH database is presented in Appendix B.

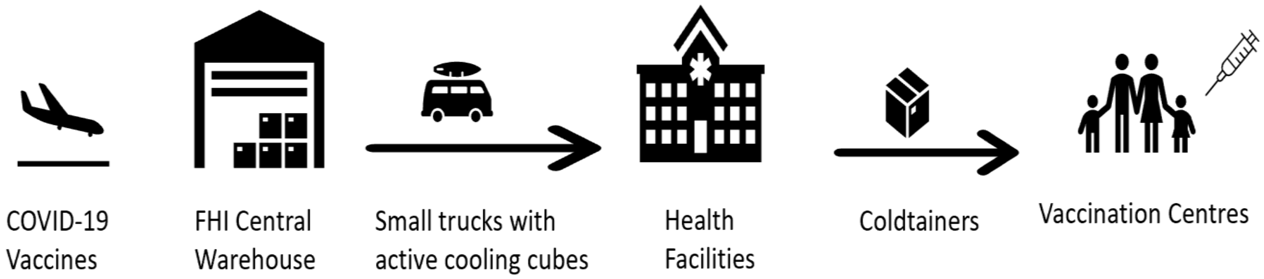


*Figure 17 Representation of COVID-19 supply chain in Norway*

### 5.1.2 Input parameters and assumptions

1. DCs and customers

For model simplification, the number of customers for the model is set at 46, assuming that there is one customer for each municipality within the county. In model 1 and 3, the DC is located in Oslo, the actual location of the NIPH's central warehouse [95] and is represented by the red icon (Figure 18). In model 2, it is assumed that a DC is opened in Hamar in order to improve the accessibility and responsiveness of the vaccine delivery network to customer locations (Figure 19). Two customer groups, (1) *Customer Group 1* and (2) *Customer Group 2* were created. *Customer Group 1* constitutes the set of customers closer to the DC, whilst *Customer Group 2* defines customers farther away from the DC represented by green and blue icons respectively, as shown in Figures 18 and 19.

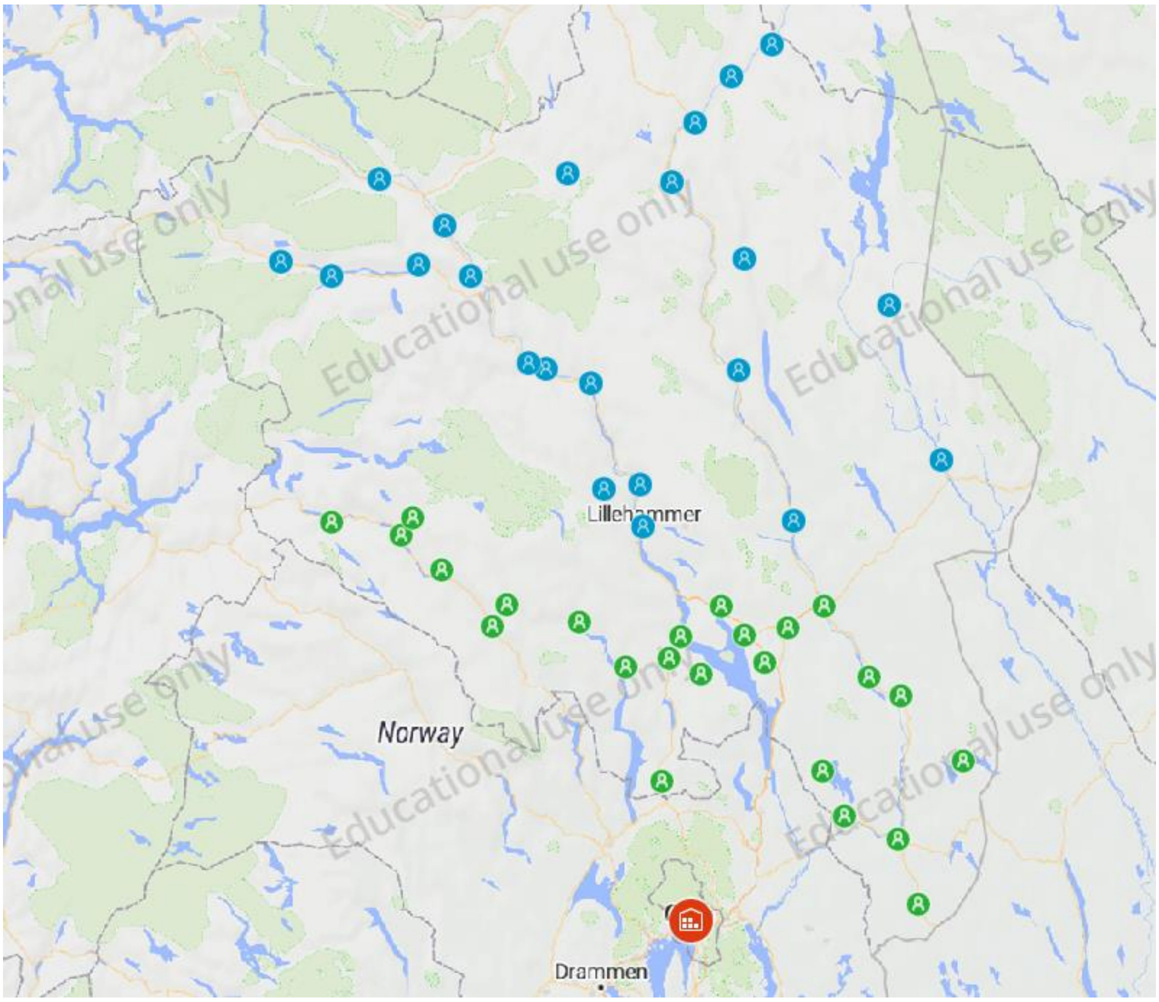


*Figure 18 Structure of Model 1 and 3*

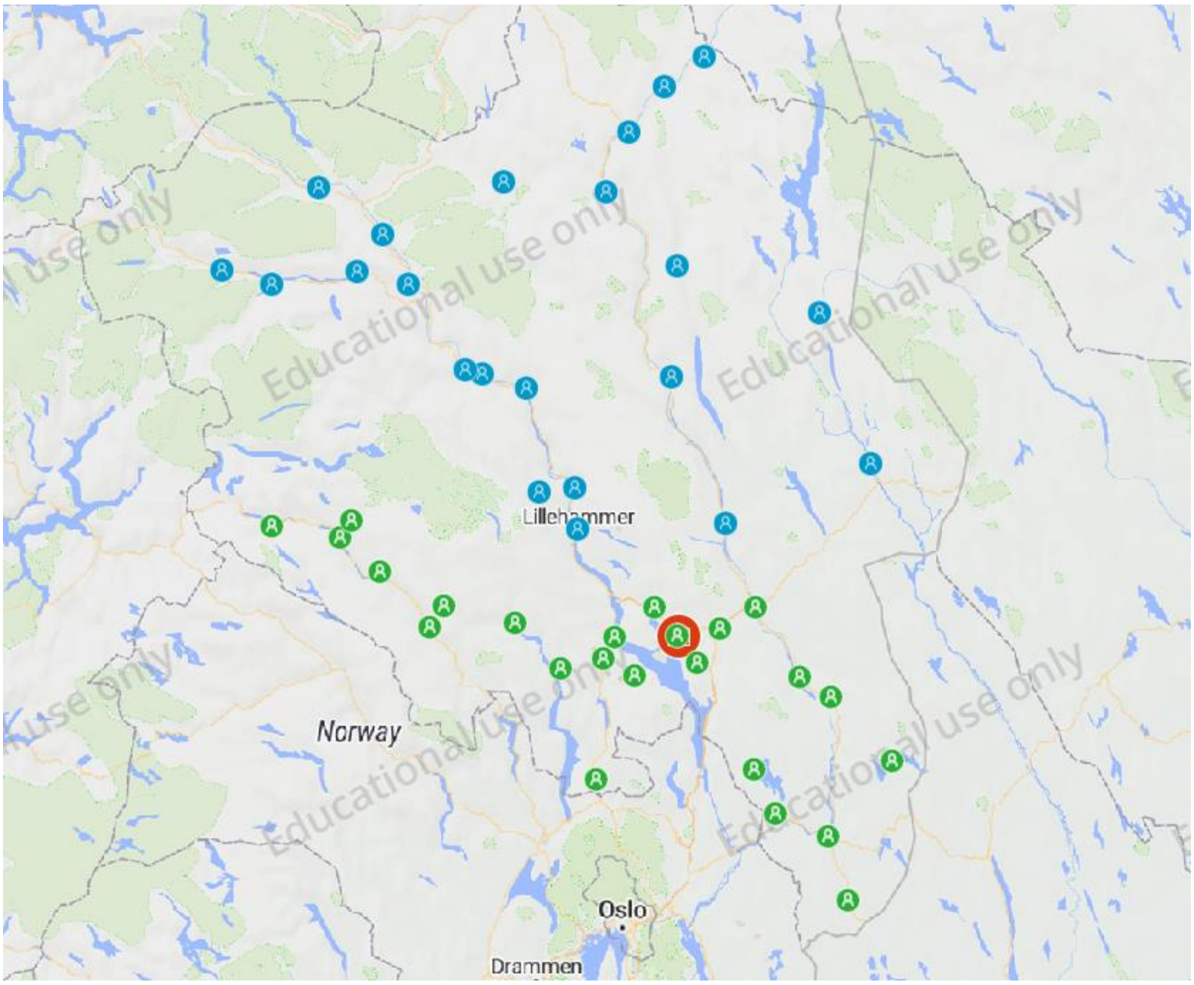


*Figure 19 Structure of Model 2*

Outbound processing time at the DC is considered to be uniform (20;30) minutes, where the minimum processing time is 20 minutes, and the maximum is set at 30 minutes. The inbound processing time for the customers is also assumed to be uniform, with a minimum of 10 minutes and a maximum time of 20 minutes. Shipment of the products is made from the DC to all customers using two types of vehicles. The shipping policy used is assumed to be LTL (Less than Truck Load) which implies that any order could be shipped regardless of the quantity and the truck does not necessarily have to be full. Priority is set at Expected Lead Time, which means orders with the least lead time is given the highest priority. Working hours are assumed to be from Mondays to Fridays based on the Norwegian Labour Act, and that shipping is carried out between the hours of 6:00 am to 3:00 pm [106]. Since the products are sourced from the central DC located in Oslo, the sourcing policy considered for this analysis is Fastest (Fixed Source) based on the delivery times to each customer.

### 2. Demand

The demand data used for developing the model is curated from NIPH (Appendix B) within a period of 12/28/2020 and 3/15/2021. The demand is based on historical demand data, in the given period of study. Since the actual demand from the case study is weekly based, the input demand data is set accordingly, with an ELT of one day for *Customer Group 1* and two days for *Customer Group 2* [93]. Based on the available data, the backorder policy is assumed to be 'Allowed Total', which means that the order is kept pending until the required number of products is available for shipping.

### 3. Products

The real problem considers two types of products for distribution, but one product type is considered for simplification of the model in this study. The COVID-19 vaccination in Norway is free; thus, the selling price of the products in the model is set to 0. The product used in the model is COVID-19 vaccines with the corresponding unit in doses. Based on Table 5, the unit conversion was estimated to be 600 doses per cubic meter (600doses/ $m^3$) in this study.

### 4. Vehicle types and paths

The distribution of the vaccines in Norway is carried out by NIPH using a 3PL service provider, with 50 active cooling cubes fitted in small trucks [95]. The model considers three types of vehicles for the distribution of the products defined in this study, (1) Nissan NV200, (2) Nissan e-NV200 (electric vehicle) and (3) Volkswagen (VW) Transporter. In model 1 and 2, the capacities of the vehicles are estimated to be 2.1 $m^3$ based on the capacity of the active cooling cubes used [107]. In model 3, the Nissan NV200 and VW transporter capacities are estimated to be 4.3 and 6.7, respectively [108, 109]. The vehicles' speed is estimated to be triangular with 40km/h as the minimum speed, 70km/h as the maximum speed and a mode speed of 50km/h based on the Norwegian traffic rules on speed limit [110]. The max path of the Nissan NV200 and the VW Transporter was estimated to be 1000km, and the electric type was estimated to be 300km (considering the range and the battery) [111].

Two paths were defined for the transportation of the products from the DC to the customers using heterogeneous vehicles. The Electric Nissan NV200 was assigned to transport the vaccines from the DC to *Customer Group 1* and the Nissan NV200 to *Customer Group 2* in model 1 and 2. In model 3, the Nissan NV 200 transports the products from DC to *Customer Group 1* and the VW Transporter to *Customer Group 2*. The transportation cost estimation used is "distance-based with fixed cost policy". Considering a variable cost estimation of 6 for the electric vehicle and 8 for the Nissan NV200, the fixed cost in model 1 and 2 was estimated to be 1500 NOK. In model 3, the variable costs were estimated to be 8 for the NV200, 10 for the VW transporter with 1500 NOK as a fixed cost for both vehicles. The variable cost estimations were based on assumptions of the amount of $CO_2$ emissions from the vehicles, fuel and electricity costs which are directly proportional to the travel distance. The fixed cost is derived from the drivers' salary and is set at a constant value of 1500 NOK because the three types of vehicles are considered in the same category as a small truck [24, 112]. These assumptions and estimations are based on data from Statistics Norway [112].

Since a 3PL performs the actual transportation, the cost of fleet maintenance, cost of vehicles and other transportation policies are not considered. The $CO_2$ emissions are also calculated based on travel distance and the variable $CO_2$ emissions from the vehicles. The $CO_2$ emission from the Nissan NV200 and VW Transporter is estimated to be 131g/km and 159g/km, respectively [108, 113], whereas the electric vehicle has zero-emission [111].

*Table 6 Summary of key input parameters used in the experiments.*

| Input Parameters | Description | Values | Units |
|---|---|---|---|
| Vehicle capacity | Nissan NV200 (* model 3) | 2.1/4.3* | $m^3$ |
| | Nissan e-NV200 | 2.1 | $m^3$ |
| | VW Transporter | 6.7 | $m^3$ |
| Vehicle speed | Variable speed | Triangular (40;70;50) | Km/h |
| Vehicle range | Nissan NV200 | 1000 | km |
| | Nissan e-NV200 | 300 | km |
| | VW Transporter | 1000 | km |
| Co2 emissions | Nissan NV200 | 131 | g/km |
| | Nissan e-NV200 | 0 | g/km |
| | VW Transporter | 159 | g/km |

| | | | |
|---|---|---|---|
| Transportation costs | Variable Cost<br>(e-NV200/NV200/VW Transporter) | 6/8/10 | NOK/km |
| | Fixed Cost | 1500 | NOK/stop |
| Expected Lead Time (ELT) | Customer Group 1 | 1 | day |
| | Customer Group 2 | 2 | |
| Processing times | Inbound shipment | Uniform(10;20) | minute |
| | Outbound shipment | Uniform(20;30) | minute |
| Shipping | Shipping time | Monday to Friday<br>6:00am to 3:00pm | day |
| Period | Experiment Duration | 12/28/2020 – 3/15/2021 | day |

### 5.1.3 Key Performance Indicators

As shown in Table 8, three groups of key performance indicators (KPIs) were considered to analyze the supply chain performance, (1) *financial*, (2) *customer*, (3) *operational* and (4) *environmental* performance.

For this study, the *financial performance* is measured by transportation cost which is computed based on the cost estimations defined in the paths' parameters. It constitutes the sum of all shipments computed for each day.

