FEASIBILITY ANALYSIS OF CENTRALIZED PROCUREMENT OF PERSONAL PROTECTIVE EQUIPMENT AT THE FINNISH HOSPITAL DISTRICTS

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ABSTRACT

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Feasibility Analysis of Centralized Procurement of Personal Protective Equipment at the Finnish Hospital Districts

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The global COVID-19 pandemic changed the world in a way that had never been seen before, having both direct and indirect impacts on everyone. Due to the epidemic, demand for personal protective equipment skyrocketed in Spring 2020. One way of responding to the situation was to acquire protective equipment to decrease the number of infections and uphold the healthcare system.

The aim of this study is to find out level of utilization of protective equipment and to evaluate the functionality of the current distributed procurement system structure in Finland. The intention is to increase the understanding of the relationship between procurement and consumption of protective equipment and to compare the healthcare system's current supply chain to an optional, more centralized model. A model was built that uses traditional inventory management calculation formulas in portraying the current situation. Then, a discrete-event Monte Carlo simulation was run using the model to estimate reference stock supply for future epidemics, in which the importance of protective equipment is significant.

The current supply chain was compared to a more centralized model that also considers the economies of scale of the procurement. Based on the results, the centralized system structure could provide more efficiency, collaboration, and better preparedness for crisis. The results of this study can be utilized in decision-making and future procurement.

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Maailmanlaajuinen COVID-19 pandemia muutti maailmaa ennennäkemättömällä tavalla, joka on ollut suorasti tai epäsuorasti vaikutuksessa jokaiseen. Pandemiasta johtuen, kysyntä henkilökohtaisista suojainvälineistä nousi rajusti keväällä 2020. Yhtenä vastauksena tilanteeseen olivat suojainvälineiden hankinnat terveydenhuoltojärjestelmän ylläpitämiseen, joilla on voitu lieventää pandemian nopeaa leviämistä ja järjestelmän ylikuormittumista.

Tutkimuksen tavoitteena on selvittää suojainvälineiden kulutusta pandemian aikana ja arvioida Suomen nykyisen hajautetun hankintajärjestelmärakenteen toimivuutta. Tarkoituksena on lisätä ymmärrystä suojainvälineiden hankintojen ja kulutuksen välisestä suhteesta sekä verrata nykyistä julkisen terveydenhuollon toimitusketjua vaihtoehtoiseen, keskitetympään malliin. Nykytilakartoituksen pohjalta rakennettiin malli, jossa sovellettiin perinteisiä varastonohjauksen laskentakaavoja. Sen jälkeen diskreetin tapahtumapohjaisen Monte Carlo simuloinnin avulla arvioitiin viitteellisiä varastotasoja tulevia epidemioita varten, joissa suojainvälineiden merkitys on avainasemassa.

Nykyistä toimitusketjumallia verrattiin keskitetympään kokonaisuuteen, joka huomioi myös hankintojen mittakaavaedut. Tulosten perusteella keskitetty järjestelmärakenne voisi tarjota taloudellisesti tehokkaamman, yhteistyökeskeisemmän, ja kriisivarautuneemman ratkaisun. Tutkimuksen tuloksia voidaan hyödyntää päätöksenteossa ja tulevissa hankinnoissa.

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These five years at LUT University have been the most glorious time of my life. New friendships, unforgettable experiences, the inspirable atmosphere of the campus are just a few to mention. I am proud of giving my input to society in the form of skills I have learned at my university. Thank you.

Espoo, April 2022

Matti Mattila

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Abbreviations

3PL	Third Party Logistics
AI	Artificial Intelligence
BPR	Business Process Redesign
DII	Days-in-inventory
EOQ	Economic Order Quantity
GPO	Group Purchasing Organisations
HC	Holding Cost
HSC	Healthcare Supply Chain
JIT	Just-in-time
KPI	Key Performance Indicator
LR	Linear Regression
MCDA	Multi-Criteria Decision Analysis
MCS	Monte Carlo Simulation
MILP	Mixed Integer Linear Programming
ML	Machine Learning
MRP	Material Requirement Planning
NPV	Net Present Value
OM	Operations Management
PC	Purchasing Cost
PPE	Personal Protective Equipment
R&D	Research & Development
SC	Supply Chain
SCM	Supply Chain Management
SEM	Structural Equations Model
SM	Simulation Modelling
TC	Total Cost
UPC	Universal Product Code
WAC	Weighted Average Cost

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1. Introduction

This study originates from the experiences of COVID-19 pandemic and deals with centralization proposal of Finnish public healthcare supply chain (SC) of the most crucial personal protective equipment (PPE). During the pandemic, Finnish healthcare was in a challenging situation, leading to various concerns to arise, such as personnel competence, adequacy of hospital facilities and criticality of PPE. This work, though, seeks to explore alternative approaches for the SC functionality by comparing alternative centralized solution to the current decentralized model. More precisely, the thesis aims to assist in decision-making on an issue which has not been extensively or scientifically studied before but has received an increasing amount of interest recently. As Blanchard (2007, 54) expressed it "disruptions in the SC lowers the operating performance for a company by proceeding to perform at lower level for the next couple of years". Therefore, suggestions by addressing for alternative Finnish healthcare sector SC structures should be addressed in order to prepare for future disruptions.

1.1 Motivation and background

Rapid and unprecedented rise in demand of PPE has drastically affected Finland and the world in the recent years. In supply management perspective, this has had a remarkable effect on the overall functionality of SCs and logistics globally. Recently published literature review by Chowdhury, Paul, and Moktadir (2021) revealed that the focus on SC resilience is arising research opportunity after the outbreak of COVID-19. For example, SC structures, resource allocation, collaboration and integration are suggested topics in research and especially epidemics-related matters but also other SC disruptions. As a consequence, the idea of centralizing critical products, especially PPEs is gaining acceptance among Finnish hospital districts and National Emergency Supply Agency (NESA). Motivation for researching the topic arises of two issues: first, from the environmental changes wherein the pandemic has required a vast number of resources to be gathered and used with an extremely challenging nonpredictable demand, and second, how coordinated and co-operative the response has been on this matter. Furthermore, academic papers have already been published which reported that the disruption and uncertainty in SCs has forced organisations to rethink their today's business models in the hospital industry (Breier et al. 2021). Therefore, this thesis reviews the impacts caused by the pandemic that have occurred during years 2020 and 2021, addresses the present state and seek solutions for the future.

Topic about alternative SC structures for Finnish hospital districts should be extensively studied because the current decentralized system may not have been as effective or cost-effective as thought earlier. The current system in which the hospital districts manage supplies and logistic flows independently has been perceived to work properly under normal circumstances. However, in times of crises the system may not be able to respond as effectively as a centralized system could. Academic studies have already addressed this topic (Sharma, Borah and Moses 2021) and Breier et al. (2021) have found that crises can enhance and accelerate business innovation in the hospital industry since weaknesses become clearly apparent during bad times. Partly due to the increasing market disruptions and unpredictable events, debate on innovative public procurement has been lively for the last two decades, concentrating on more efficient SC solutions. This is reflected in the growing body of research literature on the subject. European countries have been interested in the potential of public procurement both the efficiency of public and the innovative capacity of business. (European Commission 2006) There is a broad recognition of contribution of procurement within public administrations at every level since effective and efficient management of required inputs has a critical impact on the achievement of high-level objectives. (Patrucco, Agasisti, and Glas 2021)

There are significant differences between countries in both innovativeness of public procurement and its organization. In some countries, explicit attention has been paid to the innovativeness of projects, in others not. There are centralized procurement organizations in some countries, whereas in others procurement is decentralized, depending on the size of a company, however. (Halme and Kotilainen 2008) According to Ferraresi, Gucciardi, and Rizzo (2021) the transition toward a centralized procurement system in the public healthcare has been paid off in Italy, reducing two to eight percent health expenditure per capita during the last six years. Another study by Clark, Coviello, and De Leverano (2021) found that the statutory centralization in Italy resulted at a reduction in unit prices but delivery times increased. Moreover, a transition towards centralized SC tend to increase information sharing between partners that are involved in the system and synergy benefits are achievable (Karjalainen 2009, 400; Parker and DeLay 2008) In cases of large international companies, approximately 80% to 90% have conducted and will continue to operate a highly centralized procurement system within their operations (CAPS Research 2018). This trend has been upward sloping in recent years although changes in supply management organisational design has remained relatively slow as over 70% of companies have operated under the same SC structure for five years or more (CAPS Research 2021). The latter may indicate about complex SC structures that usually demand massive and expensive practices in order to change them.

According to Statistics Finland (2021) there were twenty-one hospital districts in Finland in 2021. Additionally, there were five special areas of responsibility in which every district only belonged to one Finnish special area of responsibility. The decree on hospital special responsibility areas was set in Finnish legislation in 2017 (156/2017). Thus, transition toward centralization has already taken place at the geographical level. However, the focus has not yet been on logistics side that much, but changes have been already conducted for special care service centralization purposes that is majorly based on a capitalization model. The social welfare and health care reform enacted in 1.6.2022 will continue the development of the current system from 1.1.2023 onwards after the reform takes place in reality (Finnish government 2022).

1.2 Objectives of the study

This study addresses a gap of comparison of an alternative SC structure for Finnish hospital districts in research by identifying the differences between centralized and decentralized procurement system of PPE and is relevant to research because the project is significant in scale, savings can be substantial, and valuable new information may emerge from the study. Since it is desired to form a feasibility analysis of the models, scientific information on previous studies is hoped to be found especially as Syahrir and Vanany (2015) revealed in their literature review that there is a plenty of room for further research concerning mathematical modelling in healthcare SCM and particularly in cases of natural disaster events such as epidemics. Chowdhury et al. (2021) noted there have not been systematic literature reviews on COVID-19 related SC studies and for that sake it has remained unclear what aspects disruption have been studied and what should be examined from now on. Besides economic significance and collaboration that the centralization would provide, possible shortcomings of the comparable model must be recognized and hence evaluate the total trade-off between the models. Changes in SC structure may also affect other parties than Finnish public healthcare. Thereby, the advantages or disadvantages may be direct or indirect.