*Customer performance* is measured using ELT service level by products: the ratio of the products delivered on time to the overall number of products shipped. It considers the transportation time to the customer. If products are delivered within the defined time windows and the expected lead time, it is considered an on-time delivery.

*Operational performance* is measured by the lead time and fleet utilization. The lead time is the time it takes for a delivery to be made from the DC to the customer. Fleet utilization is measured by the maximum number of vehicles used simultaneously each day.

*Environmental performance* is measured by the $CO_2$ emissions from the vehicles. It is a measure of the total $CO_2$ produced by the vehicles transporting the products from the DC to the customers and between customers. It is updated at the end of each day.

*Table 7 Key performance indicators*

| **KPI Groups** | **Performance Indicators** |
|---|---|
| Financial performance | Transportation cost |
| Customer performance | ELT Service level |
| Operational performance | Lead time |
|  | Fleet utilization |
| Environmental Performance | $CO_2$ emissions |

## 5.2 Experiments

As discussed in section 4.3.4, the experiments performed in this study are done in two settings using the anyLogistix simulation software with a defined experiment duration between 12/28/2020 and 3/15/21. The key parameters that were used in both experiments are presented in Table 7.

### 5.2.1 Transportation Optimization (TO)

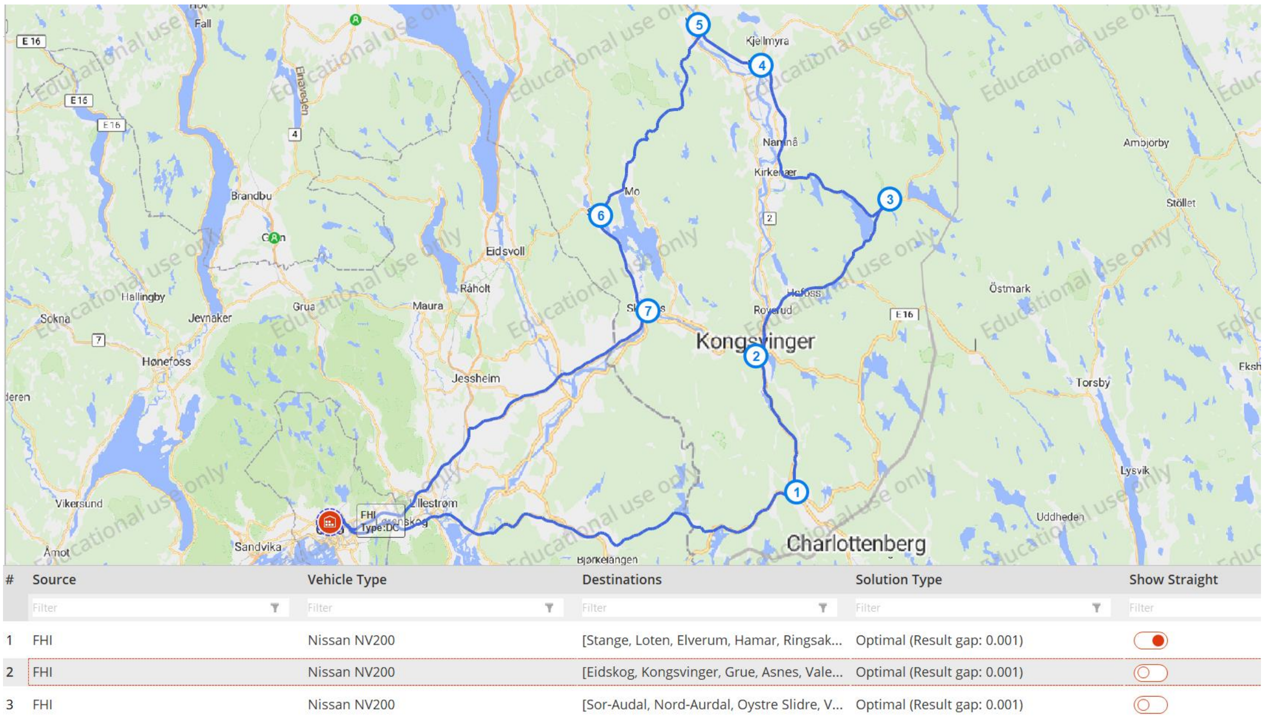
The first group of experiments were performed in TO, where three main models were developed to represent the existing vaccine distribution network. The TO experiments were performed to find optimal transportation route decisions. The first model, *Model 1* depicts a simplified mimic of the current network (Figure 18), with 46 customers grouped into two categories to simplify the model. In *Model 1* and *3*, the DC is situated in Oslo, which is the actual distribution centre for NIPH. *Model 2*, on the other hand, has its' DC located in Hamar (Figure 19), the capital city in the county. The DC is Hamar was selected using greenfield analysis (GFA) in anyLogistix, which is a centre-of-gravity analysis method used to find and determine optimal locations. The decision to create a DC close to customers was based on the travel distance from the DC to the customers, which could affect transportation costs, responsiveness, and $CO_2$ emission.

In all 3 models, three vehicle types were defined (see section 5.1.2) and the corresponding fleet size set to 0, respectively, to not place any fleet size constraints on the experiments. The parameter inputs for performing the TO experiments for the different models are presented in Table 8.

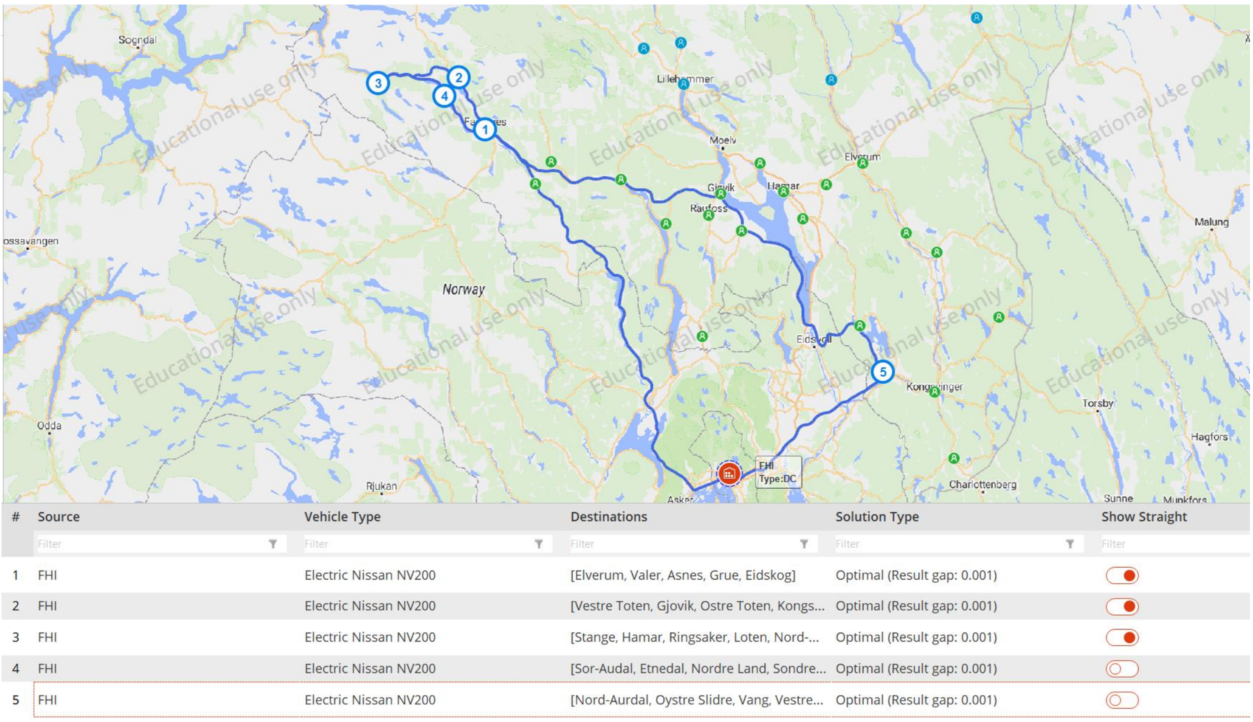
*Table 8 Input parameters for TO experiments*

| **Input Parameters** | **Model 1** | | **Model 2** | | **Model 3** | |
|---|---|---|---|---|---|---|
| Vehicle types | Electric Nissan NV200 | Nissan NV200 | Electric Nissan NV200 | Nissan NV200 | Nissan NV200 | VW Transporter |
| Max customers on a route | 5 per trip | 10 per trip | 5 per trip | 10 per trip | 10 per trip | 5 per trip |
| Travel segment limit | 300km | 500km | 300km | 500km | 500km | 500km |
| Returning segment limit | 100km | 200km | 100km | 100km | 200km | 300km |

The maximum number of customers on a route is constrained as shown in Table 8 considering the service level and responsiveness of the distribution network. Similarly, the travel segment and the returning segments are also constrained based on the range defined and servive level responsiveness. In *models 1* and *2*, five optimal routes were generated from the respective DC's to *Customer Group 1* with the Electric NV200 vehicles and three optimal routes to *Customer Group 2* with the Nissan NV200. *Model 3* generated three optimal routes from the DC to *Customer Group 1* using the Nissan NV200 and five optimal paths to *Customer Group 2* with the VW Transporter. The generated optimized routes were exported to SIM for further experiment analysis. Figure 20 shows an example of the optimal paths generated in TO.



| # | Source | Vehicle Type | Destinations | Solution Type | Show Straight |
|---|---|---|---|---|---|
| 1 | FHI | Nissan NV200 | [Stange, Loten, Elverum, Hamar, Ringsak... | Optimal (Result gap: 0.001) | ● |
| 2 | FHI | Nissan NV200 | [Eidskog, Kongsvinger, Grue, Asnes, Vale... | Optimal (Result gap: 0.001) | ○ |
| 3 | FHI | Nissan NV200 | [Sor-Audal, Nord-Aurdal, Oystre Slidre, V... | Optimal (Result gap: 0.001) | ○ |



| # | Source | Vehicle Type | Destinations | Solution Type | Show Straight |
|---|---|---|---|---|---|
| 1 | FHI | Electric Nissan NV200 | [Elverum, Valer, Asnes, Grue, Eidskog] | Optimal (Result gap: 0.001) | ● |
| 2 | FHI | Electric Nissan NV200 | [Vestre Toten, Gjovik, Ostre Toten, Kongs... | Optimal (Result gap: 0.001) | ● |
| 3 | FHI | Electric Nissan NV200 | [Stange, Hamar, Ringsaker, Loten, Nord-... | Optimal (Result gap: 0.001) | ● |
| 4 | FHI | Electric Nissan NV200 | [Sor-Audal, Etnedal, Nordre Land, Sondre... | Optimal (Result gap: 0.001) | ○ |
| 5 | FHI | Electric Nissan NV200 | [Nord-Aurdal, Oystre Slidre, Vang, Vestre... | Optimal (Result gap: 0.001) | ○ |

*Figure 20 Examples of the optimal generated paths in the TO experiment*

### 5.2.2 Simulation Experiments

The simulation experiment is used to model the delivery of the actual products on the GIS map with statistics generated in real-time. It is also used to perform a ‘what-if’ analysis to see how different decisions affect the outcome of the experiment results. The models created in the TO experiment are exported into SIM, where the optimal paths generated are used as *milk runs*. In the simulation experiment, different ELTs are defined for each model. In *Model 1* and *3*, the ELT for *Customer Group 1* is set as one day and two days for *Customer Group 2.* On the other hand, the ELT for both customer groups in *Model 2 is* set as one day. This is because the DC in *Model 2* is located close to the location of the customers. The main aim of the simulation experiment is to determine the impact of decisions on the defined KPIs and the performance of the supply chain.

A sensitivity analysis was performed on each model using 30 replications within the experiment time duration of 10 weeks which is the actual period of investigation. The result from the sensitivity analysis is presented in Appendix E. Different scenarios were created from each model by varying the fleet size and vehicle type and analysing the performance of the distribution network under the defined KPIs. The scenarios created from the sensitivity analysis are then simulated to find the actual performance of the system with respect to the KPIs. The set of scenarios are presented in Table 9.

*Table 9 Experiment scenarios*

| **Model** | **Scenarios** | **Vehicle Combination** | **Fleet size** | | | |
|---|---|---|---|---|---|---|
| | | | | **Electric Nissan** | **Nissan NV200** | **VW Transporter** |
| | Scenario 1 | Electric Nissan and Nissan NV200 | 3 | 1 | 2 | - |
| **Model 1** | Scenario 2 | Electric Nissan and Nissan NV200 | 5 | 3 | 2 | - |
| | Scenario 3 | Electric Nissan and Nissan NV200 | 6 | 4 | 2 | - |
| | | | | | | |
| | Scenario 4 | Electric Nissan and Nissan NV200 | 3 | 1 | 2 | - |
| **Model 2** | Scenario 5 | Electric Nissan and Nissan NV200 | 5 | 3 | 2 | - |
| | Scenario 6 | Electric Nissan and Nissan NV200 | 6 | 4 | 2 | - |
| | Scenario 7 | Electric Nissan and Nissan NV200 | 7 | 4 | 3 | - |
| | | | | | | |
| | Scenario 8 | Nissan NV200 and VW Transporter | 3 | - | 1 | 2 |
| **Model 3** | Scenario 9 | Nissan NV200 and VW Transporter | 5 | - | 2 | 3 |
| | Scenario 10 | Nissan NV200 and VW Transporter | 6 | - | 3 | 3 |

*Table 10 Results from simulation experiments*

| Scenario | Fleet Size | ELT Service Level | Lead Time | | Max number of vehicles used daily | Transportation Cost (NOK) | Co2 Emission |
|---|---|---|---|---|---|---|---|
| | | | Mean | Max | | | |
| **Scenario 1** | 3 | 0.423 | 1.229 | 4.369 | 2 | 567802 | 3379831 |
| **Scenario 2** | 5 | 0.946 | 0.67 | 1.486 | 3 | 605802 | 3432275 |
| **Scenario 3** | 6 | 1 | 0.628 | 1.891 | 4 | 601099 | 3379831 |
| | | | | | | | |
| **Scenario 4** | 3 | 0.511 | 0.904 | 3.329 | 1 | 448227 | 227003 |
| **Scenario 5** | 5 | 0.921 | 0.541 | 1.377 | 3 | 476930 | 227003 |
| **Scenario 6** | 6 | 0.928 | 0.518 | 1.378 | 4 | 476930 | 227003 |
| **Scenario 7** | 7 | 1 | 0.477 | 0.857 | 5 | 476930 | 227003 |
| | | | | | | | |
| **Scenario 8** | 3 | 0.657 | 1.191 | 2.751 | 2 | 705387 | 8326851 |
| **Scenario 9** | 5 | 0.969 | 0.73 | 1.62 | 3 | 726565 | 8521879 |
| **Scenario 10** | 6 | 1 | 0.652 | 1.616 | 4 | 726565 | 8521879 |

# 6 RESULTS AND DISCUSSION

Analysis of the most interesting results (Table 10) from the simulation experiments conducted in the experiments in chapter 5 is presented and discussed in detail in this chapter. To fully understand the importance of dynamic simulation in SC analysis, the findings from the different scenarios under each model are evaluated. With the set of defined KPIs, the scenarios from each model are analysed. Then, a comparative analysis of all the models is made to identify the characteristic performance of the distribution network based on the total $CO_2$ emissions, transportation costs and service responsiveness.

### 6.1.1 Model 1

The simulation results from *Model 1* are presented in Table 10. The fleet size is varied in each scenario by keeping a constant number of the Nissan NV200 vehicle type while increasing the number of the electric Nissan NV200 vehicle. With a change in fleet size and vehicle composition, different results were obtained.

It can be observed in scenario 1 that, all the KPIs have low performance since it has the most diminutive fleet size. Increasing the fleet size from 3 to 5 causes a drastic 52% increase in the ELT service level whiles reducing the average lead time from 1.229 days to 0.67. In scenario 1, only 42% of COVID-19 vaccines can be distributed to the municipalities with a fleet size of 3, making the distribution chain very unresponsive as the maximum lead time exceeds the ELT of the customers. With a fleet size of 6, as in scenario 3, a 100% service level is achieved, which is the most crucial performance indicator for the COVID-19 vaccine distribution strategy. Having a responsive supply chain in the COVID-19 pandemic is essential because it helps increase the vaccination rate and minimize wastage of the vaccines.

The total transportation cost and $CO_2$ emissions increases from scenario 1 to 2 because of the increase in fleet size. In contrast, an increase in fleet size from scenario 2 to 3, reduces total transportation cost and $CO_2$ emissions. The $CO_2$ emission in scenario 3 is lower than in scenario 2 because a total of 38 Nissan NV200 are shipped during the experiment period which is 1 less than in scenario 2 as shown in Figure 21. The graph shows the change in transportation cost and $CO_2$ emissions with respect to the number of shipped vehicles in all 3 scenarios. Figure 22 shows the maximum number of vehicles used simultaneously within a day and the total number of shipped vehicles.

The best scenario in *Model 1* is scenario 3, with 4 electric Nissan NV200 and 2 diesel Nissan NV200. The scenario achieves 100% ELT service level, with a max lead time of 1.891 days, having the best combination of transportation cost and $CO_2$ emissions.

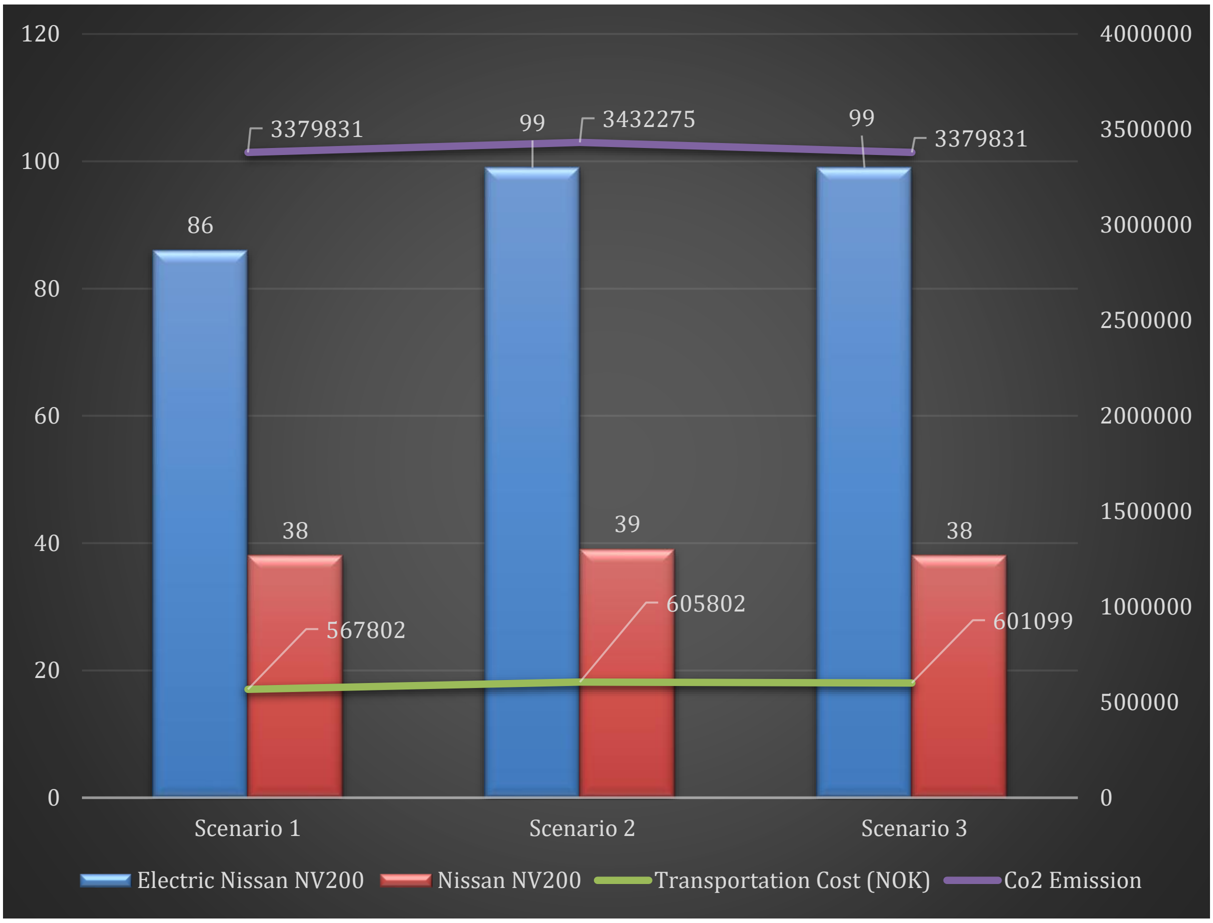
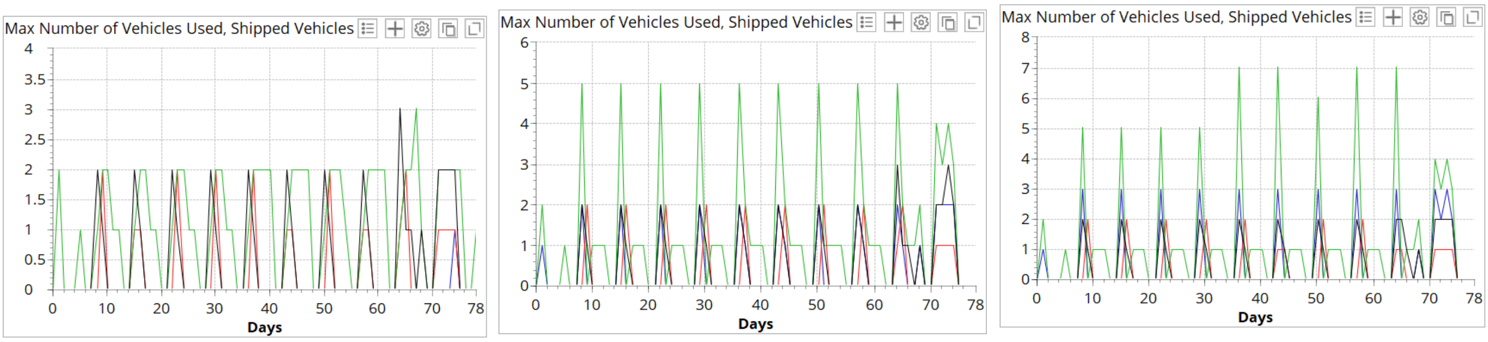


*Figure 21 Change in transportation cost and CO2 emissions in g/km with respect to the number of shipped vehicles in Model 1*



Scenario 1

Scenario 2

Scenario 3

*Figure 22 Comparison of the maximum number of vehicles used and shipped vehicles in Model 1*

### 6.1.2 Model 2

The fleet size variation in *Model 2* is shown in Table 9. It can be deduced from the results in Table 10 that with a fleet size of 3, only 51% of the COVID vaccines can be distributed to the municipalities. Adding two more electric Nissan vehicles increases the fleet size to 5 in scenario 5 and causes a 41% increase in the ELT service level. As shown in Table 10, scenarios 5 and 6 have similar results in all performance indicators. Having a fleet size of 7 in this model results in a 100% service level, with the customers' ELT set as one day. In scenario 6, a fairly good amount of the vaccines (92.8%) can be sent to the municipalities but could take a maximum of 1.38 days. To achieve a 100% service level, an additional Nissan NV200 vehicle is added to the fleet size as in scenario 7, which reduces the maximum lead time from 1.38 days to 0.857, making the distribution chain very responsive.

It can be observed that scenario 4 has the least transportation cost mainly because it has the least number of fleets in the model, but the $CO_2$ emission is the same as in scenarios 5,6 and 7. The transportation cost and $CO_2$ emissions remain constant from scenario 5 to 7, although each scenario increases fleet size by 1. In scenario 7, when an additional Nissan NV200 vehicle was added to the fleet, ELT level increased to 100% whilst transportation and $CO_2$ emissions remained the same as in scenario 5 and 6. As shown in Figure 23, there is an equal number of shipped vehicles in scenarios 5,6 and 7. The equal amount of transportation costs and $CO_2$ emissions imply that fleet utilization, which is the maximum number of vehicles used simultaneously daily, significantly impacts transportation costs and $CO_2$ emissions. The maximum number of vehicles used, and the total number of shipped vehicles are shown in Figure 24. Increasing the fleet size does not necessarily cause an increase in the transportation cost and $CO_2$ emissions if the fleets are not fully utilized. This implies that the use of heterogeneous vehicles in fleet composition can improve the service responsiveness performance of the distribution network without necessarily increasing transportation cost.

The best scenario in *Model 2* is scenario 7, with 4 electric Nissan NV200 and 3 diesel Nissan NV200. The scenario achieves 100% ELT service level, with a max lead time of 0.857 days, having the best combination of transportation cost and $CO_2$ emissions.

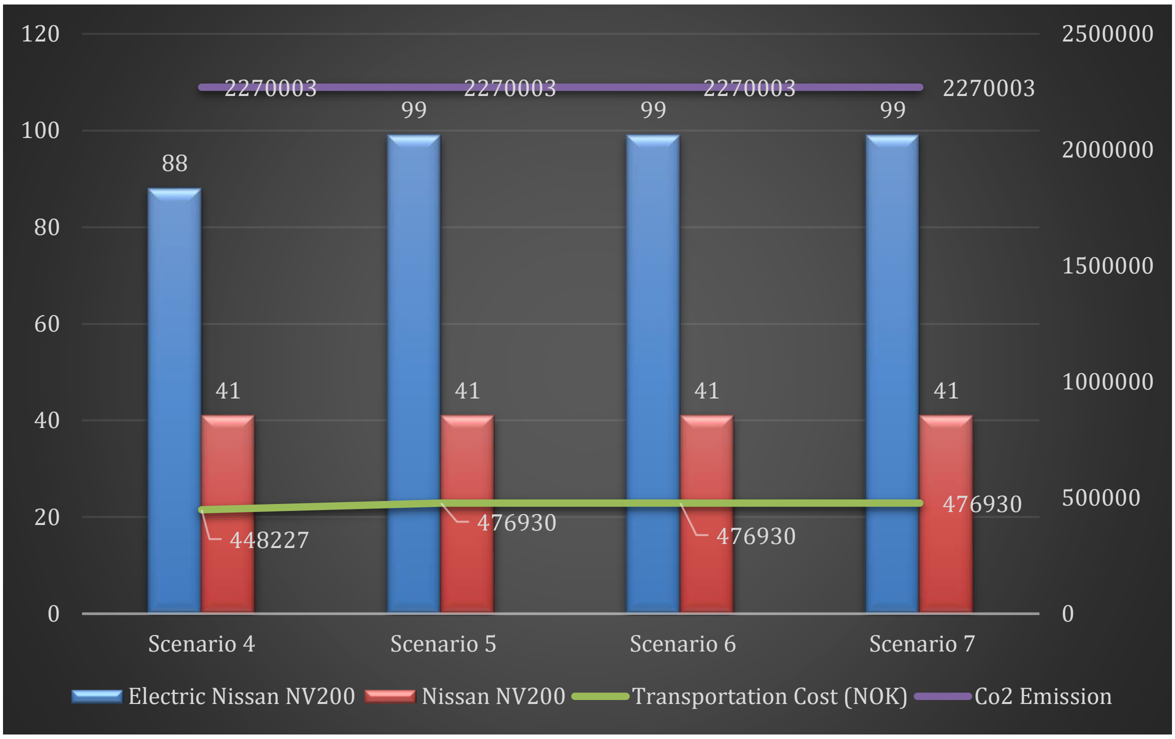
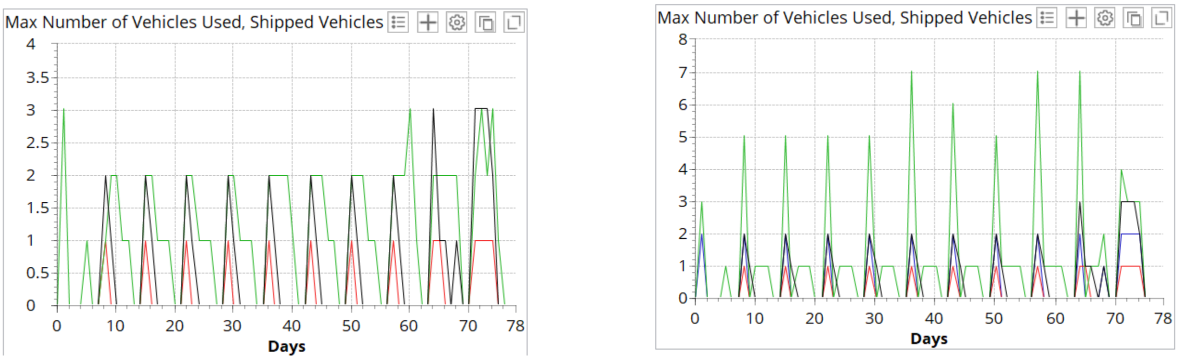
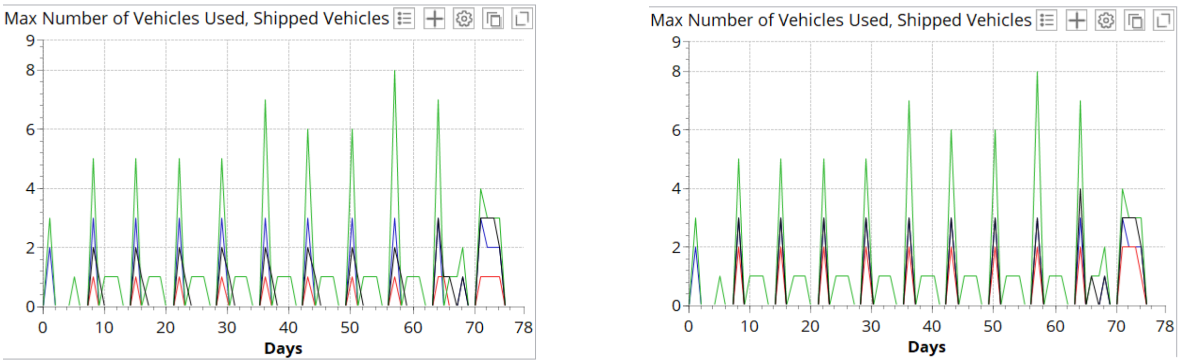


*Figure 23 Change in transportation cost and CO2 emissions in g/km with respect to the number of shipped vehicles in Model 2*



Scenario 4

Scenario 5



Scenario 6

Scenario 7

*Figure 24 Comparison of the maximum number of vehicles used and shipped vehicles in Model 2*

### 6.1.3 Model 3

Analysing the results in *Model 3*, the minimum fleet size in scenario 8 has corresponding lower transportation cost and $CO_2$ emissions. 65.7% of vaccines can be delivered with a fleet size of 3 with a delay of 0.75 days. In scenario 9, the 97% ETL service level is achieved when the fleet size increases from 3 to 5 and the maximum lead time is reduced from 2.75 days to 1.62 days. A 100% service level is achieved when the fleet size is doubled from 3 to 6 in scenario 10 but the maximum days in which all the vaccines could be delivered is the same as in scenario 9.