The study involves two main objectives. First, to create a feasibility analysis of the models. It is noteworthy to find out which factors have the greatest impact on profitability, and on the other hand, which factors are not really that significant. Second objective is to model proactive strategies or suggestions for similar upcoming crises and times between them, as Stefanovic (2014) mentioned that predictive analytics can provide valuable insights in SC performance that are capable of adapting future environment with better responsiveness. The research area of the work is shown in Figure 1.

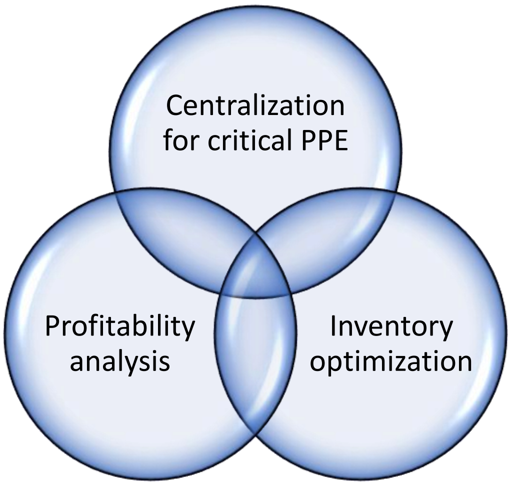

Figure 1. The research area of the work.

As there are many factors associated within the analysis, providing a beneficial support and overall view of the present model and the alternative model for decision-makers is the ideal outcome. Further, quantitative research is relevant to implement in addition to qualitative research as Hennink, Hutter, and Bailey (2020) have stated. Economic significance, transparency within SC, and crisis-preparedness are the key themes in which this work focuses on.

1.3 Research problem and methodology

Projects come with a cost, and companies have limited amount of capital to invest. Capital budgeting has been used for major projects or investments to find out if there are opportunities that enhance shareholder value. (Kenton 2022) However, the difficulty arises in estimating the outcome of the project particularly since there are both tangible and intangible resources associated. To elaborate this, the case is not about an initial investment that would generate income from sales over time (with a break-even). Instead, it is about saving opportunities and efficiencies that are generated through inventory SC reorganisation, optimization, and co-operation. Unfortunately, all of these changes cannot be evaluated accurately in the model comparison. Thus, the focus of the study is on the economic side of the project.

Concepts such as economic order quantity (EOQ), lead time, inventory turnover and days-in-stock (DIS) are commonly used traditional metrics in inventory management (IM). These can be used in monitoring the situation at a given time to maintain daily operations, but the extreme uncertainty of demand poses challenges to the appropriateness of these metrics for the future because they assume that the fluctuations in demand are small (Brewer et al. 2001, 198; Hugos 2018, 6). The difficulty is compounded when it is not a question of seasonal fluctuations in demand but of pure uncertainty about the future. Therefore, a method that can take high uncertainty into account would be ideal. Monte Carlo simulation (MCS) might alleviate the fundamental problem of uncertainty as it utilizes probabilities by creating a big picture for all scenarios, but the model set-up can be challenging. (Schmidt and Wilhelm 2000)

The applied method is quantitative, and data acquired from four sources. The first two are from large hospital districts and from a database. Both of these are confidential and thus non-accessible to be used outside this research. Second, surveys on economies of scale from suppliers are included and NESA provides relevant data to support the analysis. As the data is acquired from multiple sources, processing and consolidating these require a great deal of work. The datasets are processed with MS Excel as it has the necessary tools for this purpose. Empirical analysis focuses on the calculations of cost structures and scenarios that are presented for the two comparable models. Subsequently, projections of potential savings are compared to the current "as is" model. The visual presentation of the two SC structures is shown in Figure 2. The one on the right illustrates the centralized SC design.

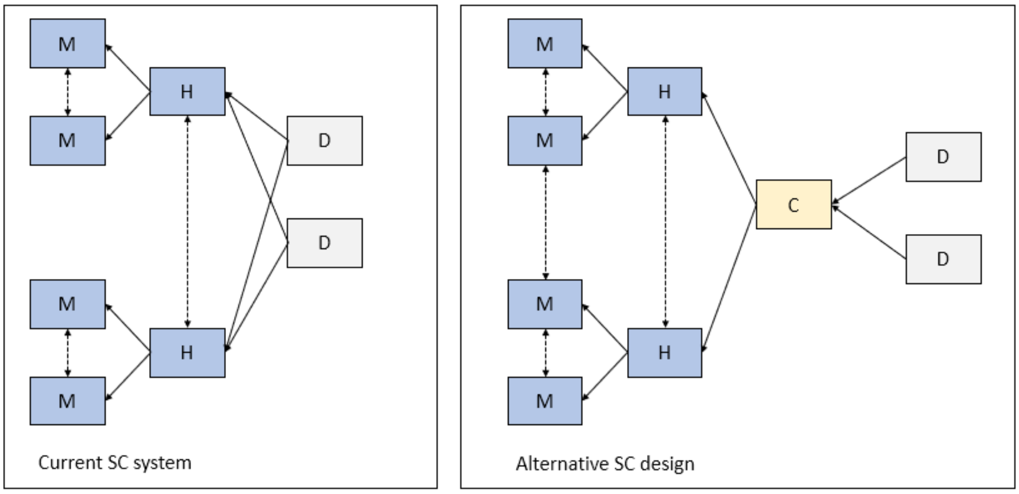

Figure 2. The current SC structure versus the alternative one for Finnish hospital districts.

Empirical part proceeds as follows: after the data has been inquired, acquired, processed, and consolidated, it is possible to start building the base model. This, in turn provides the basis for the new model. The model consists of "modules" which parse the structure. This makes it easier to build or remove links with each other. Scenarios are made to consider different consumption levels to the corresponding inventory balances. This helps to outline how much different PPE would be needed against a particular consumption. Assumptions of PPE surplus or deficit can be made after the national consumption and inventory balances are known. Finally, economics of scale is added to the new model. Among calculations, the study evaluates the advantages and disadvantages of the base model and the new model.

1.4 Research questions

Studies have found centralization of inventory management relevant concerning this subject, and Iannone, Lambiase, Miranda, Riemma, and Sarno (2014) say that three major logistic strategies have emerged in healthcare SC integration due to constantly challenging environment: centralization of inventory, group purchasing organisations (GPO), and third-party logistics (3PL). These are all large concepts since SCs are complex structures per se. In healthcare though, SCs may set its own challenges because healthcare is prioritized and everything else comes after it, implying about the differences between traditional SC and healthcare supply chain (HSC). (Kritchanchai, Krichanchai, Hoeur, and Tan 2019).

The impacts of COVID-19 have gained attention to question for the centralization of PPE. However, there are no documented attempts, at least in the public domain, of centralization of critical medical equipment among the Finnish hospital districts. Critical medical equipment consists of different categories, depending on the nature of the crisis. In this particular case, pandemic-categorised critical medical products include personal protective equipment. To ponder why centralization of critical medical equipment has not been on stage in the past may help in examining the reasons behind. First, the large size of the project may have slowed the implementation down if the hospital districts have experienced their SCs to be functional enough in the past. Second, policy makers might have been reluctant to change the SC structure for several reasons. According to Kogan, Leu and Chernonog (2014), personal goals and values as well as a lack of negotiation and difficulties in being heard in large organisations are just a few of the possible reasons why healthcare professionals resist consolidation and centralization. Third, data and information management rise its value constantly because it plays an essential role in business. Information management is constantly gaining popularity, which may not have been seen as vital in the past. As Chen, Preston, and Swink (2015) stated, valuable insights that data management may provide affect organisations management policies to rethink their business strategies.

Although theories and research focusing on centralization of SC exist, the latent potential in resilience, feasibility, and economic importance of the alternative SC structure may be currently unclear for policy makers since no quantitative analysis has been made. As similar empirical research cannot be easily found on the related topic, it is justified to study the matter now. The thesis seek answers to the research questions as follows:

1. *According to the literature, how the economic feasibility of different SCM-policies of centralization and decentralization can be evaluated using computational models?*
2. *How to model centralized procurement of personal protective equipment in the Finnish hospital system and what would be the estimated amount of savings compared to the current situation?*

Despite the centralization project is still under early phase of development and some of its legal aspects are already investigated, the thesis does not directly target to answer the question of whether to implement or not. On the contrary, this thesis aims to find answers of how different the situation would be if a similar epidemic occurred, and a new model was in place.

1.5 Limitations and structure of the thesis

SCM is an enormous concept per se, thus it is reasonable to delineate this study to address inventory management. SCs belong under SCM, but again, the entity of SC is too large to study for this purpose. It must be mentioned that a single SC may consist of multiple core activities even though procurement and operations management normally consider majority of the entity. In that sense, it is challenging to limit the SC clearly in this work especially because SCs differ from each other too.

Logistic costs divide into four major part that are transportation, warehousing, carrying, administration, and others (Kantasila and Ojala 2012). In addition, procurement is its own field in SC. The model has a few limitations regarding these. Acquisition costs are included, but ordering costs are not. Carrying costs are taken into account, but the rest are excluded from numerical analysis and evaluated by the support of previous scientific papers. The focus is on reviewing and evaluating inventory levels due to these are substantial relative to normal times. Additionally, capital tied up in inventories is the most sensitive variable. Including all these factors would be far beyond the scope of this study.

Inbound logistics, products in warehouses, and outbound logistics form the framework of inventory management. Everything else, such as ABC-analysis or delays in lead times are excluded from the study. ABC-analysis means the planning of product location in the warehouse for operational efficiency. State-of-the-art literature of SCs and healthcare inventory management will be reviewed in a way that the European and North American countries[1] that have equivalent standard of living and/or other similarities identified by economic metrics are within the scope.