In Figure 25, the total number of shipped vehicles is plotted against transportation cost and $CO_2$ emissions. It can be deduced from the graph that; the total number of shipped vehicles has an impact on the transportation cost and amount of $CO_2$ emissions. In scenario 8, the least number of vehicles are shipped accounting for the low $CO_2$ emissions and transportation cost. Scenarios 9 and 10 show the same values in $CO_2$ emissions and transportation cost because they have an equal set of shipped vehicles. The maximum number of vehicles used, and the total number of shipped vehicles are shown in Figure 26.

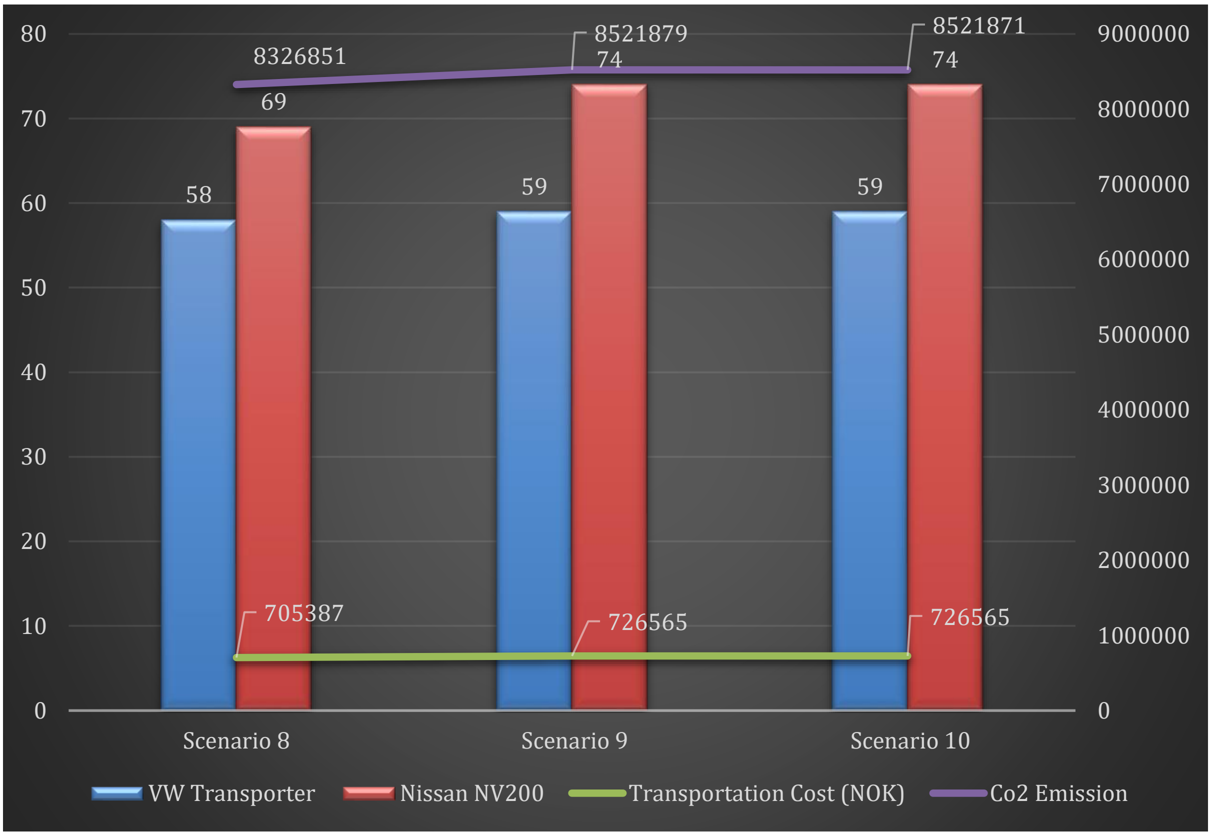
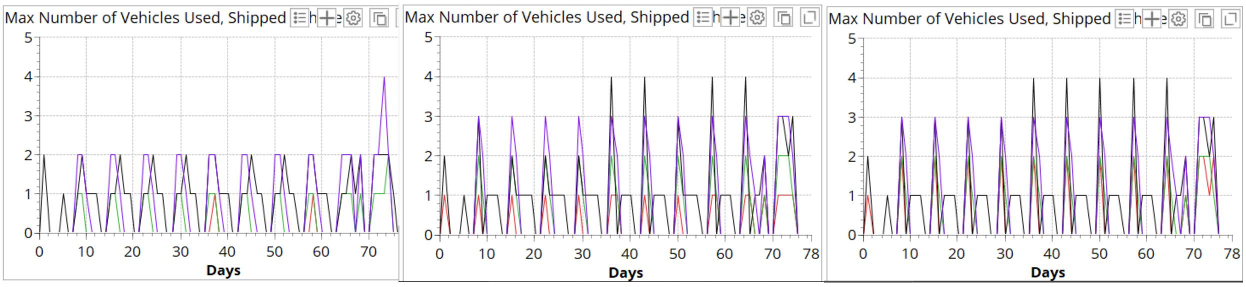


*Figure 25 Change in transportation cost and CO2 emissions in g/km with respect to the number of shipped vehicles in Model 3*



Scenario 8 Scenario 9 Scenario 10

*Figure 26 Comparison of the maximum number of vehicles used and shipped vehicles in Model 3*

## 6.2 Comparative Analysis

In this section, a comparative analysis is conducted on all scenarios in the three models based on the defined KPIs. Each KPI is evaluated to see the behaviour and performance of each of the models.

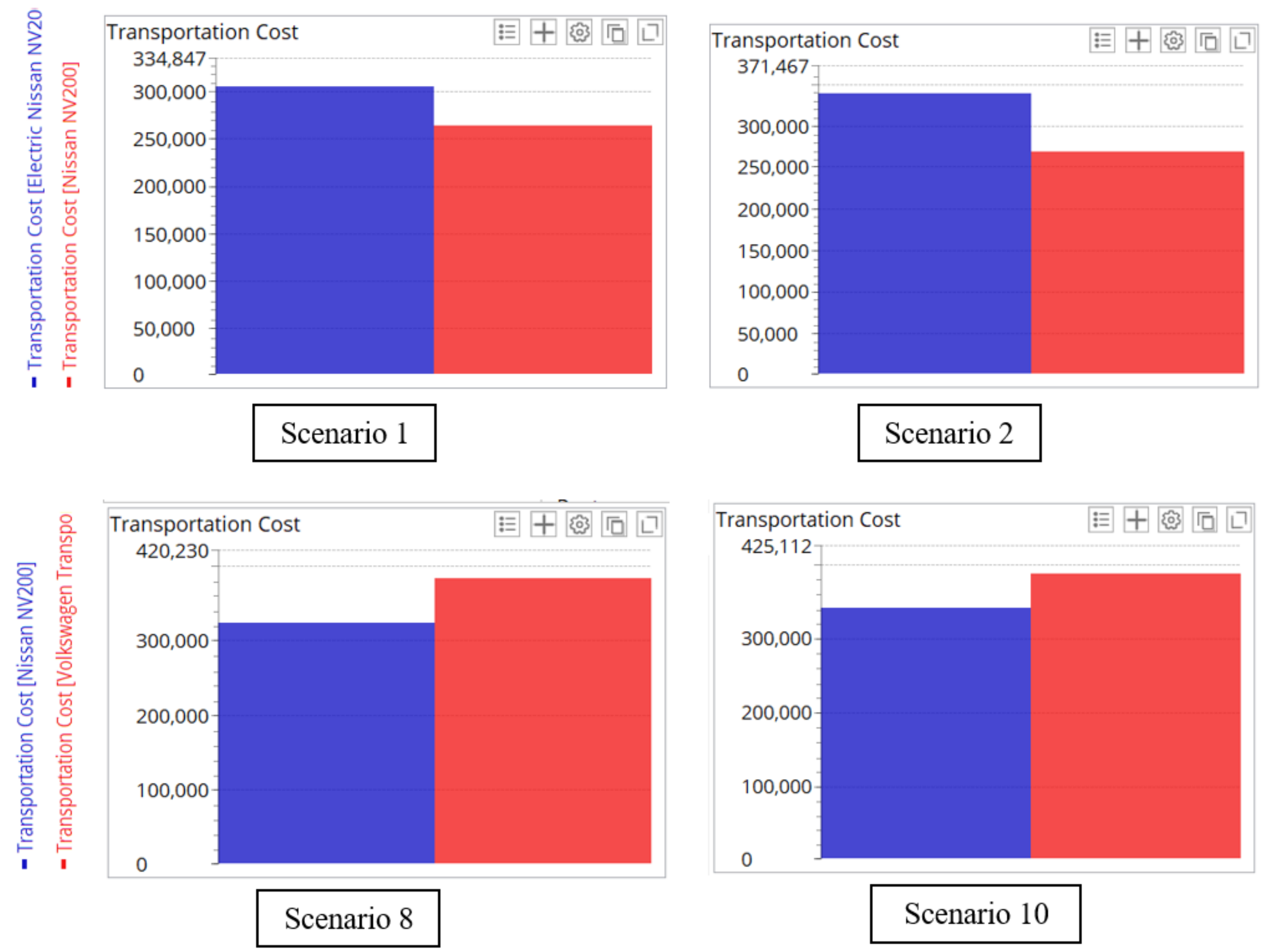
### 6.2.1 Financial Performance

As discussed in the early sections of this report, the financial performance of the COVID-19 vaccine distribution is measured by the transportation cost of delivering the vaccines to the municipalities. The transportation costs from the various scenarios in the three models are

*Figure 27 Comparison of transportation costs from SIM experiments*

presented in Figure 27. As can be seen from the graph, *Model 2* has the least transportation cost amongst all three models. This is because the proposal of locating a DC within the county reduces the travel distance of the vehicles in distributing the vaccines to the various customers, which directly affects the transportation cost. By comparing models 1 and 2 based on having the same fleet size and composition, *Model 1* seems to have higher transportation costs than *Model 2* because of the longer travel distance from the DC to the customers.

The transportation costs seen in *Model 1* is significantly lower than those in *Model 3* even though the delivery of the vaccines occur from the same DC to the same set of customers. The difference in the transportation cost between these two models is because of the different fleet composition. Figure 28 shows the transportation cost performance of the different vehicle compositions in *Model 1* and *Model 3*. *Model 1* utilizes Electric Nissan NV200 and Nissan NV200, whereas *Model 3* has a Nissan NV200 and VW Transporter fleet composition. The



Scenario 1

Scenario 2

Scenario 8

Scenario 10

*Figure 28 Comparison of transportation costs in Model 1 and Model 3* transportation cost parameters defined in section 5.1.2 assigned different cost calculation variables for each vehicle type. This accounts for the significant difference in the transportation cost of these two models with the same distribution network structure.

### 6.2.2 Customer Performance

One crucial performance indicator of the last mile distribution of COVID-19 vaccines is the responsiveness of the SC. This is measured by the ELT service level by products in this study. Getting the right quantity of vaccines to the municipalities on time indicates how responsive the last mile distribution network is and could help increase vaccination rate and minimize vaccine wastage.

In analysing the ELT service level by products, an interesting observation was that the variation in fleet size directly impacted the ELT service level, as shown in Figure 29. *In Model 1,* increasing the fleet size in scenario 1 by 66.7% causes the ELT service level to increase from 42% to 94% in scenario 2. A 100% ELT service level is achieved in scenario 3 because of a 100% increase in the fleet size from 3 to 6. Similarly, in *Model 3,* having a minimum fleet size of 3 had a corresponding ELT service level of 65.7%, which is better than the ELT service level achieved in Model 1 with the same minimum fleet size. However, just like in scenario 3 *(Model 1),* a 100% service level is also achieved when the fleet size is increased from 3 to 6.

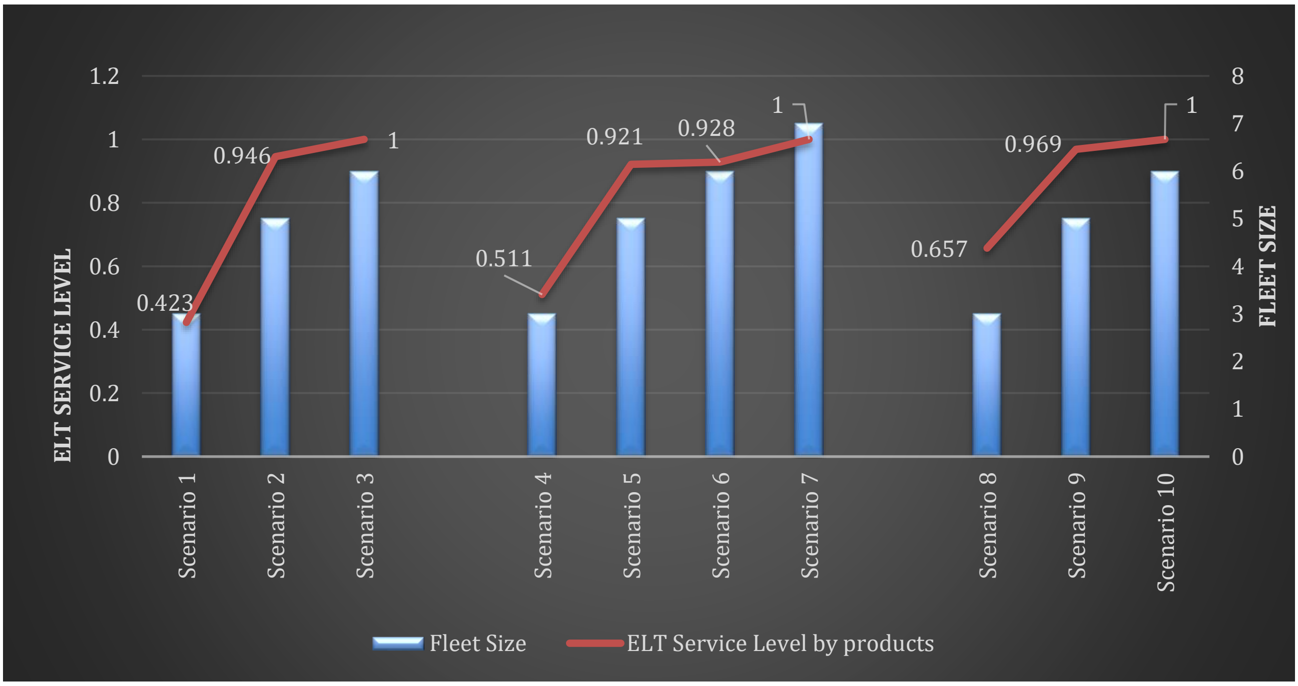
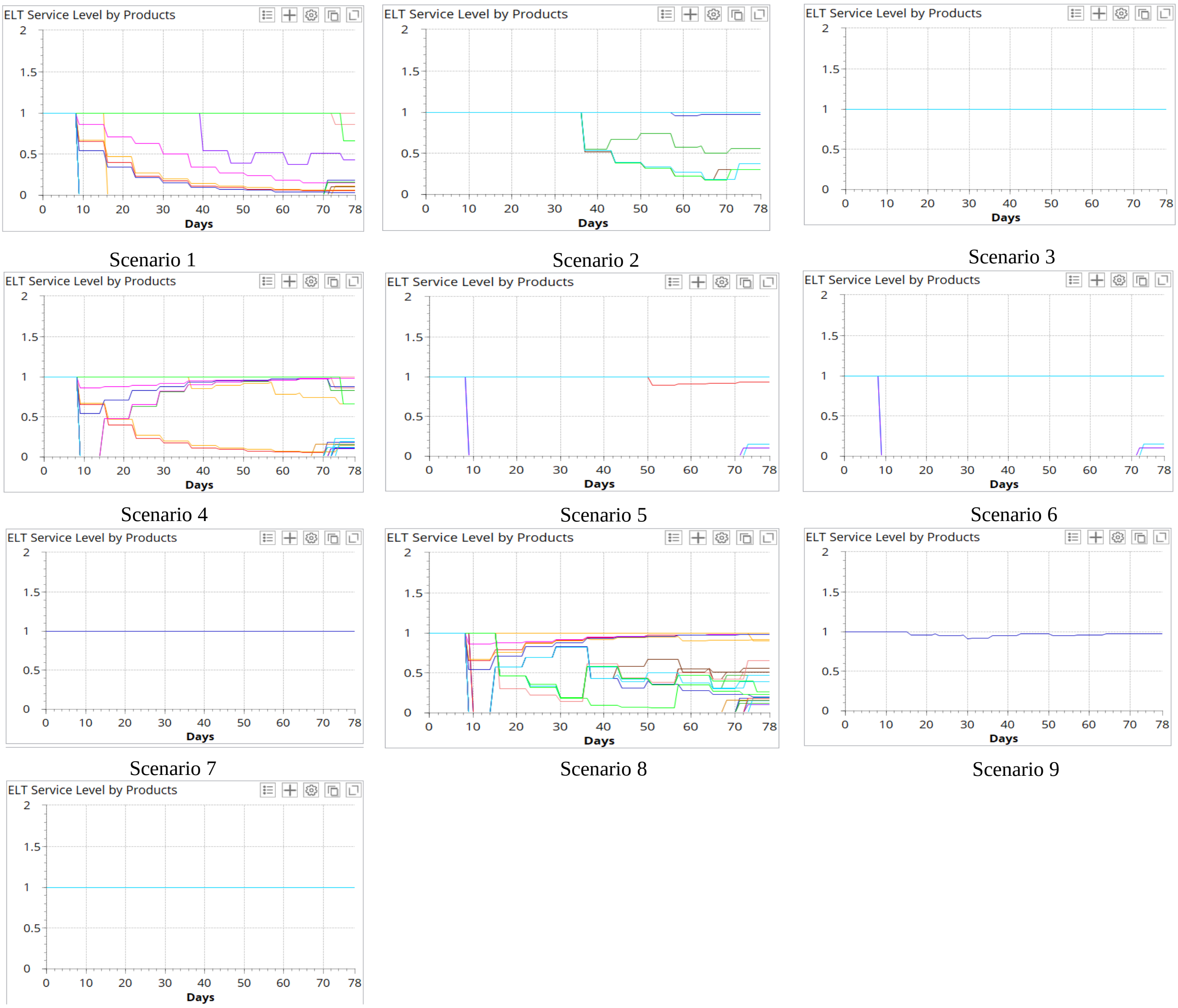