Statutory statements and legal clarifications are excluded. These consider the policy making procedures for the company establishment and all related preparations. For example, issues relating to ownership of products and services are out of scope. Public Procurement Act is also excluded from the work. It is justified that lawyers and other specialists in this area address these subjects. There is a lot to research as several stakeholders would be involved and the project is in Finnish public sector. It is noteworthy that legal clarifications for the centralization proposal have already been paid attention and work at some extent. Moreover, the effects of globalisation will not be evaluated because the phenomenon under study concerns nationwide inventory operations.

The structure of the thesis first introduces theoretical SCM characteristics and mentions the fundamentals about operations management and SC structures. These concepts lead to inventory management which includes different ways of conducting inventory management and relevant mathematical metrics for inventory maintenance. Literature review on approaches of SC demand modelling and comparison of traditional SC and healthcare SC is

[1] I.e., developed countries or advanced economies.

also presented. These form the theoretic model that allow to answer the first research question. The structure of the thesis is shown in Figure 3.

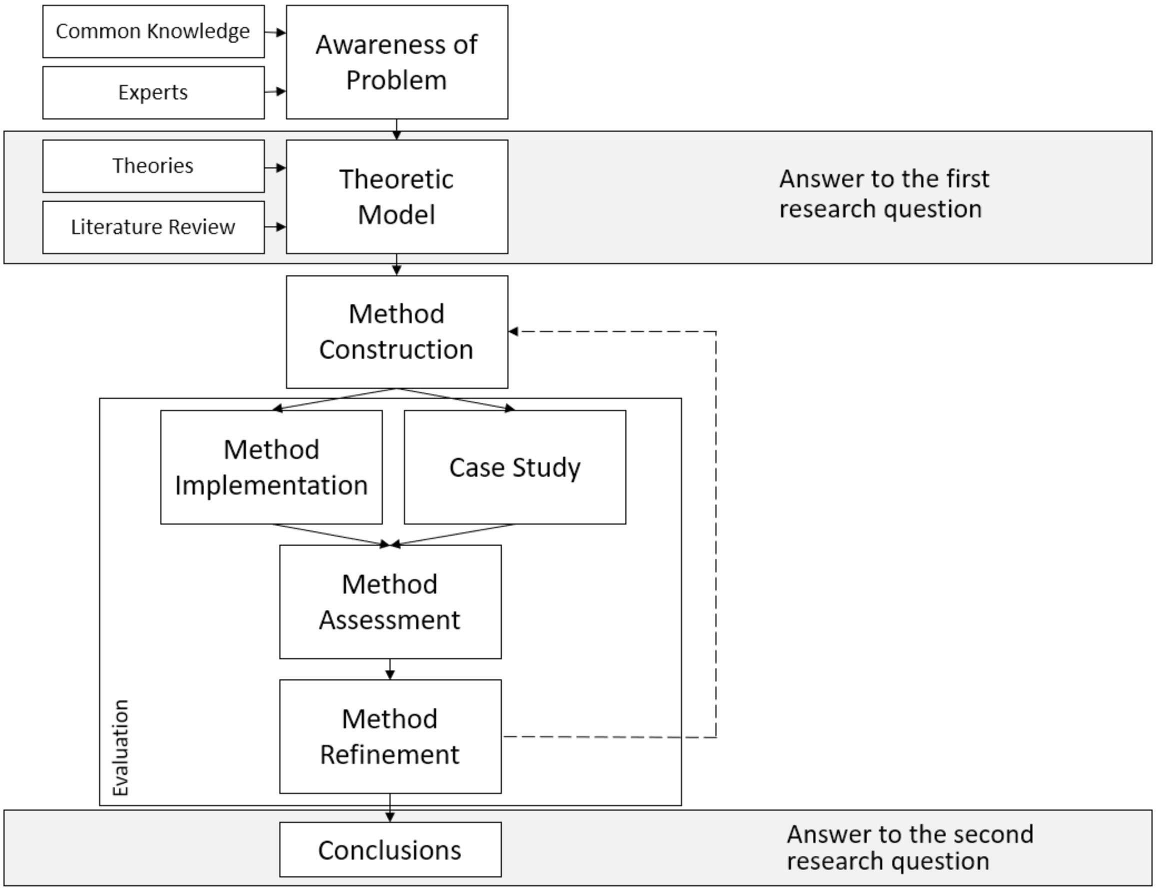

Figure 3. Structure of the work.

In order to answer the second question, the appropriate research method must be clear and constructed. Answer to the first research question provide benefits to find an appropriate research method. After the model is built, it is assessed and refined to make conclusions.

2. Theoretical background

This chapter defines the concept of supply chain management (SCM) and operations management (OM) in the modern environment and proceeds to focus on two related subtopics: typical SC structures and inventory management. The first identifies the SC structures under their typical environments and explains why one structure might not work for other circumstances. The latter delves into ways of conducting demand modelling in the SC environment. Because of the wide variety of SC modelling not all but the most common techniques are introduced.

2.1 Supply chain management

There are various definitions for SCM. According to Hugos (2018, 4) SCM is the coordination of production, location, transportation, and inventory among the members in a SC to get the best combination of efficiency and responsiveness for the market being served. SCM involves design, planning, execution, monitoring, and control of SC activities with the aim of creating value (Blanchard 2007, 8). Furthermore, SCM policy relies on logistics, procurement, information technology, operations management, marketing, and industrial and systems engineering, and seeks for an integrated and multimethod approach. Therefore, it is difficult to separate these areas completely when researching a topic under SCM because of the interconnectivity. That said, SCM complexity is characterised by variety of factors such as uncertainty, copiousness, variability, variety, and interdependency. (Greasley 2008, 85; Hugos 2018, 6)

SC is the network of companies, resources, individuals, technologies, and activities used to manufacture and sell services or products. It starts by delivering materials from a supplier to a manufacturer and concludes with delivering the end-product or service to the customer. SCM monitors every touchpoint of a product or service, from the creation to closing the sale. Because there are many points along the SC that can lose value through increased expenses or add value through efficiencies, adequate SCM can decrease costs, increase revenues, and impact a company’s bottom line. (Fernando 2022)

The underlying concepts of SCM that include production, inventory, location, transportation, and information, have not changed much over time (Hugos 2018, 2-6). However, speaking of the evolution of SCM, the growth of data has remarkably made differences in today’s management practices. While in the past SCs concentrated on the availability, cost of physical assets, and movement, today’s SCs are more about the management of data, products, and services. (Karl et al. 2018) Figure 4 shows the interconnection between the five major SC drivers.

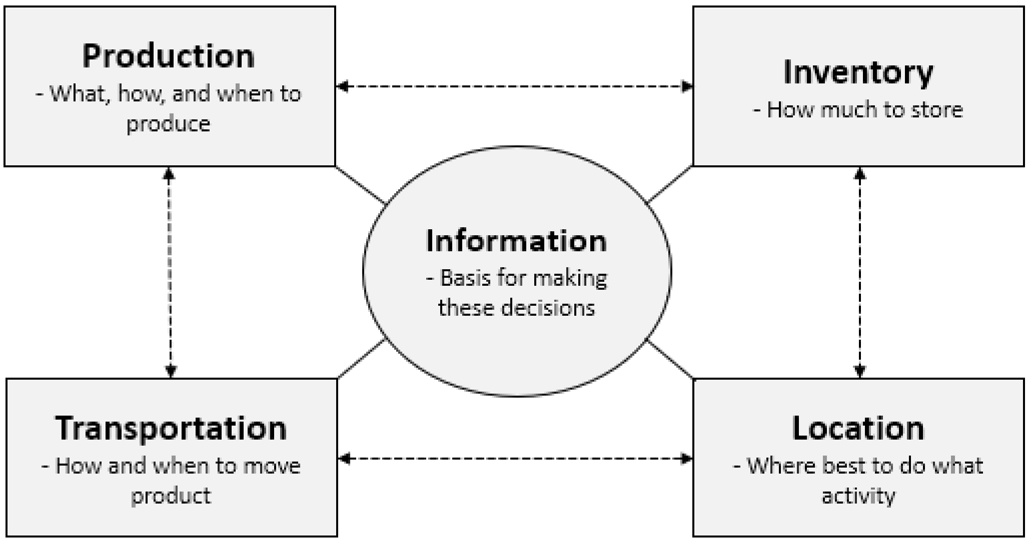

Figure 4. The five major supply chain drivers (adapted from Hugos 2018, 17).

A 2017 survey by IDC revealed that a typical SC accessed fifty times more data than five years prior, but only less than a quarter of this data was being processed and analysed (Ellis and Santagate 2017). When products are produced and sold on multiple continents and time zones, compliance with international rules and regulations and keeping up to date with rapidly changing market demand makes the process complex, challenging, and even fragile. Based on this viewpoint, the importance of information is very crucial in the modern business environment. There is a trade-off on information sharing, though. Companies should decide of how much information to share and keep private, because sharing valuable information to others may be harmful for the company, for example in case of collaboration (Blanchard 2007, 224, Karl et al. 2018). Hugos (2018, 16) emphasizes that even though accurate and abundant information can provide better forecasts and efficient decisions in operational level for a firm, the cost of planning, building, and installing systems to enable this data can be high and require advanced know-how competence. On the other hand, the right combination of efficiency and responsiveness in each of the five major drivers allows a SC to increase throughput while reducing operating expense and inventory at the same time. (Hugos 2018, 17; Karl et al. 2018)

2.1.1 Operations management

To model supply and demand in different SC structures, mathematical approach to must be taken into account that belong to the area of operations management. By one definition, operations management is to design and control the process of production in an efficient way by using as little resources as needed to meet customer requirements (Greasley 2008, 3). OM handles various strategic issues, including determining the size of manufacturing plants, various project management methods, and implementation of the information technology network structure. Other issues include the management of inventory levels that consist of material handling, acquisition, quality control, and maintenance policies. (Hayes 2021a)

OM involves studying the use of materials and making sure that waste is minimized. Managers use equations like the EOQ to monitor when and how large an inventory order is being processed and how much inventory is to be kept on hand. (Brewer, Button, and Hensher 2001, 198) According to McClay (2021), the modern OM include four theories: business process redesign (BPR), Six Sigma, lean manufacturing, and reconfigurable manufacturing systems. The first is introduced by Hammer in 1993 and the concept analyses and designs business processes within an organisation. Six sigma focuses on quality management, lean manufacturing is an approach to eliminate wasteful resource consumption, and reconfigurable manufacturing systems focuses on changes in production capacity and functionality with an aim to quickly adapt to them. (McClay 2021) A common goal for all these four theories is optimization, but these are assessed and measured with different lenses.

OM is prevalent in the healthcare sector. According to Hayes (2021a), today's healthcare system overuses expensive and emergency-based treatment. The high costs of care are often not reimbursed because of patients without insurance. A prevalence of services in costly environments is a burden on taxpayers, health policyholders, and healthcare facilities themselves.

2.1.2 Supply chain design and structures

The formation of SC environment and the arrival of the SCM are the natural consequences resulting from seeking alliances on a huge scale for organisations to gain competitive advantages. Procurement management has shifted from basic internal service specialization to a more strategic function in integrating both external and internal resources, operational function in lowering costs, and management function in risk control. (Jiang 2017) The choice between centralized and decentralized SC varies and many large level businesses involve both centralized and decentralization of some extent when operations locate in several places (Riley 2014).

During crises, the great macro shocks may contribute to decentralized businesses as the value of local information increases, but in turn, the obligation to make decisions might favour centralized businesses. A 2021 study says companies that delegated more power from the central HQs to local managers performed better than their centralized counterparts that were hit heaviest by the Great Recession, measured by product durability and export growth. (Aghion, Bloom, Lucking, Sadun, and Van Reenen 2021) Today, risk management has gained attention as an increasing topic among scientists in SCM. One answer to respond to macro shocks on inventories management is to plan operations with far-reaching and carefully designed resiliency strategy (Chowdhury et al. 2021). Kamalahmadi and Parast (2016) define resilience as a set of capabilities to manage unforeseen changes in the situation with reactive and proactive actions so as to learn from previous disruptive events. Karl et al. (2018) found only few papers that focused on the relationship between KPIs and resilience to improve SC resilience. That indicates many companies might rely on existing practices because they perform well at normal times but cannot respond if a severe market disrupt takes place.

The structure of a SC can be either decentralized, centralized, or a combination of these. If the SC has characteristics of both of the two first mentioned, the structure is hybrid, per se (Davis-Sramek, Germain and Krotov 2015). Figure 5 presents the general linkages of each structure. In a centralized SC central headquarters and warehouse are located in a single place. From a SCM standpoint, headquarters handles all decision, such as procurement, distribution, and other logistics. Operations in a decentralized SC are distributed in a series of network nodes. These nodes are often small warehouses and offices designed to be geographically located closer to the end customer of the organisation. (Greasley 2008, 72) Hybrid SC includes characteristics of both previous models. By centralizing strategic functions such as long-term capacity and sourcing and decentralizing operational functions such as shipment handling and order fulfilment, SC can maximize customer requirements while lowering costs. (Chopra and Meindl 2013)

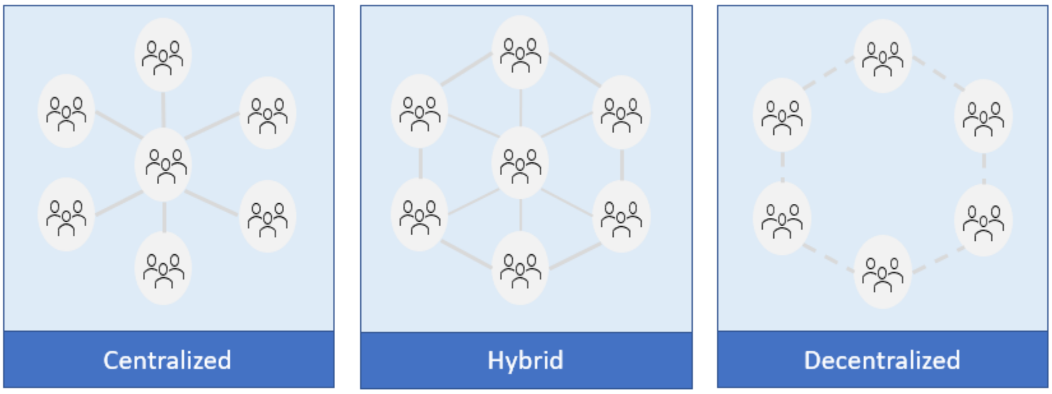

Figure 5. Generic supply chain structures.

Theory of pooling effect can be utilized in centralizing and streamlining inventories. Hopp (2011) defines the pooling principle as follows: "combining the sources of variation so that they can share a common buffer reduces the number of total buffers required for a given performance". According to Oeser (2015) the pooling effect can be exploited by combining individual fluctuations in demand or delivery times, therefore reducing overall variability and uncertainty. The reduction in centralized buffer in the pooling effect is based on that the individual independent variations cancel each other out, thus smoothing the overall variation. (Hopp 2011)

According to Clark et al. (2021), centralization of procurement has brought in lower prices in many cases, but the reduction of a product's unit price might show up at delivery times of longer time periods and in other dimensions. The latter is true because in a decentralized model inventories are located closer to the customer than in the decentralized model. The decision to decentralize and centralize inventories needs to be considered holistically as it is influenced by many factors. Figure 6 summarizes the factors that significantly affect the centralization of inventories.

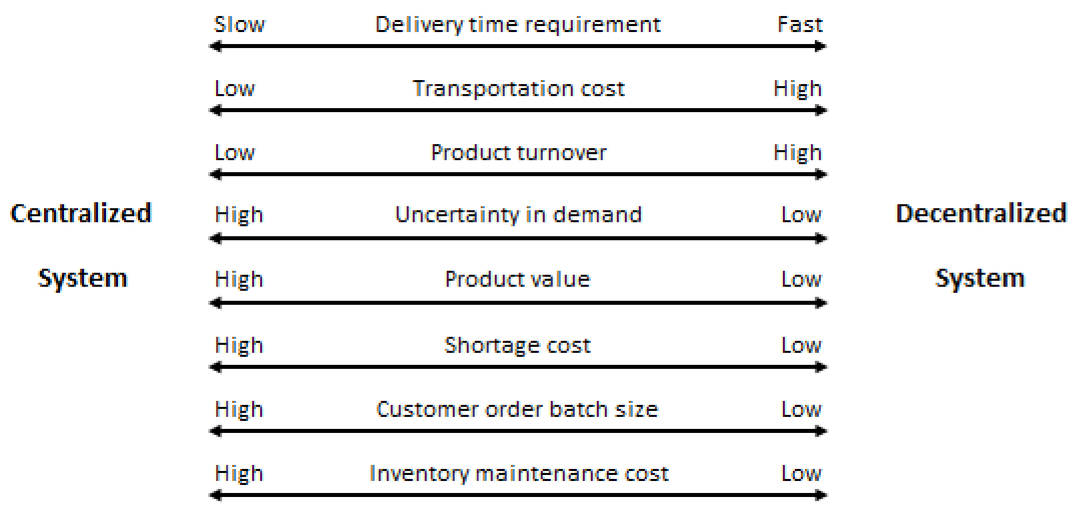

Figure 6. Factors affecting the centralization of inventories (adapted from Chopra and Meindl 2013).

If a product is needed immediately, it is rational to place the product in a storage nearby a customer. If not, then centralized inventory is more reasonable. The same logic applies to the others. If the transportation cost of an individual product to the customer is low, it may be wise to ship it from a central warehouse. On the other hand, if transporting single-piece products is expensive, decentralizing stocks may reduce costs. (Chopra and Meindl 2013, 346) Demand has an important impact in SCs. If the uncertainty in demand is high, centralized warehouse provides buffer whereas decentralized does not. However, decentralized systems are likely to work better when fluctuations in demand are low. (Greasley 2008, 72)

The value of the items must be taken into account, because the more expensive the products, the greater economic benefits of centralization. In addition, the impact of shortage costs should be considered when planning locations. If the cost of deficiency is high, the likelihood of it can be reduced by centralization. (Oeser 2015, 19)

2.2 Inventory management

It is essential to understand the purpose of inventory. It is true that some businesses can cope without an inventory at a whole, but usually that is not the case. There are many factors associated within the inventory and SC, therefore recognising the key elements is vital in order to succeed. For example, predictability, fluctuations in demand, reliability of supply, inventory planning, and monitoring are some key concepts the managers usually are aware of. (Muller 2019, 3-4) Figure 7 illustrates the concept of inventory management.

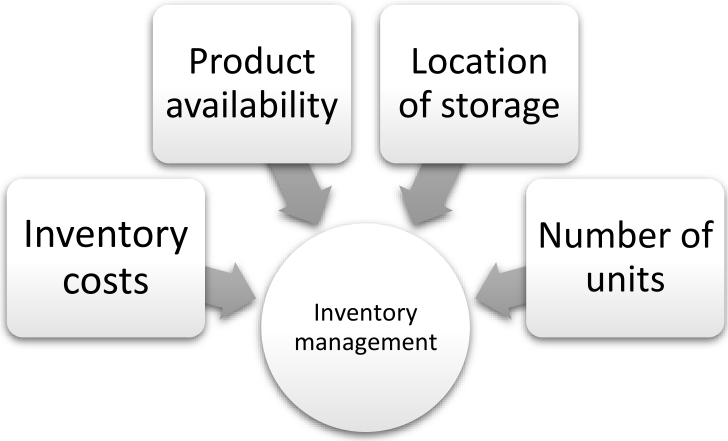

Figure 7. Fundamental elements in inventory management.

Inventory management is by definition a business process which is responsible for managing, moving, storing, counting, arranging, and maintaining the inventory (Greasley 2008, 71). The environment is dynamic because the products are transferred from a place to another. Some products are in place for a longer period of time than others, and this is measured by inventory turnover. It tells the speed at which a firm purchases and resells products in its inventory. Product turnover is usually fast on, take daily consumables whereas luxury products tend to have slower turnover ratio. (Greasley 2008, 72) The goal of inventory management is to be as efficient as possible while minimizing costs. It is challenging formula though, and various methods have been introduced to get as close as possible to this ultimate goal.