*Figure 29 Impact of fleet size variation on ELT service level*

Considering that both models 1 and 3 have the same distribution network structure, the general performance of the ELT service level in *Model 3* can be said to be better than in *Model 1*, as can be seen in Figure 29.

*Model 2*, on the other hand, achieved a 92.8% ELT service level when the fleet size was increased from 3 to 6. An additional increase in fleet size from 6 to 7 realises a 100% ELT service level. Therefore *Model 2*, requires a fleet size of 7 to fulfil all the orders within the expected lead time. The ELT service level by product at each scenario is shown in Figure 30.



Scenario 1

Scenario 2

Scenario 3

Scenario 4

Scenario 5

Scenario 6

Scenario 7

Scenario 8

Scenario 9

Scenario 10

*Figure 30 Comparison of the ELT service level by products at each scenario.*

### 6.2.3 Operational Performance

In this analysis, the lead time taken into consideration is the maximum lead time and is compared with fleet size variation shown in Figure 31. In models 1 and 3, the max expected lead time of the customers two days. When the fleet size is at its minimum of 3, the max lead time in *Model 3* (2.75 days) is comparatively lower than in *Model 1* (4.37 days). When the fleet size increases by 66.7%, the max lead time in *Model 1* is reduced to 1.49 days which is lower than in *Model 3,* which has a max lead time of 1.62 days. Doubling the fleet size from 3 to 6 reduces the max lead time in *Model 1* by 56.7% and 41.3% in *Model.* For *Model 2,* the customers expected lead time is 1 day, and on-time delivery is achieved with a fleet size of 7, which is more than required in the other two models to achieve on-time delivery. By comparing all models, the trendline, which is the linear movement of the max lead time, declines from model 1 to 3. The trendline indicates that *Model 3* has the best lead times combination as per fleet size. The maximum lead time at each scenario from the simulation experiments is presented in Figure 32.

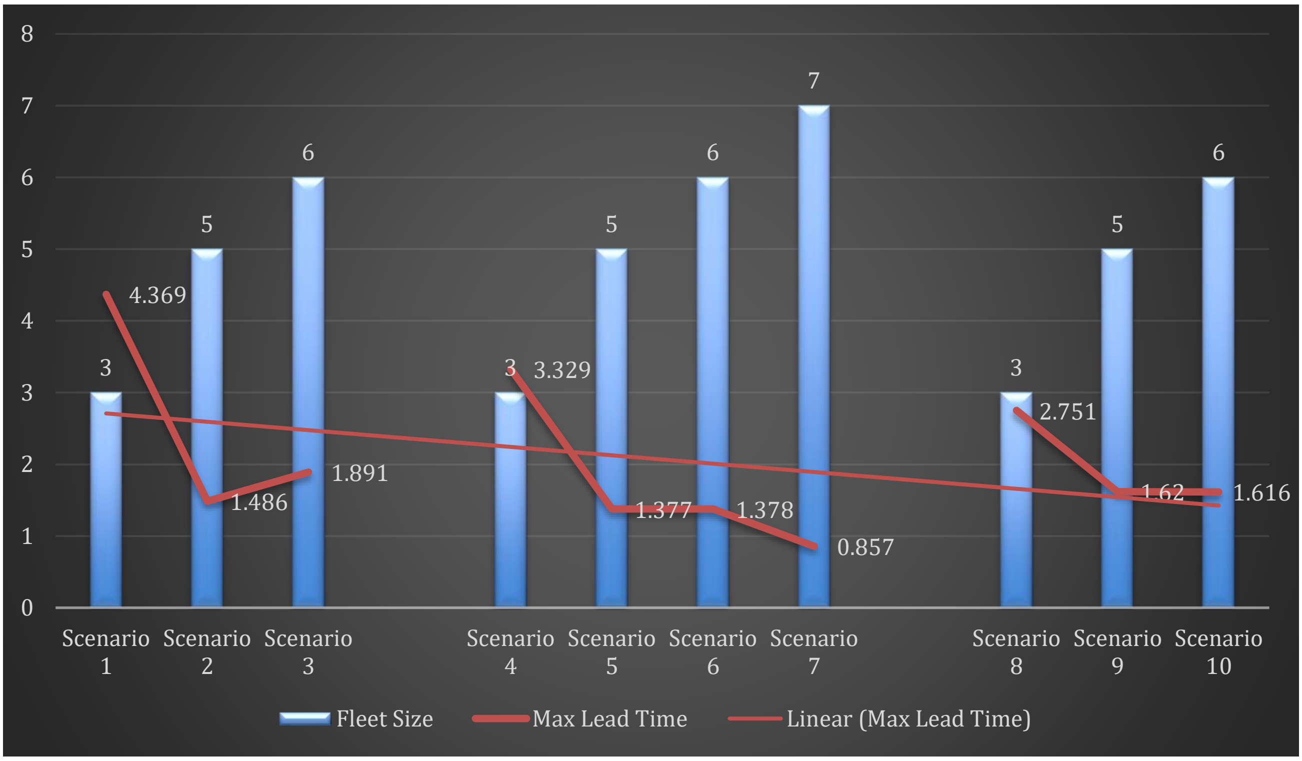
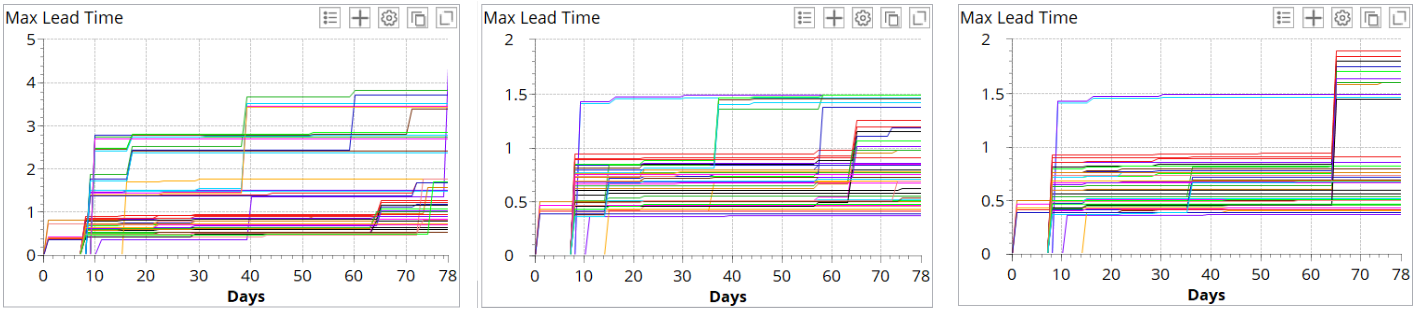
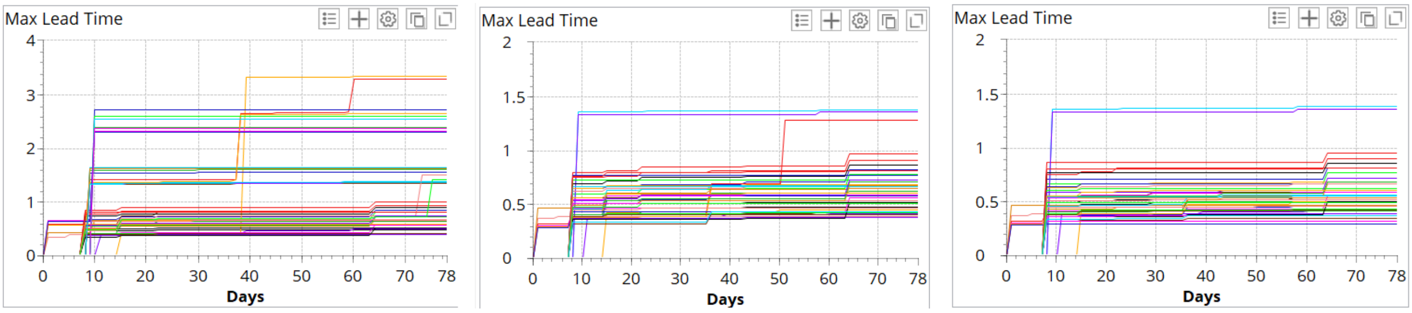


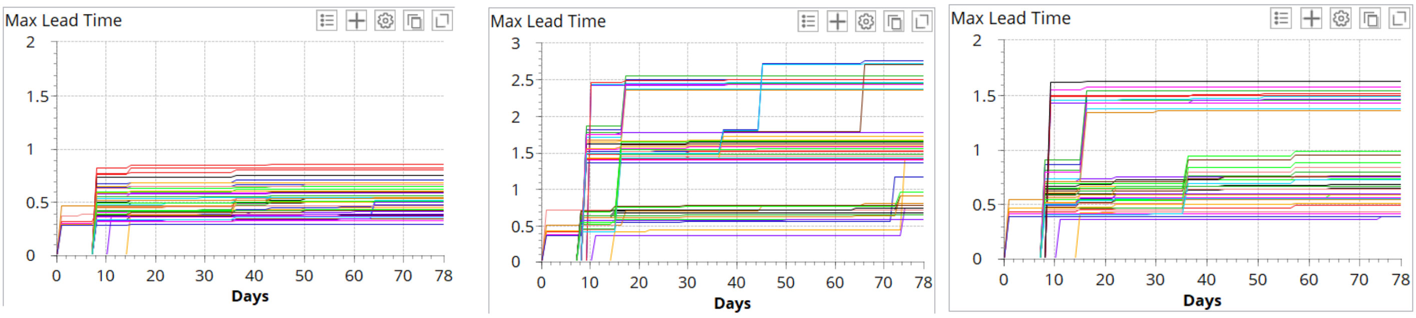
*Figure 31 Impact of fleet size on Max lead time*



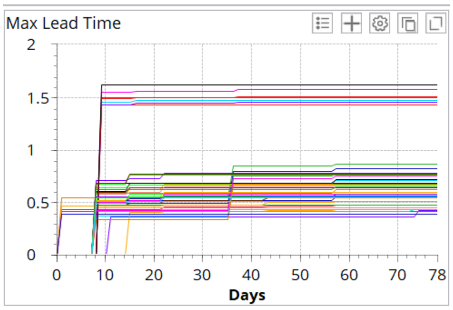
Scenario 1 Scenario 2 Scenario 3



Scenario 4 Scenario 5 Scenario 6



Scenario 7 Scenario 8 Scenario 9



Scenario 10

*Figure 32 Comparison of the max lead time by customers at each scenario.*

### 6.2.4 Environmental Performance

Figure 33 shows the $CO_2$ emissions from the models in this study. The $CO_2$ emissions from *Model 1* and *Model 2* are compared because they have the same heterogeneous fleet composition (Electric Nissan NV200 and Nissan NV200). Since there are no emissions from the electric vehicle, the $CO_2$ emissions are only from the Nissan NV200. As can be observed from the graph, *Model 2* generally has lower $CO_2$ emissions than *Model 1* because the total travel distance from the DC to customers in *Model 2* is much lesser than in *Model 1*, where the DC is in proximity to the location of the customers.

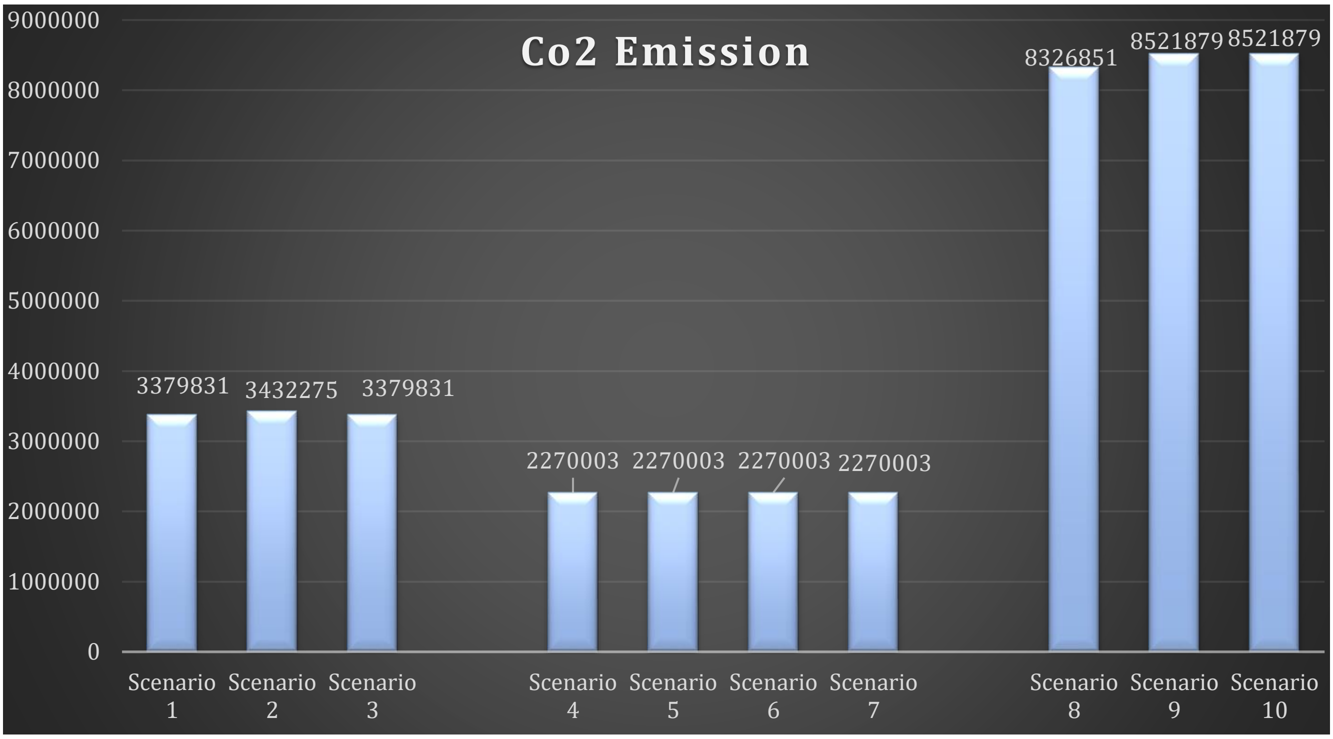


*Figure 33 CO2 emissions in g/km comparison results*

Another interesting observation is seen when *Model 1* and *Model 3* are compared. These two models are compared on the basis that the structure of the distribution network is the same. The $CO_2$ emissions in *Model 3* are significantly higher than in Model 1, which is about a 148% increase. This notable increase is because of the vehicles used in each model. *Model 1* combines electric vehicles with gas vehicles; thus, many deliveries can be achieved with no $CO_2$ emission. *Model 3,* on the other hand, uses only gas vehicles resulting in much greater $CO_2$ emissions.

## 6.3 Managerial Insights

The operations of an effective cold chain in the COVID-19 vaccine distribution solely rely on good managerial decisions. Whether the vaccines are delivered on time or in the right conditions, are impacted by the transportation decisions made by the stakeholders involved. The result from this study highlights some managerial insights, which are as follows:

*Insight 1*: The overall performance of the distribution system is greatly influenced by the size of the fleet, fleet composition and the type of vehicle used. Performance drops with a small fleet size in the scenarios, and the system performs less effectively due to the lack of capacity to handle all demands, resulting in a lower service level and responsiveness. Increasing the fleet size may cause increased performance, depending on how the fleet is utilized and the types of heterogeneous vehicles used.

*Insight 2*: The balance between achieving responsiveness and cost efficiency requires a well-managed fleet composition focused on vehicle type, fleet utilization, scheduling, and routing decisions that need to be optimized. Optimizing network design is imperative to the supply chain operation since a good logistics distribution network can reduce transportation costs and significantly improve customer service levels.

*Insight 3*: The use of heterogeneous vehicles in the distribution network directly affects transportation cost. Observations made in this study suggest that different vehicle types that consume different energy have a bearing on transportation costs. Basing transportation cost decisions on these parameters instead of just travel distance is an effective means of allocating and assessing transportation costs.

*Insight 4*: A heterogeneous fleet of vehicles contributes significantly to the level of CO2 emissions. The result from this study indicates that different types of vehicles that consume different energies have different amount of CO2 emissions. The decision to include electric vehicles in last-mile distribution is an effective way to control the environmental performance of the distribution network without significantly increasing transportation costs.

# 7 CONCLUSION

How do we ensure that the COVID-19 vaccines that are globally allocated by WHO through the COVAX facility are effectively distributed at the last mile? This thought-provoking question drives the motivation behind this thesis. The research conducted in this thesis addresses the problem by analysing the last mile distribution of the COVID-19 vaccine distribution in Norway using simulation.

Mass vaccination is regarded as the most promising method of controlling the spread of the pandemic and for everything to get back to normalcy. However, because of several influencing factors, planning a responsive and cost-effective distribution of COVID-19 vaccines is a complex problem. These influencing factors include uncertainty about vaccine supplies from manufacturers, strict temperature requirements for storage and transportation, changes in vaccine distribution policies, and resource constraints. There is therefore an important need to effectively plan the transportation logistics of the distribution network to achieve high service responsiveness to avoid wastage of vaccines.

This thesis presents a simulation-based analysis of the cold chain logistics system for effective distribution of the COVID-19 vaccines in Inland county, Norway. With different (Table 10) fleet configurations, optimal vehicle routing decisions are first determined by the TO experiments in anyLogistix. The results are then tested and validated in simulation experiments under dynamic conditions. The findings from the simulation experiments outline some managerial guidelines to support the decisions of stakeholders involved in the COVID-19 vaccine distribution.

## 7.1 Research Contribution

- This study presents a simulation-based analysis to improve cold chain logistics performance for effective COVID -19 vaccine distribution at the last mile. A simulation-optimization method was developed to improve the cold chain logistics performance for COVID-19 vaccine distribution. The applicability is shown through a case study in Norway.
- The research shows the impact of fleet size variation, the use of heterogeneous vehicles, fleet composition and routing decisions on the transportation cost, service level and environmental performance.

- This study demonstrates the applicability of dynamic simulation in real-life cases to help decision-makers effectively organize the distribution of COVID -19 vaccines.
- The research proposes key management insights to help logistics managers better understand the interactions between the key parameters of a cold chain vaccine distribution system.
- The study adds to the existing literature on vaccine supply chain and cold chain logistics.

## 7.2 Research Limitations

Just like any research, some limitations were encountered during this study, some of which are discussed below.

- With regards to the literature review, there were no existing research and literature on similar works at the time of conducting this study to refer to.
- The data curated for this study were mainly obtained through online web searches. Some of the required input data for the method development were not accessible because of confidentiality. Due to this, several assumptions and estimations were made based on relevant literature, expert opinions, and intuitions.
- The topic under investigation is very dynamic and changes with time. For instance, the vaccine distribution strategy and decisions by the NIPH were progressively changing as the rate and the dynamics of the infection changed. The data on the vaccine candidates changed weekly throughout the study, likewise the rate of the disease infection from the WHO database.
- The complexity of the case had to be reduced due to some missing information and details.
- This thesis spanned 27 weeks with 18 weeks dedicated for the case study analysis which includes the method development. The time constraints may not have allowed different scenarios to be analysed to see a bigger picture of the overall system performance. Also, the experiment period studied was between 10 weeks where less than 50% of the estimated COVID-19 vaccines had been received.

## 7.3 Future Research Direction

This study opens some research opportunities and improvement related to this work.

- A comparative study between countries with different economic status can be performed to identify the similarities and differences in their vaccine distribution strategies and networks that influence the last mile distribution.
- Although anyLogistix offers a solution that integrates optimization and simulation tools to analyse cold chain vaccine logistical problems, it is limiting in terms of flexibility. As a complex optimization problem, the vehicle routing decisions could be optimized using more efficient mathematical models which can incorporate multiple routing objectives.
- More detailed scenarios and KPIs can be explored when performing the simulation analysis. This can increase the complexity when different operational decisions are incorporated.
- Due to the dynamic nature of the vaccine distribution, future works should factor this when designing the model to facilitate changes or disruptions in the distribution network. Collaborations between stakeholders of the COVID-19 vaccine distribution and the researcher is important in this case.
- Since the demand for vaccines is influenced by uncertainty, comprehensive data should be gathered and used in modelling the demand for the vaccination. The results from the simulation may be validated with the use of more accurate real-world data.

# REFERENCES

[1] "WHO Coronavirus (COVID-19) Dashboard." https://covid19.who.int/ (accessed 9th May, 2021).

[2] U. H. Kartoglu, K. L. Moore, and J. S. Lloyd, "Logistical challenges for potential SARS-CoV-2 vaccine and a call to research institutions, developers and manufacturers," *Vaccine*, vol. 38, no. 34, pp. 5393-5395, 2020/07/22/ 2020, doi: https://doi.org/10.1016/j.vaccine.2020.06.056.

[3] Pfizer. https://www.pfizer.com/news/hot-topics/covid_19_vaccine_u_s_distribution_fact_sheet (accessed 16th February, 2021, 2021).

[4] G. Thomas, "A Typology for the Case Study in Social Science Following a Review of Definition, Discourse, and Structure," *Qualitative Inquiry*, vol. 17, no. 6, pp. 511-521, 2011, doi: 10.1177/1077800411409884.

[5] S. Crowe, K. Cresswell, A. Robertson, G. Huby, A. Avery, and A. Sheikh, "The case study approach," *BMC Medical Research Methodology*, vol. 11, no. 1, p. 100, 2011/06/27 2011, doi: 10.1186/1471-2288-11-100.

[6] S. S. Patel, J. Kalma, and E. M. Bluman, "Understanding COVID-19 Vaccines and Their Development," (in English), *J Bone Joint Surg Am*, Article vol. 102, no. 20, pp. 1759-1769, 2020, doi: 10.2106/JBJS.20.01191.

[7] S. N. Chaudhry *et al.*, "New insights on possible vaccine development against SARS-CoV-2," (in English), *Life Sci.*, Review vol. 260, 2020, Art no. 118421, doi: 10.1016/j.lfs.2020.118421.

[8] S. P. Kaur and V. Gupta, "COVID-19 Vaccine: A comprehensive status report," (in English), *Virus Res.*, Review vol. 288, 2020, Art no. 198114, doi: 10.1016/j.virusres.2020.198114.

[9] A. K. Dutta, "Vaccine Against Covid-19 Disease – Present Status of Development," (in English), *Indian J. Pediatr.*, Review vol. 87, no. 10, pp. 810-816, 2020, doi: 10.1007/s12098-020-03475-w.

[10] R. Mukherjee, "Global efforts on vaccines for COVID-19: Since, sooner or later, we all will catch the coronavirus," (in English), *J. Biosci.*, Review vol. 45, no. 1, 2020, Art no. 68, doi: 10.1007/s12038-020-00040-7.

[11] F. Krammer, "SARS-CoV-2 vaccines in development," (in English), *Nature*, Review vol. 586, no. 7830, pp. 516-527, 2020, doi: 10.1038/s41586-020-2798-3.

[12] A. J. Marian, "Current state of vaccine development and targeted therapies for COVID-19: impact of basic science discoveries," (in English), *Cardiovasc. Pathol.*, Review vol. 50, 2021, Art no. 107278, doi: 10.1016/j.carpath.2020.107278.

[13] K. L. Flanagan *et al.*, "Progress and Pitfalls in the Quest for Effective SARS-CoV-2 (COVID-19) Vaccines," (in English), *Front. Immunol.*, Review vol. 11, 2020, Art no. 579250, doi: 10.3389/fimmu.2020.579250.

[14] Y. Dong, T. Dai, Y. Wei, L. Zhang, M. Zheng, and F. Zhou, "A systematic review of SARS-CoV-2 vaccine candidates," (in English), *Signal Transduct. Target. Ther.*, Review vol. 5, no. 1, 2020, Art no. 237, doi: 10.1038/s41392-020-00352-y.

[15] "<novel-coronavirus-landscape-covid-191cf012d2866d4102b9430ef02369d152 (1).pdf>."

[16] B. Y. Lee *et al.*, "Re-designing the Mozambique vaccine supply chain to improve access to vaccines," *Vaccine*, vol. 34, no. 41, pp. 4998-5004, 2016/09/22/ 2016, doi: https://doi.org/10.1016/j.vaccine.2016.08.036.

[17] S. Lemmens, C. Decouttere, N. Vandaele, and M. Bernuzzi, "A review of integrated supply chain network design models: Key issues for vaccine supply chains," *Chemical Engineering Research and Design*, vol. 109, pp. 366-384, 2016/05/01/ 2016, doi: https://doi.org/10.1016/j.cherd.2016.02.015.

[18] L. E. Duijzer, W. van Jaarsveld, and R. Dekker, "Literature review: The vaccine supply chain," (in English), *European Journal of Operational Research*, Article vol. 268, no. 1, pp. 174-192, 2018, doi: 10.1016/j.ejor.2018.01.015.

[19] M. Rastegar, M. Tavana, A. Meraj, and H. Mina, "An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic," *Vaccine*, vol. 39, no. 3, pp. 495-504, 2021/01/15/ 2021, doi: https://doi.org/10.1016/j.vaccine.2020.12.022.

[20] M. Brison and Y. LeTallec, "Transforming cold chain performance and management in lower-income countries," *Vaccine*, vol. 35, no. 17, pp. 2107-2109, 2017/04/19/ 2017, doi: https://doi.org/10.1016/j.vaccine.2016.11.067.

[21] Y. Yang, H. Bidkhori, and J. Rajgopal, "Optimizing vaccine distribution networks in low and middle-income countries," (in English), *Omega*, Article vol. 99, 2021, Art no. 102197, doi: 10.1016/j.omega.2020.102197.

[22] A. Saif and S. Elhedhli, "Cold supply chain design with environmental considerations: A simulation-optimization approach," *European Journal of Operational Research*, vol. 251, no. 1, pp. 274-287, 2016/05/16/ 2016, doi: https://doi.org/10.1016/j.ejor.2015.10.056.

[23] L. Leng, J. Zhang, C. Zhang, Y. Zhao, W. Wang, and G. Li, "Decomposition-based hyperheuristic approaches for the bi-objective cold chain considering environmental effects," (in English), *Comp. Oper. Res.*, Article vol. 123, 2020, Art no. 105043, doi: 10.1016/j.cor.2020.105043.

[24] L. Leng, C. Zhang, Y. Zhao, W. Wang, J. Zhang, and G. Li, "Biobjective low-carbon location-routing problem for cold chain logistics: Formulation and heuristic approaches," *Journal of Cleaner Production*, vol. 273, p. 122801, 2020/11/10/ 2020, doi: https://doi.org/10.1016/j.jclepro.2020.122801.

[25] N. Privett and D. Gonsalvez, "The top ten global health supply chain issues: Perspectives from the field," *Operations Research for Health Care*, vol. 3, no. 4, pp. 226-230, 2014/12/01/ 2014, doi: https://doi.org/10.1016/j.orhc.2014.09.002.

[26] B. Yong, J. Shen, X. Liu, F. Li, H. Chen, and Q. Zhou, "An intelligent blockchain-based system for safe vaccine supply and supervision," (in English), *Int J Inf Manage*, Article vol. 52, 2020, Art no. 102024, doi: 10.1016/j.ijinfomgt.2019.10.009.

[27] T. K. Dasaklis, C. P. Pappis, and N. P. Rachaniotis, "Epidemics control and logistics operations: A review," *International Journal of Production Economics*, vol. 139, no. 2, pp. 393-410, 2012/10/01/ 2012, doi: https://doi.org/10.1016/j.ijpe.2012.05.023.

[28] Y. K. Dwivedi, M. A. Shareef, B. Mukerji, N. P. Rana, and K. K. Kapoor, "Involvement in emergency supply chain for disaster management: a cognitive dissonance perspective," *International Journal of Production Research*, vol. 56, no. 21, pp. 6758-6773, 2018/11/02 2018, doi: 10.1080/00207543.2017.1378958.

[29] B. Y. Lee and L. A. Haidari, "The importance of vaccine supply chains to everyone in the vaccine world," *Vaccine*, vol. 35, no. 35, Part A, pp. 4475-4479, 2017/08/16/ 2017, doi: https://doi.org/10.1016/j.vaccine.2017.05.096.