2.2.1 Traditional inventory management

A typical organisation holds stocks in their inventories after acquisitions before the need to ship to as customer. Managers in turn want to organize the company’s inventory as efficiently as possible to avoid costs. (Brewer et al. 2001, 195) Various metrics have been created for this purpose. Economic order quantity (EOQ) is probably the most common scientific quantitative model of an inventory system that aims to minimize costs by avoiding shortages. (Greasley 2008, 75) The EOQ balances four costs associated with IM:

1. The unit cost
2. The reorder cost
3. The holding cost
4. The shortage cost

The EOQ presumes that shortage costs are so expensive that they must be avoided, so it balances the other three costs. In cases of demand being relatively constant over time, the EOQ is best applied because of its static nature, and on the contrary, the EOQ loses its efficiency when uncertainty increases because it does not take that into account. (Brewer et al. 2001, 198; Fernando 2022) Derivation of the EOQ is as follows:

$$EOQ = \sqrt{\frac{2DS}{H}} \quad (1)$$

where D is the stochastic variable or forecast demand (units), S is cost per order (€), and H is holding cost (%). After the best order size is found, the next question is when to place orders. In theory, it is optimal to place an order when the amount of remaining stock is the same as the presumed demand in lead time, but there can be uncertainty depending on the environment. Therefore, keeping safety stock in reserve reduces the uncertainty and the level of reserve is estimated depending on environment. (Brewer et al. 2001, 199) The equation for reorder point (ROP) is a following:

$$ROP = DR + LT + SS \quad (2)$$

where DR is demand rate, LT is lead time, and SS is safety stock. These two formulas define the fundamental policies of IM. (Greasley 2008, 70; Brewer et al. 2001, 200) The problem is however that it is challenging to maintain the optimal inventory in order to minimize costs. If the focus is on cost minimizing, the downside is inventory stockout that can lead to even higher costs. The converse is that uncertainty is minimized, and demand can be met, but a very high stock reserve may lead to product expirations and high inventory costs in overall. (AbuKhousa et al. 2014; Brewer et al. 2001, 198-199; Hugos 2018, 6)

Figure 8 below presents the usual cycle of inventory stock level. When a stock level is low, a new order takes place based on the EOQ equation. After the order arrives, the amount of demand is monitored. Reorder level informs when to place another order to avoid stockout. The cycle goes on and on. It is noteworthy that demand is not constant over time, and EOQ works different on different markets, so the model is intended to be indicative. (Brewer et al. 2001, 199)

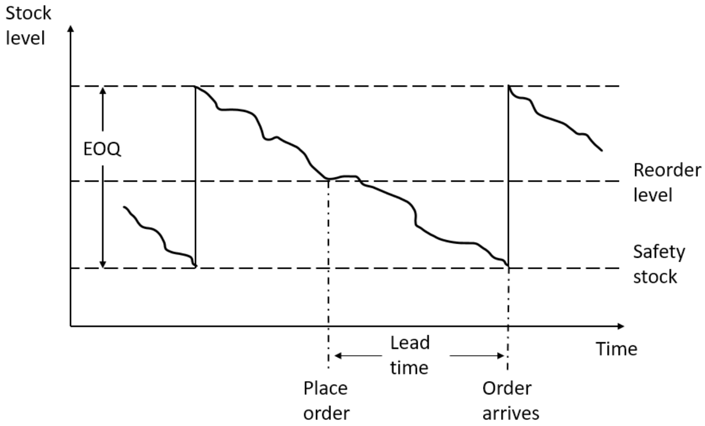

Figure 8. Illustration of stock level variation with EOQ (adapted from Brewer et al. 2001).

The level of safety stock is determined by the firm since no universal formula exists. Appropriate safety stocks permit operations to be continued according to plan. The reason of having safety stock is to meet customer demand at all times: under high uncertainty the need for safety stock increases to avoid stockouts and maintain the level of service. (Baudin 2012; Dinesh and Roberto 2018, 6)

Modelling the functionality of SCs has been researched and implemented by various methods, and new techniques are being constantly developed as technology advances (Zougagh et al. 2020). Generally known and used approaches for SC issues include linear programming models, multi-criteria analysis models, discrete event simulation models, and secondary data analysis, according to previous literature (Chowdhury et al. 2021; Kleijnen 2005; Parker and DeLay 2008). Unfortunately, quantitative approaches on previous research on healthcare SC is scarce about centralization of logistics to the best of my knowledge.

However, the same principles may be used as in normal SC modelling. Nevertheless, it might be a challenge to choose a proper method. Another important and generic modelling issue is validity. To measure this, one should examine the algorithms and relationships to see how it corresponds to the actual system. Graphical presentation is an effective way of measuring validity for complex models because humans tend to understand visual outputs faster than numeric ones. (Brooks 2014)

According to Brewer et al. (2001, 211) the key issue in inventory management seems to be the role of technology for the future. Relations between suppliers and their customers are changing as customers are becoming involved at earlier phases in the SC. These changes create opportunities for redesigned SCs and new channels of distributions. Typically, the changes are consequences of natural continuations of trends, but some of the more intriguing ones might be at the level of theoretical concepts. (Brewer et al. 2001, 211) Some of such changes, which have become possible with technological development are presented later.

2.2.2 Inventory costs and valuation

Inventory management controls the capital and material flows tied up in the inventory. However, storage usually involves a significant amount of capital. Inventory is thus a significant cost factor in organisations and developing it can improve cost efficiency. If inventory is mismanaged, costs can pile up and lead a company to financial problems. There are several factors in inventory cost management, and it is necessary to identify them to reduce costs. Inventory costs usually include ordering, carrying, and stockout costs, but there are other cost factors as well, and the cost structure can vary significantly depending on the organisation. (Kantasila and Ojala 2012) Figure 9 presents the parse of storage costs.

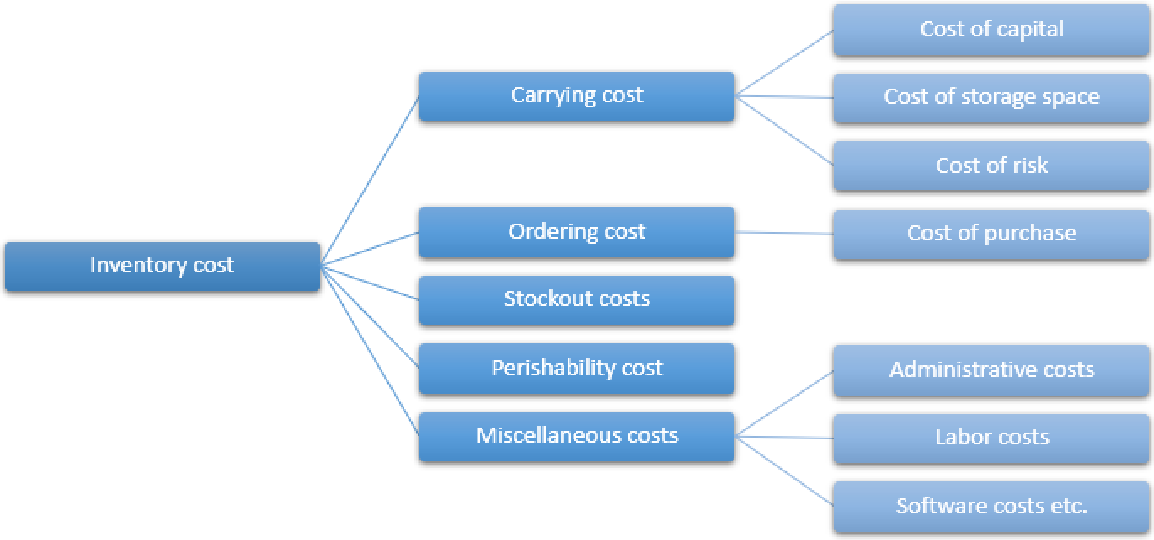

Figure 9. Inventory cost structure.

The fundamental inventory cost structure resembles to the above figure, but the mutual costs may vary in different proportion. There are also differences between industries. Carrying cost represent usually 20 % - 30 % of total inventory costs but may depend heavily on inventory management method (Tuovila 2020). Some businesses conduct operations such as "just-in-time" in which the goal is that there is no or very little stock. (Greasley 2008, 77-78). The total inventory cost includes intangibles such as opportunity cost and depreciation as well as storing costs (Tuovila 2020).

Inventory as money is crucial to identify because it ties up a firm's capital. Depending on industry, inventory cost is in a major role in logistics costs. (Kantasila and Ojala 2012) Muller (2011, 18-19) and Peterson (2004, 178) have listed three common inventory valuation methods as follows:

1. First-in, First-out (FIFO) valuation assumes that the first goods purchased are the first to be sold regardless on the actual timing of their sale. This valuation method is tied to actual physical flow of stock-keeping units in inventory.
2. Last-in, First-out (LIFO) valuation assumes that the recently purchased items are the first to be sold regardless of the actual timing of their sale. This method best matches current costs with current revenues.

3. Weighted Average Cost method of inventory valuation recognizes the inventory value and cost of items sold by calculating an average unit cost for all items available for sale during a given time period.

WAC considers cost of goods available for sale and divides it by the number of units available for sale and thereby gives a weighted average cost per unit. An actual count is calculated on the ending inventory to determine the number of goods left, and this quantity if multiplied by weighted average cost per unit to give an estimate of ending inventory cost. (Morah 2021) According to the situation, any of these methods might be adequate. (Muller 2011, 19)

2.2.3 Dependent demand inventory systems

The traditional forecast models assume items to be independent from each other. This is not always the case because majority of products contain more than one part, such as computer or smartphone. Dependent demand focuses on managing raw material inventories rather than finished goods inventories. Analysis and tracking of lead times, delivery capacity, and delivery schedules of suppliers play an essential role in dependent demand inventory systems. (Forghani, Mirzazadeh, and Rafiee 2012) The demand for products can move in tandem or in the opposite direction. This makes demand modelling even challenging because there are more counterparts to consider simultaneously.