[30] K. De Boeck, C. Decouttere, and N. Vandaele, "Vaccine distribution chains in low- and middle-income countries: A literature review," *Omega*, p. 102097, 2019/08/09/ 2019, doi: https://doi.org/10.1016/j.omega.2019.08.004.

[31] A. Ashok, M. Brison, and Y. LeTallec, "Improving cold chain systems: Challenges and solutions," *Vaccine*, vol. 35, no. 17, pp. 2217-2223, 2017/04/19/ 2017, doi: https://doi.org/10.1016/j.vaccine.2016.08.045.

[32] J. Lloyd and J. Cheyne, "The origins of the vaccine cold chain and a glimpse of the future," *Vaccine*, vol. 35, no. 17, pp. 2115-2120, 2017/04/19/ 2017, doi: https://doi.org/10.1016/j.vaccine.2016.11.097.

[33] W. H. Organisation, "The Vaccien Cold Chain." [Online]. Available: https://www.who.int/immunization/documents/IIP2015_Module2.pdf

[34] G. Li, "Development of cold chain logistics transportation system based on 5G network and Internet of things system," *Microprocessors and Microsystems*, vol. 80, p. 103565, 2021/02/01/ 2021, doi: https://doi.org/10.1016/j.micpro.2020.103565.

[35] X. Xiaofeng and Z. Xuelai, "Simulation and experimental investigation of a multi-temperature insulation box with phase change materials for cold storage," *Journal of Food Engineering*, vol. 292, p. 110286, 2021/03/01/ 2021, doi: https://doi.org/10.1016/j.jfoodeng.2020.110286.

[36] Y. Zhao, X. Zhang, X. Xu, and S. Zhang, "Development of composite phase change cold storage material and its application in vaccine cold storage equipment," *Journal of Energy Storage*, vol. 30, p. 101455, 2020/08/01/ 2020, doi: https://doi.org/10.1016/j.est.2020.101455.

[37] B. Y. Lee *et al.*, "The impact of making vaccines thermostable in Niger's vaccine supply chain," *Vaccine*, vol. 30, no. 38, pp. 5637-5643, 2012/08/17/ 2012, doi: https://doi.org/10.1016/j.vaccine.2012.06.087.

[38] C. L. Karp *et al.*, "Evaluating the value proposition for improving vaccine thermostability to increase vaccine impact in low and middle-income countries," *Vaccine*, vol. 33, no. 30, pp. 3471-3479, 2015/07/09/ 2015, doi: https://doi.org/10.1016/j.vaccine.2015.05.071.

[39] H. Yu, G. Tinghang, and L. Meng, "Design of Data Transfer Module Based on STM32 in Monitoring System of Cold Chain Transportation," in *2015 Fifth International Conference on Instrumentation and Measurement, Computer, Communication and Control (IMCCC)*, 18-20 Sept. 2015 2015, pp. 77-80, doi: 10.1109/IMCCC.2015.24.

[40] J. C. S. d. Santos *et al.*, "Optimized ultra-low power sensor-enabled RFID data logger for pharmaceutical cold chain," in *2015 IEEE Brasil RFID*, 7-8 Oct. 2015 2015, pp. 1-5, doi: 10.1109/BrasilRFID.2015.7523835.

[41] L. Zhou and S. Chakrabartty, "Self-powered continuous time-temperature monitoring for cold-chain management," in *2017 IEEE 60th International Midwest Symposium on Circuits and Systems (MWSCAS)*, 6-9 Aug. 2017 2017, pp. 879-882, doi: 10.1109/MWSCAS.2017.8053064.

[42] J. Tang, Y. Zou, R. Xie, B. Tu, and G. Liu, "Compact supervisory system for cold chain logistics," *Food Control*, vol. 126, p. 108025, 2021/08/01/ 2021, doi: https://doi.org/10.1016/j.foodcont.2021.108025.

[43] A. Mohsin and S. S. Yellampalli, "IoT based cold chain logistics monitoring," in *2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI)*, 21-22 Sept. 2017 2017, pp. 1971-1974, doi: 10.1109/ICPCSI.2017.8392059.

[44] S. Zhang, N. Chen, X. Song, and J. Yang, "Optimizing decision-making of regional cold chain logistics system in view of low-carbon economy," *Transportation Research Part A: Policy and Practice*, vol. 130, pp. 844-857, 2019/12/01/ 2019, doi: https://doi.org/10.1016/j.tra.2019.10.004.

[45] M.-x. Song, J.-q. Li, Y.-q. Han, Y.-y. Han, L.-l. Liu, and Q. Sun, "Metaheuristics for solving the vehicle routing problem with the time windows and energy consumption in cold chain logistics," *Applied Soft Computing,* vol. 95, p. 106561, 2020/10/01/ 2020, doi: https://doi.org/10.1016/j.asoc.2020.106561.

[46] K. Arifoğlu, S. Deo, and S. M. R. Iravani, "Consumption externality and yield uncertainty in the influenza vaccine supply chain: Interventions in demand and supply sides," (in English), *Manage Sci,* Article vol. 58, no. 6, pp. 1072-1091, 2012, doi: 10.1287/mnsc.1110.1469.

[47] L. Melone, L. Altomare, A. Cigada, and L. De Nardo, "Phase change material cellulosic composites for the cold storage of perishable products: From material preparation to computational evaluation," (in English), *Appl. Energy,* Article vol. 89, no. 1, pp. 339-346, 2012, doi: 10.1016/j.apenergy.2011.07.039.

[48] S. Kraiselburd and P. Yadav, "Supply chains and global health: An imperative for bringing operations management scholarship into action," (in English), *Prod. Oper. Manage.,* Article vol. 22, no. 2, pp. 377-381, 2013, doi: 10.1111/j.1937-5956.2011.01315.x.

[49] K. Kim, H. Kim, S. K. Kim, and J. Y. Jung, "I-RM: An intelligent risk management framework for context-aware ubiquitous cold chain logistics," (in English), *Expert Sys Appl,* Article vol. 46, pp. 463-473, 2016, doi: 10.1016/j.eswa.2015.11.005.

[50] T. Dai, S. H. Cho, and F. Zhang, "Contracting for on-time delivery in the U.S. Influenza vaccine supply Chain," (in English), *Manuf. Serv. Oper. Manage.,* Article vol. 18, no. 3, pp. 332-346, 2016, doi: 10.1287/msom.2015.0574.

[51] X. Zhu, R. Zhang, F. Chu, Z. He, and J. Li, "A flexsim-based optimization for the operation process of cold-chain logistics distribution centre," (in English), *J. Appl. Res. Technol.,* Article vol. 12, no. 2, pp. 270-278, 2014, doi: 10.1016/S1665-6423(14)72343-0.

[52] M. Lütjen, P. Dittmer, and M. Veigt, "Quality driven distribution of intelligent containers in cold chain logistics networks," (in English), *Prod. Eng.,* Article vol. 7, no. 2-3, pp. 291-297, 2013, doi: 10.1007/s11740-012-0433-3.

[53] X. Li, Y. Wang, and X. Chen, "Cold chain logistics system based on cloud computing," (in English), *Concurrency Comput. Pract. Exper.,* Article vol. 24, no. 17, pp. 2138-2150, 2012, doi: 10.1002/cpe.1840.

[54] R. Miller Neilan and S. Lenhart, "Optimal vaccine distribution in a spatiotemporal epidemic model with an application to rabies and raccoons," (in English), *J. Math. Anal. Appl.,* Article vol. 378, no. 2, pp. 603-619, 2011, doi: 10.1016/j.jmaa.2010.12.035.

[55] S. Mejjaouli and R. F. Babiceanu, "Cold supply chain logistics: System optimization for real-time rerouting transportation solutions," (in English), *Comput Ind,* Article vol. 95, pp. 68-80, 2018, doi: 10.1016/j.compind.2017.12.006.

[56] H. Liu, L. Pretorius, and D. Jiang, "Optimization of cold chain logistics distribution network terminal," (in English), *Eurasip J. Wireless Commun. Networking,* Article vol. 2018, no. 1, 2018, Art no. 158, doi: 10.1186/s13638-018-1168-4.

[57] A. B. Samii, R. Pibernik, P. Yadav, and A. Vereecke, "Reservation and allocation policies for influenza vaccines," (in English), *European Journal of Operational Research,* Article vol. 222, no. 3, pp. 495-507, 2012, doi: 10.1016/j.ejor.2012.05.003.

[58] Z. Ding, L. Wang, H. Zhao, H. Zhang, and C. Wang, "Numerical study and design of a two-stage ejector for subzero refrigeration," (in English), *Appl Therm Eng,* Article vol. 108, pp. 436-448, 2016, doi: 10.1016/j.applthermaleng.2016.07.104.

[59] H. Hasan, E. AlHadhrami, A. AlDhaheri, K. Salah, and R. Jayaraman, "Smart contract-based approach for efficient shipment management," (in English), *Comput Ind Eng*, Article vol. 136, pp. 149-159, 2019, doi: 10.1016/j.cie.2019.07.022.

[60] H. Yu and W. D. Solvang, "A fuzzy-stochastic multi-objective model for sustainable planning of a closed-loop supply chain considering mixed uncertainty and network flexibility," *Journal of Cleaner Production*, p. 121702, 2020.

[61] K. De Boeck, C. Decouttere, and N. Vandaele, "Vaccine distribution supply chains in developing countries: A literature review," *FEB Research Report KBI_1815*, 2018.

[62] N. Al Theeb, H. J. Smadi, T. H. Al-Hawari, and M. H. Aljarrah, "Optimization of vehicle routing with inventory allocation problems in Cold Supply Chain Logistics," (in English), *Comput Ind Eng*, Article vol. 142, 2020, Art no. 106341, doi: 10.1016/j.cie.2020.106341.

[63] C. Huai, G. Sun, R. Qu, Z. Gao, and Z. Zhang, "Vehicle Routing Problem with Multi-type Vehicles in the Cold Chain Logistics System," in *2019 16th International Conference on Service Systems and Service Management (ICSSSM)*, 13-15 July 2019 2019, pp. 1-4, doi: 10.1109/ICSSSM.2019.8887612.

[64] S. Dou, G. Liu, and Y. Yang, "A New Hybrid Algorithm for Cold Chain Logistics Distribution Center Location Problem," (in English), *IEEE Access*, Article vol. 8, pp. 88769-88776, 2020, Art no. 9079803, doi: 10.1109/ACCESS.2020.2990988.

[65] S. Shahparvari, A. Nasirian, A. Mohammadi, S. Noori, and P. Chhetri, "A GIS-LP integrated approach for the logistics hub location problem," *Computers & Industrial Engineering*, vol. 146, p. 106488, 2020/08/01/ 2020, doi: https://doi.org/10.1016/j.cie.2020.106488.

[66] Y. Yang, H. Bidkhori, and J. Rajgopal, "Optimizing vaccine distribution networks in low and middle-income countries," *Omega*, p. 102197, 2020/01/11/ 2020, doi: https://doi.org/10.1016/j.omega.2020.102197.

[67] N. Al Theeb, H. J. Smadi, T. H. Al-Hawari, and M. H. Aljarrah, "Optimization of vehicle routing with inventory allocation problems in Cold Supply Chain Logistics," *Computers & Industrial Engineering*, vol. 142, p. 106341, 2020/04/01/ 2020, doi: https://doi.org/10.1016/j.cie.2020.106341.

[68] J. Lim, B. A. Norman, and J. Rajgopal, "Redesign of vaccine distribution networks," (in English), *Int. Trans. Oper. Res.*, Article 2019, doi: 10.1111/itor.12758.

[69] L. PG Petroianu *et al.*, "A light - touch routing optimization tool (RoOT) for vaccine and medical supply distribution in Mozambique," *International Transactions in Operational Research*, 2020.

[70] Q. Lin, Q. Zhao, and B. Lev, "Cold chain transportation decision in the vaccine supply chain," *European Journal of Operational Research*, vol. 283, no. 1, pp. 182-195, 2020/05/16/ 2020, doi: https://doi.org/10.1016/j.ejor.2019.11.005.

[71] R. G. Ingalls, "Introduction to supply chain simulation," presented at the Proceedings of the 2014 Winter Simulation Conference, Savannah, Georgia, 2014.

[72] X. Sun, H. Yu, and W. D. Solvang, "Solving the Location Problem of Printers in a University Campus Using p-Median Location Model and AnyLogic Simulation," in *International Workshop of Advanced Manufacturing and Automation*, 2019: Springer, pp. 577-584.

[73] M. Mofrad, L. M. Maillart, B. A. Norman, and J. Rajgopal, "Multi-dose vial administration with non-stationary demand and delayed service," *Operations Research for Health Care*, vol. 19, pp. 66-79, 2018/12/01/ 2018, doi: https://doi.org/10.1016/j.orhc.2018.03.003.

[74] Z. Azadi, H. Gangammanavar, and S. Eksioglu, "Stochastic Optimization of Vaccine Vial Replenishment."

[75] A. A. C. Vieira, L. M. S. Dias, M. Y. Santos, G. A. B. Pereira, and J. A. Oliveira, "Supply chain data integration: A literature review," *Journal of Industrial Information Integration,* vol. 19, p. 100161, 2020/09/01/ 2020, doi: https://doi.org/10.1016/j.jii.2020.100161.

[76] D. Dai, X. Wu, and F. Si, "Complexity Analysis and Control in Time-Delay Vaccine Supply Chain considering Cold Chain Transportation," (in English), *Mathematical Problems in Engineering,* Article vol. 2020, 2020, Art no. 4392708, doi: 10.1155/2020/4392708.

[77] L. E. Mueller *et al.*, "The impact of implementing a demand forecasting system into a low-income country's supply chain," *Vaccine,* vol. 34, no. 32, pp. 3663-3669, 2016/07/12/ 2016, doi: https://doi.org/10.1016/j.vaccine.2016.05.027.

[78] E. Shittu, M. Harnly, S. Whitaker, and R. Miller, "Reorganizing Nigeria’s Vaccine Supply Chain Reduces Need For Additional Storage Facilities, But More Storage Is Required," *Health Affairs,* vol. 35, no. 2, pp. 293-300, 2016/02/01 2016, doi: 10.1377/hlthaff.2015.1328.

[79] R. D. Tordecilla, A. A. Juan, J. R. Montoya-Torres, C. L. Quintero-Araujo, and J. Panadero, "Simulation-optimization methods for designing and assessing resilient supply chain networks under uncertainty scenarios: A review," *Simulation Modelling Practice and Theory,* vol. 106, p. 102166, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.simpat.2020.102166.

[80] K. Dillon and J. Colton, "A design methodology for the economic design of vaccine warehouses in the developing world," (in English), *Build. Environ.*, Article vol. 82, pp. 160-170, 2014, doi: 10.1016/j.buildenv.2014.07.024.

[81] N. I. o. P. Health. "Norhealth Population." http://www.norgeshelsa.no/norgeshelsa/ (accessed 13th March, 2021).

[82] Wikipedia. "Norway." https://en.wikipedia.org/wiki/Norway (accessed 7th March, 2021).

[83] Å. Ringard, A. Sagan, I. Sperre Saunes, and A. K. Lindahl, "Norway: health system review," (in eng), *Health Syst Transit*, vol. 15, no. 8, pp. 1-162, 2013.

[84] E. H. I. Gateway. "Gross Domestic Product Per Capita." https://gateway.euro.who.int/en/indicators/hfa_33-0260-gross-domestic-product-gdp-us-per-capita/visualizations/?country=NOR#id=27549 (accessed 7th March, 2021).