Material requirement planning (MRP) has been implemented to alleviate complexity as MRP matches stocks of materials to production needs. However, it only works effectively in circumstances where a reliable and stable master schedule, accurate inventory records, and complete bills of materials exist. In addition, problems may show up with the suggested pattern of orders. For example, it may not consider the material production – the optimal schedule for utilizing materials might differ significantly from the optimal schedule to produce them. (Brewer et al. 2001, 201-203)

2.2.4 Just-in-time operations

In the traditional view of IM mismatches between supply and demand are tolerated. MRP looks further than this and defines that S&D can be coordinated to reduce inventory. Just-in-time (JIT) operations takes this further by proposing that well designed and planned operations can make stock completely unnecessary. (Greasley 2008, 77-78) This means that the managers do not have to buy the materials and keep them in warehouses, but when production needs the necessary materials, they are arranged to be delivered to the process. (Brewer et al. 2001, 204) JIT requires working closely with reliable suppliers and forecast demand accurately. The goal is to minimize the on-hand inventory to meet demand. The advantage is that capital if freed up for other uses, but there is a risk that demand may not be met effectively, especially if demand varies a lot. (Chen and Hua Tan 2011) Therefore, conducting JIT-operations may be poor option when a company aims for a resiliency strategy, but it is more designed for retailers, restaurants, tech manufacturing, and automobile manufacturing, for instance.

2.2.5 Simulation modelling

Modelling is the process of producing a model and a model is a representation of the construction and working of a system of interest. One purpose of a model is to enable the prediction of the effect of changes to the system, and it needs to be a precise approximation of the real system and include most of its salient features. However, a model should not be too complicated that it is hard to grasp and experiment with it. Therefore a useful model is a compromise between simplicity and realism. (Maria 1997)

Simulation means imitating the processes and operations of a real-world system. The main idea of simulation modelling (SM) is to analyse and assess “what-if” hypothesis about a system in the real-world to foresee its efficiency and outputs after hypothetical changes to the system. (AbuKhousa, Al-Jaroodi, Lazarova-Molnar, and Mohamed 2014) Simulation is applied before a new system is created to minimize the changes of failing to meet expectations, to prevent resources’ over or under-utilization, and to eliminate already identified or potential bottlenecks. Moreover, simulation optimizes the system performance by means of experiments. (Maria 1997) According to Katsaliaki and Mustafee (2010), simulation modelling help in reducing risks, costs, and redundant human labour if such experiments are met in real-world. Furthermore, R&D in simulation modelling allows policy makers to develop better grasp of the challenges they face and new point of views about the relationships between the system's elements of interest and the metrics of its efficiency. (Katsaliaki and Mustafee 2010)

The iterative nature of the simulation process is indicated by the system under examination that becomes the altered system which thereafter becomes the system under study, and this cycle repeats. To develop a simulation model, it starts with recognition of a real-world system to be studied. (AbuKhousa et al. 2014) Figure 10 illustrates the typical simulation process.

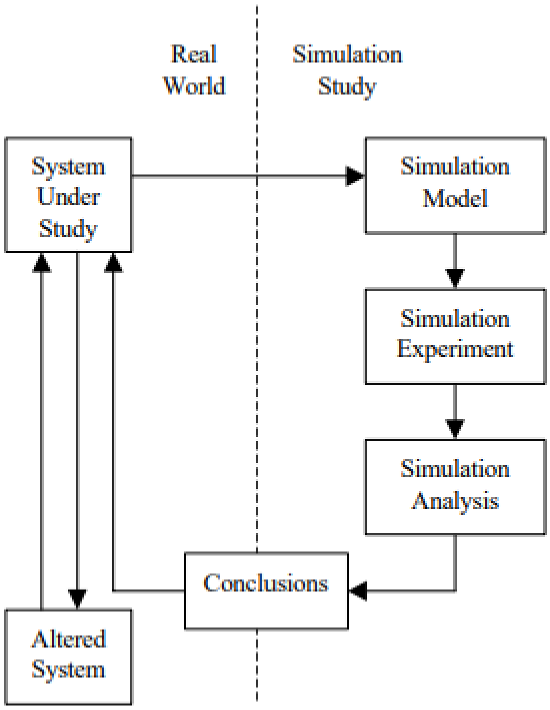

Figure 10. Simulation study schematic (adapted from Maria 1997)

Maria (1997) has listed simulation process into 11 steps. All of the steps are not required or possible to perform. However, some extra procedures might have to be added to perform simulation. These 11 steps are introduced as a following order:

1. Problem identification
2. Problem formulation
3. Data collection and procession from real system
4. Model formulation and develop
5. Model validation
6. Future use documentation
7. Adequate design selection
8. Experimental condition establishment for simulation runs
9. Simulation runs execution
10. Results interpretation and presentation
11. Recommendations for further course of action

However, SM is not without its challenges. For example, it might be difficult and time-consuming to collect sufficient amount of relevant input data. Poor or skewed data may end up to misleading outputs. Second, model validation and verification can cause inconveniences because errors can be difficult to notice. Third, implementation of the project usually requires expensive ICT infrastructure that may create resistance from decision makers. Other issues are poor generalization of the model, match between SM methods, SCM problems and lack of expert modelers and users. (AbuKhousa et al. 2014; Maria 1997)

3. Literature review

Research about healthcare SCs has become more extensive in the recent years, indicated by the increasing number of scientific search results (see Figure 11). This may already point out that there are various issues in HSCs as the number of academic papers surge. The same trend for respective search results can be seen from different databases, such as in Scopus and Google Scholar. These three databases were used to find relevant articles for this study, using combinations of terms such as “healthcare supply chain”, “demand modelling”, and “inventory management”. Thereafter, titles and abstracts with the years of publication were skimmed to find the relevant peer-reviewed articles and educational books for further analysis. The aim was to utilize the most up-to-date research data possible by sorting the release years in descending order in the cases when there was good number of academic papers available. Moreover, the focus was highly on HSC rather than usual SC, and this made a significant difference in the number of results as they dropped about 20-fold. The systematic literature review process traced a scientific practice by Webster and Watson (2002).

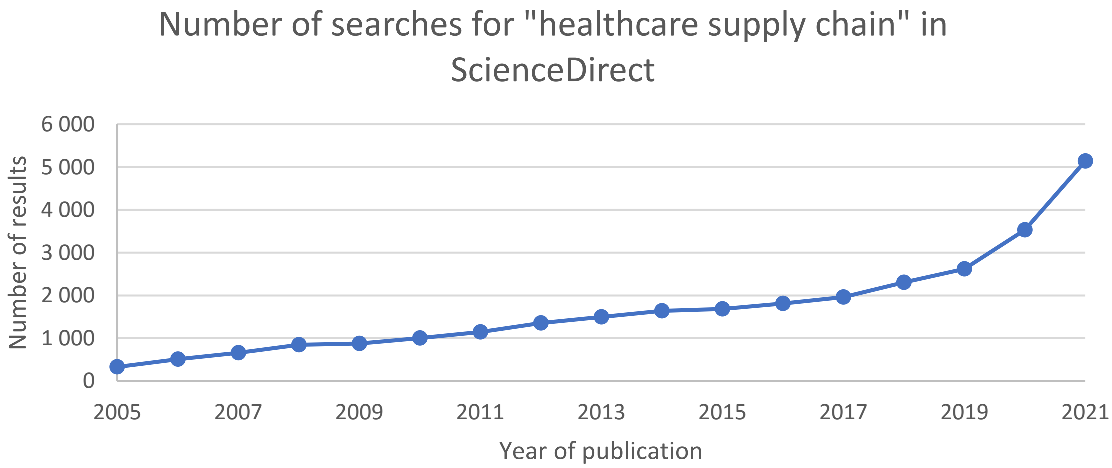

Figure 11. Healthcare supply chain search results in ScienceDirect by the publication year.

Current SCM research addresses issues related to risk management and sustainability among others. It is noteworthy that risk management is closely related to information management although different terminology is sometimes used. Moreover, resilience has attracted great interest in the scientific academy because of an increasing concern in SC, caused mostly by globalization and unexpected events. (Karl, Micheluzzi, Leite, and Pereira 2018; Suryawanshi and Dutta 2022). This makes sense, because according to the US Federal Emergency Management Agency, circa 40% of businesses that are heavily affected by a disruption in the SC go bankrupt (FEMA 2016). Especially delivery times, stock levels, and customer satisfaction play a necessary role that support resilience (Karl et al. 2018).

Although there are multiple topics on HSC in overall, it is evident that researchers have addressed a range of various issues to an increasing extent, according to scientific databases. Also, some quantitative approaches for HSC improvement have been published on which this thesis is primarily focused. By the conceptual perspective, research methodologies used in the reviewed articles were divided into four segments: empirical, quantitative, literature review, and researchers' opinions. By April 2021, the largest number of articles related to SC disciplines had used researchers' opinions as main technique of investigation. In addition, Chowdhury et al. (2021) found that four clear themes emerged from 74 articles published before September 2020 that related SC disciplines during COVID-19: impacts of the pandemic, resilience strategies, the role of technology, and sustainability of SCs. Furthermore, most papers have concentrated on SC healthcare products and high-demand necessities.

3.1 Research on supply chain management approaches

There are two ways of conducting scientific research: quantitative and qualitative methods. Quantitative research is often of interest in multiple classifications, comparison, causation, and explaining a phenomenon based on numeric results. The quantitative method involves an assortment of statistical and computational methods for analysis. (Hoy and Adams 2015, 1) Qualitative research also can be executed in different ways. These methods have some things in common, such as elements related to the background and environment of the object's occurrence, the meaning and purpose of the object, language, and expression. Although the difference between a qualitative and a quantitative methodological trend is repeatedly emphasized, both trends can also be utilized for the same study they can be used to explain a same subject, even if the methods are different. (Hennink, Hutter, and Bailey 2020) Table 1 below presents the key methods of Covid-19 related SC studies.

Table 1. The breakdown of research methodologies used in the reviewed papers during Covid-19 (Adapted from Chowdhury et al. 2021).

Methodology	**Specific Technique**	**Number of Articles**
Empirical	Case study	3
	Survey (descriptive statistics)	3
Quantitative	Mathematical model	6
	Analytical model	5
	Simulation	7
	Secondary data analysis	9
	MCDC method	1
Review	Literature review	5
	Systematic/structured literature review	4
	Analytical review	1
Researchers’ opinions	Perspective / commentary / viewpoint / opinion	25
	Conceptual	2
	Discussion	4

Analysing the table above, researchers’ opinions have the largest portion of the academic papers of the SC issues. This is understandable because there has not been a real-world data that researchers could have been collected and utilized. Additionally, the sudden occurrence of the pandemic and limited time has forced researchers to rely heavily on opinions. (Chowdhury et al. 2021)

Quantitative approaches have been the second-largest category, which include simulation and mathematical modelling. Simulation is used to predict the need for structurally adaptable

SCs and real-time visibility during a pandemic. Mathematical methods included game-theoretical modelling, linear and non-linear modelling, and stochastic optimization. Secondary data analysis included cluster analysis and principal component analysis. Literature reviews and empirical methods were in a smaller role of the number of papers. The first included resilience modelling literature and theoretical response plans. The former gathered real-world data and surveys. However, the minor role of these is explained by the scarcity of data. (Chowdhury et al. 2021)

Some authors propose quantitative models over qualitative to manage SCs, such as advanced analytics and blockchain technology (Razak et al., 2020; Rowan and Laffey 2020). Nonetheless, researchers can also utilize many qualitative demand forecasting techniques and quantitative modelling is not always even necessary. There is not just one correct way to choose a proper method, instead it is situational. It is noteworthy that one model works better to one situation than another and finding a suitable model can pose challenges to researchers. In some cases, it makes sense to use both qualitative and quantitative methods to robust the findings. However, this might be time consuming. (Saaranen-Kauppinen and Puusniekka 2006).

3.1.1 Demand modelling

Literature on prediction models of demand in SCM is variegated and abundant per se. This is reflected by the fact that demand prediction can decrease the inventory cost and maintain the right quality of products at the right time, which has seen vital to satisfy customer demand (Zougagh, Charkaoui, and Echchatbi 2020). Moreover, the key performance indicators (KPIs) have been developed to streamline and monitor the SC, and there are an array of metrics that can be used in inventory management. To capture measures for processes, a company generates its own KPIs according to goals and responsibilities (Karl, Micheluzzi, Leite, and Pereira 2018). According to Chae (2009), the challenge for businesses is to develop KPIs, and usually less indicators is better to avoid the complexity.

Various modelling techniques exist and some of them are more advanced than others due to technological advances. Remembering that most advanced models are not always the best option for every case as they are overly complex entities is good to keep in mind. Brewer et al. (2001) state that there is no correct way of organizing all inventories by using a generalized method, but the most useful alternatives are dependent on the operation types, objectives, restrictions, and an entire array of related components for each case. Despite this, there generally is an apparent trend towards smaller inventory balances because they tie up companies' capital.

3.2 Global supply chain management characteristics in healthcare

HSCs have been considered different from the generic SCs for three reasons: the level of complexity tend to be higher, medical materials are valuable and complex and these materials deal with human lives. (Iannone et al. 2014) HSC is made to guarantee a high level of service by aiming to maximize the allocation of resources to promptly and effectively respond to the needs of patient care. (Syahrir, Suparno, and Vanany 2015) In addition, HSCs operate under modern environment wherein the competition is constantly increasing by putting pressure to unnecessary costs while improving product quality to provide a better care for patients. (Iannone et al. 2014) Smith, Nachtmann, and Pohl (2012) say that identification and traceability of products is a major difference between retail SC and HSC due to Universal Product Code (UPC) that is present on products on retail shelves. Thus, products in HSCs are not as standardized as they could be. Moreover, whereas patients are classified as the end customers of products delivered through SCs, they do not have control on choosing these products. When the expiry date approaches, products cannot be auctioned or promoted, but are destroyed. (AbuKhousa et al., 2014)

Smith et al. (2012) say that logistics process is a key driver of the quality and the cost of healthcare delivery. The lack of standardization of data all over the healthcare industry has been identified as a challenge, because there are many stakeholders involved, and the item data are large and changing, resulting in inaccurate and obsolete product data. (Kritchanchai et al. 2019) Medical technology has evolved and will continue from here on out, but as a result, the main focus has been on product quality: making products better, safer, and easier to use. One remarkable downside is the functions of healthcare deliveries which have remained stable. (Parker and DeLay 2008) The irregular and detached digitalization of protocols already in use makes it challenging to seek for the maximum potential of these actions (Beaulieu and Bentahar 2021). Many existing practices should be completely overhauled, which is a significant decision. With major reform the risks may increase, which might reduce the willingness to update processes. On the other hand, it has become a consensus that more integration, coordination, and management of HSCs will be needed to reduce the negative impacts of the pandemics. (Bhaskar et al. 2020)

Ali (2011) states that one critical characteristic of the HSC is chance of stockout. In pharmacy operations, inventory generally represents the largest asset in pharmacy practice. Unlike traditional SCs in which the difficulties in availability impair sales or production, lack of availability of products in HSC can lead to fatal outcomes. Besides the negative impacts on financial consequences, inventory mismanagement could have deleterious outcomes on customer safety, such as from expired, counterfeit, substandard products, and product shortages. To respond to these challenges, predictive analytics can provide insights and solutions. The advantages appear on both cost and efficiency side, and additionally the information of the market is greater. (Pollock, Carter, Dowdy, Dunlay, Habermann, and Kor 2021) As cost savings and efficiencies arise, an organisation can take advantage of time spent on something else it has not previously had time for. For example, more resources can be spent on research and strategic activities. (Ali 2011)

Patient care is enabled by HSC through delivering the medical professionals with services and products they require to give precise and high-quality medical care. Further, consumers have variegated needs. Every consumer's demand must be met and needs satisfied, providing another challenge. Simultaneously, maximizing patient care and minimizing cost is a strategy to aim for. Consequently, many elements such as cost, inventory management, profitability, and standardization, must be considered in the process of policy making in healthcare. (AbuKhousa et al. 2014; Mathew, John, and Kumar 2013) The modern healthcare SCM process is shown in Figure 12.

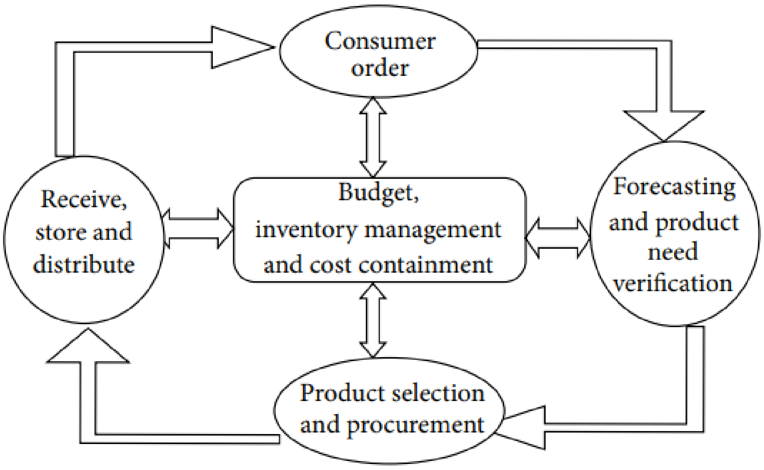

Figure 12. Modern healthcare SCM process (from AbuKhousa et al. 2014)

Although the process is similar than a typical SC process, it differs in that the customer is not at the central focus, but cost to revenue. To explain this, SC managers aim to optimize the relations between meeting consumers' demands and the fiscal responsibility in order to find competitive advantage. (AbuKhousa et al. 2014) Decision making can be further classified at tactical, strategic, and operational level. The first includes SC structure related long-term decisions. Moreover, a decision to standardize products for consumers is not an easy one, because the consumers have preferences on products for a multitude of reasons. One more challenge in strategic decision making comes from the capabilities and location of warehouse facilities. At tactical level, decision relate to the implementation of strategic decisions. Operational decisions are day-to-day operations to maintain the processes. (Schmidt and Wilhelm 2000) One of the biggest challenges is to maintain adequate stock levels to maintain quality and prompt patient care. At an optimal level demand matches supply, consumer requirement is met, and no extra costs are originated. (AbuKhousa et al. 2014)

3.2.1 Research on Finnish healthcare supply chain management

Kotavaara, Pohjosenperä, Juga, and Rusanen (2017) claim that increase of warehouses in healthcare logistics does not significantly affect delivery efficiency in Northern Finland. Pressure for centralized management would be high even though centralization of logistics led to significant savings. Shamsuzzoha, Ndzibah, and Kettunen (2020) found that a centralized system for a Finnish pharmaceutical distributor company may provide better information flow, reduced CO_2 emissions, and higher freight capacity to support sustainable logistics processes. Karjalainen (2011) found that centralized purchases do not have to happen at very large scale before the benefits of processes are already visible, and this addresses the case of price savings resulting from decentralized to centralized tendering processes[2].

Decentralized public healthcare functions in Finland have enabled engaging in local level actions and it is investigated that COVID-19 pandemic has increased the speed of the advancement of digital health services in many areas of the healthcare system. Although the distributed operations have been perceived successful, management of the system may face serious challenges when more severe circumstances arise. The challenge for the COVID-19 epidemic has materialized in procurement of PPE, non-acute services and implementation of testing, for instance. (Tiirinki, Tynkkynen, Sovala, Atkins, Koivusalo, Rautiainen, Jormanainen, and Keskimäki 2020)

3.2.2 Evidence from medical supply centralization

Inventory centralization has become a topic of discussion since the diffusing of distribution networks began. According to Essoussi and Ladet (2009), a group of Swiss hospitals obtained a saving of five percent of the cost of logistic activities that centralized purchasing procedures. Iannone et al. (2014) demonstrated that economies of scale are achievable by centralizing medical inventory, but there are more to look for. Savings in purchasing costs reduced although the consumed quantities remained the same for both centralized and decentralized systems. The logistic cost structure was more complicated when these models were compared. Handling costs and transportation costs increased while ordering costs, stockout costs, and warehousing costs reduced. In overall, the centralized system generated more savings compared to the decentralized. (Iannone et al. 2014)

[2] In other words, lower purchasing prices and economies of processes.