[85] Wikipedia. "List of Municipalities in Norway." https://en.wikipedia.org/wiki/List_of_municipalities_of_Norway (accessed 7th March, 2021).

[86] S. Legemiddelverk. "The Norwegian health care sysren and pharmaceitical system." https://legemiddelverket.no/english/about-us/the-norwegian-health-care-system-and-pharmaceutical-system (accessed 7th March, 2021).

[87] N. I. o. P. Health. "Life Expectancy in Norway." https://www.fhi.no/en/op/hin/population/life-expectancy/ (accessed 7th March, 2021).

[88] W. Atlas. "Maps of Norway." https://www.worldatlas.com/maps/norway (accessed 5th April, 2021).

[89] A. Dorse. "Norway." https://www.pinterest.com/pin/68609594297596993/ (accessed 5th April, 2021).

[90] V. Coronavirus. https://www.vg.no/spesial/corona/vaksiner/ (accessed 7th March, 2021, 2021).

[91] J. Johnson. https://www.jnj.com/johnson-johnson-announces-submission-of-european-conditional-marketing-authorisation-application-to-the-ema-for-its-investigational-single-shot-janssen-covid-19-vaccine-candidate (accessed 7th March, 2021, 2021).
[92] M. o. H. a. C. Services. "Address by the Minister of Health and Care Services " https://www.regjeringen.no/en/aktuelt/address-by-the-minister-of-health-and-care-services-to-the-storting-on-18-january-2021-regarding-norwegian-authorities-work-on-vaccines-against-covid-19/id2829245/ (accessed 16th March, 2021).
[93] T. N. I. o. P. Health. https://www.fhi.no/nettpub/koronavaksinasjonsveilederen-for-kommuner-og-helseforetak/distribusjon-av-koronavaksiner/vaksinasjon-ved-koronapandemi/ (accessed 7th March, 2021, 2021).
[94] T. N. I. o. P. Health. "Changes in the Vaccine Strategy." https://www.fhi.no/en/news/2021/changes-in-the-vaccine-strategy/ (accessed 13th March, 2021).
[95] B. W. Knut Jønsrud, E. A. Andoh, Ed., ed, 2020.
[96] S. J. Joakim Reigstad. "Covid-19 Vaccine Vehicles." https://www.nrk.no/norge/slik-skal-koronavaksinen-distribueres-1.15293621?fbclid=IwAR0YPFbW1Tmb4ljFmpgUnZNFCQSixoq6KzLgvVv5VdbebWecHGMcMzBsYh4 (accessed 9th March, 2021).
[97] T. Pedersen. "Koronavaksinen har ankommet Ullevål sykehus i Oslo." https://www.varingen.no/koronavaksinen-har-ankommet-ulleval-sykehus-i-oslo/s/5-92-215806 (accessed 9th March, 2021).
[98] Pfizer. "Koronavaksinen kommer til Trondheim 5. januar." https://bydelsnytt.no/2020/12/31/koronavaksinen-kommer-til-trondheim-5-januar/?fbclid=IwAR1TB1F-hRbRzB5O3GSS0LdzqsH9Wv8I6BxCJNCd2kamNhKsulCRklyF2Ko (accessed 9th March, 2021).
[99] T. N. D. o. Health. https://www.helsedirektoratet.no/veiledere/koronavirus/vaksiner-smittevernutstyr-og-legemidler/vaksinering-og-vaksineutstyr#bruk-av-kjolebokser-og-temperaturloggere (accessed 7th March, 2021, 2021).
[100] Europa. "Clean COVID-19 Vaccine SmPC-PL 21-DEC-2020." https://ec.europa.eu/health/documents/community-register/2020/20201221150522/anx_150522_en.pdf (accessed March, 2021).
[101] Europa. "COVID-19 Vaccine AstraZeneca, COVID 19 Vaccine." https://www.ema.europa.eu/en/documents/product-information/covid-19-vaccine-astrazeneca-product-information-approved-chmp-29-january-2021-pending-endorsement_en.pdf (accessed March, 2021).
[102] Europa. "COVID-19 Vaccine Moderna, INN-Covid-19 mRNA Vaccine." https://www.ema.europa.eu/en/documents/product-information/covid-19-vaccine-moderna-epar-product-information_en.pdf (accessed March, 2021).
[103] I. Fylkeskommune. "About Inland Norway." https://innlandetfylke.no/om-fylkeskommunen/om-innlandet/regioner-og-kommuner/ (accessed 18th March, 2021).
[104] AnyLogistix. "Anylogistix Features Overview." https://www.anylogistix.com/alx-features/ (accessed 19th March, 2021).
[105] I. D., *Supply Chain Simulation and Optimization with anyLogistix*, 5th updated edition ed. Berlin: Berlin School of Economics and Law, 2021.
[106] Arbeidstilsynet. "Working Hours." https://www.arbeidstilsynet.no/en/working-conditions/working-hours/ (accessed 9th April, 2021).

[107] ThermoKing. "TK80017_ColdCube_Pharma-07-2020-EN_V1.0.pdf." https://europe.thermoking.com/wp-content/uploads/2019/07/TK80017_ColdCube_Pharma-07-2020-EN_V1.0.pdf (accessed 5th March, 2021).
[108] V. Bilguden. "VG Bilguiden - Nissan." https://www.vg.no/bil/nissan/nv200/spesifikasjoner (accessed 5th March, 2021).
[109] Parkers. "Volkswagen Transporter dimensions (2015-on)." https://www.parkers.co.uk/vans-pickups/volkswagen/transporter/2015-dimensions/ (accessed 5th March, 2021).
[110] Nyinorge. "Traffic Rules." http://www.nyinorge.no/en/Ny-i-Norge-velg-sprak/New-in-Norway/Transport-and-services/Motor-vehicles/Traffic-rules/ (accessed 9th April, 2021).
[111] Nissan. "Technical Information." https://www.nissan.no/biler/nye-biler/e-nv200/teknisk-informasjon.html#freeEditorial_contentzone_f70d (accessed 5th March, 2021).
[112] S. Norway. "Statbank-Earnings." https://www.ssb.no/en/statbank/table/11421/ (accessed 7th April, 2021).
[113] NextGreenCar. "VW Transporter Kombi Crew Van T6.1 CO2 and NOx emissions 2021." https://www.nextgreencar.com/emissions/make-model/vw/transporter%20kombi%20crew%20van%20t6.1/ (accessed 5th March, 2021).

# APPENDIX

## A) COVID-19 Vaccine Candidates

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2021%20Novel%20Co

## B) Vaccine Demand Data

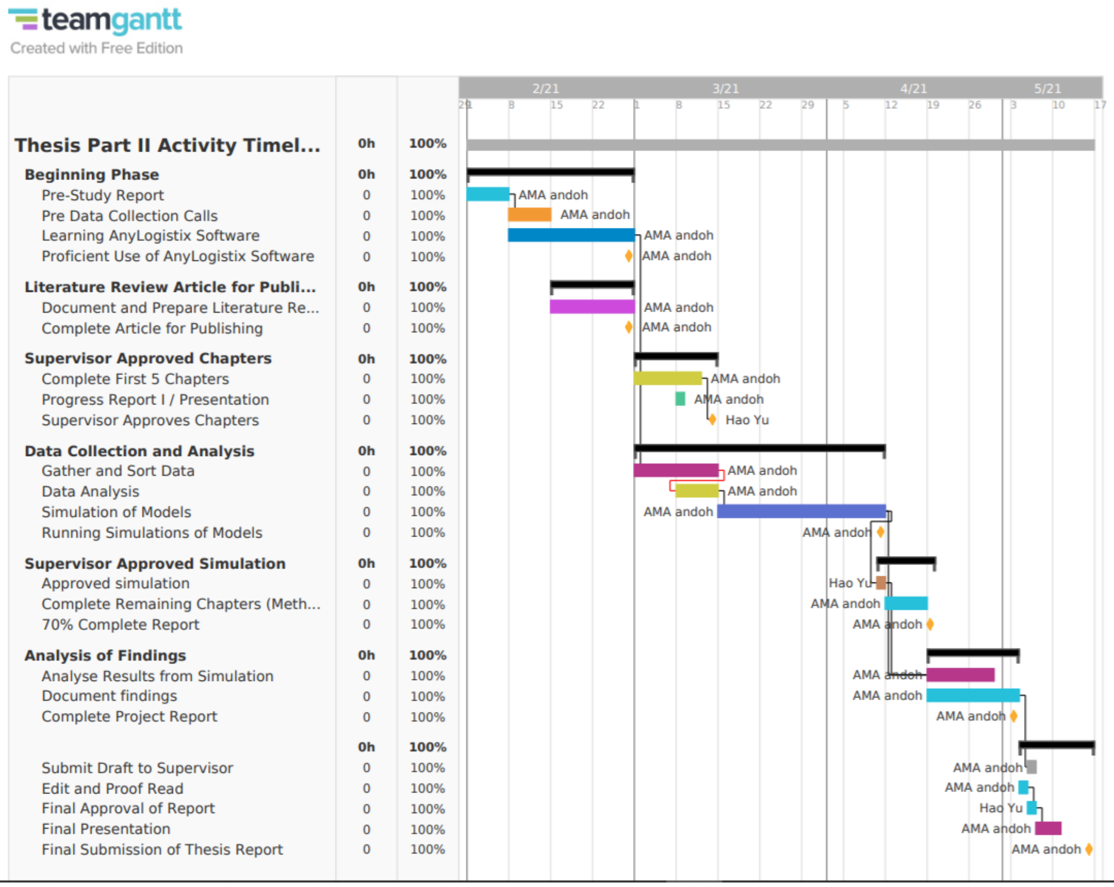
2021-03-09_vaksined
oser_distribuert_til_ko

## C) 2020 Norway Population with Age Distribution

| Geography | Age | 2020 Population |
|---|---|---|
| ***Norway*** | all ages | 5367580 |
| | 0-17 years | 1118608 |
| | 80 years + | 230710 |
| **Counties** | | |
| Oslo | all ages | 693494 |
| | 0-17 years | 133128 |
| | 80 years + | 21337 |
| Viken | all ages | 1241165 |
| | 0-17 years | 269533 |
| | 80 years + | 52228 |
| **Innlandet** | **all ages** | **371385** |
| | **0-17 years** | **69410** |
| | **80 years +** | **20490** |
| Vestfold og Telemark | all ages | 419396 |

| | | |
|---|---|---|
| | 0-17 years | 83755 |
| | 80 years + | 20705 |
| Agder | all ages | 307231 |
| | 0-17 years | 67195 |
| | 80 years + | 13031 |
| Rogaland | all ages | 479892 |
| | 0-17 years | 112032 |
| | 80 years + | 17253 |
| Vestland | all ages | 636531 |
| | 0-17 years | 136349 |
| | 80 years + | 29039 |
| Møre og Romsdal | all ages | 265238 |
| | 0-17 years | 55593 |
| | 80 years + | 13306 |
| Trøndelag | all ages | 468702 |
| | 0-17 years | 96431 |
| | 80 years + | 20357 |
| Nordland | all ages | 241235 |
| | 0-17 years | 47452 |
| | 80 years + | 12550 |
| Troms og Finnmark | all ages | 243311 |
| | 0-17 years | 47730 |
| | 80 years + | 10414 |

## D) Thesis Activity Gantt Chart



| | | |
|---|---|---|
| **Thesis Part II Activity Timel...** | **0h** | **100%** |
| **Beginning Phase** | **0h** | **100%** |
| Pre-Study Report | 0 | 100% |
| Pre Data Collection Calls | 0 | 100% |
| Learning AnyLogistix Software | 0 | 100% |
| Proficient Use of AnyLogistix Software | 0 | 100% |
| **Literature Review Article for Publi...** | **0h** | **100%** |
| Document and Prepare Literature Re... | 0 | 100% |
| Complete Article for Publishing | 0 | 100% |
| **Supervisor Approved Chapters** | **0h** | **100%** |
| Complete First 5 Chapters | 0 | 100% |
| Progress Report I / Presentation | 0 | 100% |
| Supervisor Approves Chapters | 0 | 100% |
| **Data Collection and Analysis** | **0h** | **100%** |
| Gather and Sort Data | 0 | 100% |
| Data Analysis | 0 | 100% |
| Simulation of Models | 0 | 100% |
| Running Simulations of Models | 0 | 100% |
| **Supervisor Approved Simulation** | **0h** | **100%** |
| Approved simulation | 0 | 100% |
| Complete Remaining Chapters (Meth... | 0 | 100% |
| 70% Complete Report | 0 | 100% |
| **Analysis of Findings** | **0h** | **100%** |
| Analyse Results from Simulation | 0 | 100% |
| Document findings | 0 | 100% |
| Complete Project Report | 0 | 100% |
| | **0h** | **100%** |
| Submit Draft to Supervisor | 0 | 100% |
| Edit and Proof Read | 0 | 100% |
| Final Approval of Report | 0 | 100% |
| Final Presentation | 0 | 100% |
| Final Submission of Thesis Report | 0 | 100% |

## E) Results from sensitivity analysis in SIM

|  |  |  | **Mean Values** |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | **Number of Electric Nissan NV200** | **Number of Nissan NV200** | **Transportation Cost** | **ELT Service Level by products** | **Mean Lead Time** | **Max Lead Time** | **Co2 Emission** |
|  | 1 | 2 | 571,598.00 | 0.424 | 1.227 | 4.265 | 3413046 |
|  | 3 | 2 | 604,391.00 | 0.947 | 0.67 | 1.554 | 3416542 |
|  | 4 | 2 | 604,391.00 | 1 | 0.616 | 1.526 | 3416542 |
| **MODEL 1** | 1 | 3 | 583,060.00 | 0.425 | 1.174 | 4.27 | 3540063 |
|  | 3 | 3 | 615,384.00 | 0.947 | 0.62 | 1.497 | 3540063 |
|  | 4 | 3 | 615,384.00 | 1 | 0.567 | 1.007 | 3540063 |
|  |  |  |  |  |  |  |  |
|  | 1 | 2 | 448,494.00 | 0.514 | 0.894 | 3.355 | 2270003 |
|  | 3 | 2 | 476,930.00 | 0.888 | 0.546 | 1.382 | 2270003 |
| **MODEL 2** | 4 | 2 | 476,930.00 | 0.928 | 0.517 | 1.378 | 2270003 |
|  | 1 | 3 | 448,371.00 | 0.585 | 0.852 | 3.331 | 2270003 |
|  | 3 | 3 | 476,930.00 | 0.963 | 0.503 | 1.327 | 2270003 |
|  | 4 | 3 | 476,930.00 | 1 | 0.476 | 0.86 | 2270003 |
|  |  |  |  |  |  |  |  |
|  | **Number of Nissan NV 200** | **Number of Volkswagen Transporter** | **Transportation Cost** | **ELT Service Level by products** | **Mean Lead Time** | **Max Lead Time** | **Co2 Emission** |
|  | 1 | 2 | 701,118.00 | 0.661 | 1.174 | 3.115 | 8274110 |
|  | 2 | 3 | 726,565.00 | 0.942 | 0.746 | 1.625 | 8521879 |
| **MODEL 3** | 3 | 3 | 726,565.00 | 1 | 0.654 | 1.625 | 8521879 |
|  | 2 | 4 | 726,565.00 | 0.938 | 0.668 | 1.533 | 8521879 |
|  | 3 | 4 | 726,565.00 | 1 | 0.577 | 1.516 | 8521879 |
|  | 2 | 5 | 726,565.00 | 0.941 | 0.611 | 1.532 | 8521879 |
|  | 3 | 5 | 726,565.00 | 1 | 0.519 | 0.856 | 8521879 |