Baboli et al. (2011) studied the replenishment challenge from a central storage to hospital pharmacies. Here, the differences between the centralized and decentralized models were examined too. In the decentralized system companies have been seen to try to reduce their expenditures whereas in the centralized system associates have been perceived to try to find the optimal system level as a team. Therefore, transportation costs may reduce over time. (Baboli et al. 2011)

3.3 Summary of the literature review

Resilience, sustainability, information, and risk management are currently highlighted in SC research. Numerous methodologies exist depending on what SC topic is under concern. As Chowdhury et al. (2021) found in their review, most of studies were made using qualitative methods. Quantitative methods included in most cases simulation modelling, mathematical, analytical, or secondary data-analysis. According to Maria (1995), simulation is the most powerful tool to analyse randomness in a system when the problem is known, and real-world observations are too expensive to execute under high uncertainty. However, simulation is complex and time-consuming exercise that requires the involvement of specialists and policy makers in the process, and pitfalls must be checked at all times.

There are a lot of ways to conduct SCM and each industry has certain of its characteristics. In healthcare industry, human lives are of the greatest importance, thus they cannot be compromised. As a consequence, HSC might lack of efficient information systems and logistics operations in industry comparison. However, all SCs regardless of industry have several features in common, such as that they control some kind of enterprise resource system to maintain daily operations. (AbuKhousa et al. 2014; Ali 2011) Broadly recognized issues in HSC for example lack of inventory control, excess inventory levels, expensive rework, and frequent stockouts. (Joseph et al. 2013) Therefore, allocating resources to ICT -related projects might provide solutions to currently faced key issues.

4. Empirical part

This section consists of a brief case description which concentrates on the epidemic that caused disruptions in the SCs of Finnish public healthcare sector in 2020. Content and sources of the quantitative material are presented. The data continues to model building and comparison of “as is” and “to be” models. Feasibility analysis is based on the traditional inventory management calculation methods which the MCS was built upon.

4.1 Case description

Majority of personal protective equipment has been manufactured in China in the recent years, but changes in demand of them were unprecedented worldwide in 2020 and 2021 since every state called for this equipment. Hospital capacities were put to test after people became ill more and more from the COVID-19 disease. Additionally, there was at least a temporary shortage of PPE in some regions or even countries. (Bhaskar et al., 2020; Mahmood et al., 2020) Among other countries, Finland tried to import PPE because domestic production could not meet demand at that particular time. This led to a situation where every hospital district tried to acquire the necessary amount of PPE on their own and without transparent cooperation. The reason for this is deducted from the present SC structure, i.e., hospital districts have had their own suppliers, and no major PPE-related joint purchases had been largely conducted to the best of the author’s knowledge. This raises questions of whether the pandemic came as a surprise with no preparations thought beforehand. Could this have been seen in advance and responded to accordingly with a proactive strategy?

Either way, aggregating reports of previously occurred events together can provide a picture of the overall situation if no continuous data monitoring has been conducted before. On the basis of historical data, it would be possible to illustrate the phenomenon in a numerical way in order to design and model alternative strategies for similar upcoming events. In this way, the cost-effectiveness of SCs is possible to be estimated, and other insights may be revealed.

Anticipation and strategic planning cannot be overemphasized as these play a key role in logistics of unprecedented events. Especially since SC is designed to be as optimal as possible per se, it is fragile to unknown market disrupts[3]. On the other hand, strategic planning is an expense that companies are not willing to invest in due to high initial investments. Nevertheless, a new disastrous event may shape the perception of optimality towards a more resilient way that is beneficial in the long term. (Farrell and Newman 2020)

4.1.1 Geographical distribution

In 2021, there were twenty-one hospital districts in Finland. All districts were classified into five special areas of responsibility (Association of Finnish Municipalities 2021). Figure 13 presents the population distribution and the geographical locations of special areas of responsibility in Finland. In 2020, the overall population was circa 5.5 million in Finland, and the majority of the population was located to Southern Finland. Nearly 40% of residents were located in Helsinki University Hospital Specific Catchment Area. Population sizes among other four Catchment Areas were relatively even, ranging between 738 690 and 900 724. Thus, each of them covered about 15% of total population in Finland. Some special care services were organized across the borders of the hospital districts under the special areas of responsibility. The Government Decree stipulates which the special areas of responsibility are and which hospital districts belong to which special areas of responsibility (Ministry of Social Affairs and Health 2021).

[3] Also known as Black swan theory.

Helsinki University Hospital Specific Catchment Area	**2 173 797**
Helsinki and Uusimaa	1 667 203
Etelä-Karjala	128 756
Kymenlaakso	166 623
Päijät-Häme	211 215
Kuopio University Hospital Specific Catchment Area	**805 133**
Pohjois-Savo	245 602
Etelä-Savo	100 226
Itä-Savo	41 060
Keski-Suomi	252 676
Pohjois-Karjala	165 569
Oulu University Hospital Specific Catchment Area	**738 690**
Pohjois-Pohjanmaa	409 418
Kainuu	73 061
Keski-Pohjanmaa	77 689
Lappi	117 350
Länsi-Pohja	61 172
Tampere University Hospital Specific Catchment Area	**900 724**
Pirkanmaa	535 044
Etelä-Pohjanmaa	194 316
Kanta-Häme	171 364
Turku University Hospital Specific Catchment Area	**869 786**
Varsinais-Suomi	481 478
Satakunta	218 624
Vaasa	169 684
Finland population (excluding Ahvenanmaa):	**5 488 130**

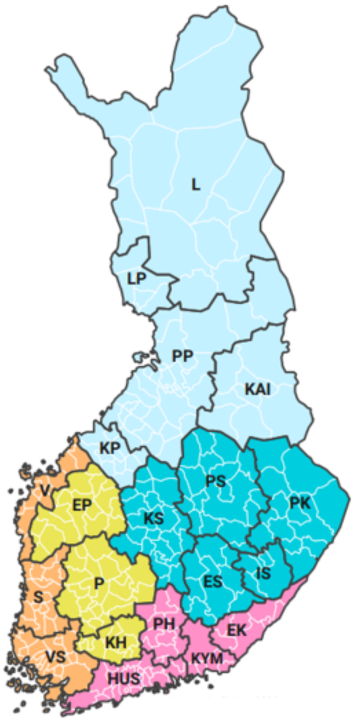

Figure 13. Hospital districts Special Areas of Responsibility (Association of Finnish Municipalities 2020).

The demand for PPE can be derived in various methods, but in an epidemic situation population size and incidence rate have a strong correlation on PPE consumption. Population size can be split into demographic factors such as age, location, and income level, for instance. Incidence rate, in turn, measures the probability of occurrence of a given medical condition in a population within a period of time. These two variables illustrate why consumption is as it is, but attention should be paid to the accuracy of correlation. There is also a chance of inappropriate use of PPE that increases the risks of infection and higher mortality. (Gorgon and Thompson 2020) However, it is sufficient that national consumption (demand) and the corresponding inventory (supply) are known because this study addresses the whole country instead of a particular area of it.

4.2 The datasets

The data for analysis was acquired from four major sources. The first dataset was acquired from a web-portal wherein the national data exists. The second source of data was from two hospital districts. NESA provided the third source of data. Last, three suppliers were surveyed to seek real market view of economies of scale. All data was acquired directly from the authors since it includes confidential material. Table 2 shows the number of sources obtained for analysis.

Table 2. Acquired data for the study.

Data sources	**Quantity**
1. Web-portal	
Excel files per week	5
Number of sheets	1
Number of weekly reports	53
Number of sources which an aggregation has been made	265
2. First hospital district	
Excel files (product groups included)	7
Number of sheets (unit prices, inventory balances, consumptions)	3
Number of sources which an aggregation has been made	21
3. Second hospital district	
Excel files per week	1
Number of sheets	1
Number of weekly reports	82
Number of sources which an aggregation has been made	82
4. NESA	
Estimates and knowledge on general inventory costs	-
5. Suppliers	
Price inquiries	3
Total number of sources	**371**

Referring to Table 2, NESA provided data for this study in order to assess potential cost savings. Detailed sources from NESA are not expressed, but they were reviewed to be relevant for this study. This allows the analysis to be more reliable on the cost assumptions of inventory planning. The datasets consisted of following profiles below:

National data for each category of PPE between April 2020 and May 2021 included

- Weekly consumption
- Weekly inventory

Hospital districts' time series data for each category of PPE between January 2020 and December 2021 included

- Weekly consumption
- Weekly inventory
- Unit prices of purchase transactions

Organisation data included

- Market price of warehouse rental (and by capacity)
- EUR-pallet capacity for PPE
- EUR-pallet market price
- Estimates on other logistic costs

With the information above it was possible to create a model that estimates inventory levels and cost structure simultaneously. Total cost of capital can be estimated, and potential savings can be calculated. Because the quantities are large, the accuracy of input values has a great sensitivity in the calculations. However, a few assumptions are reasonable to list to avoid complexity. First, shortage costs are considered to be zero due to resilience strategy. Second, risk costs are challenging to be estimated. They include for example product obsolescence, product damage, and theft. Third, product revaluation can be estimated from data, but historical prices do not guarantee future prices. Therefore, the analysis utilizes price levels within the time period. Fourth, changes in labor costs between the models are difficult to assess precisely. Finally, there are other costs associated with storage, such as service costs and insurances.

4.2.1 National data

The national data obtained through the portal was spread through several reports (see Table 2). The original purpose of this data was to compare the national PPE consumption to inventory levels to the extent that no shortage of PPE would incur. The original reports were created once a week and structured as follows:

- Each hospital district in Finland (excluding Ahvenanmaa) reported its PPE-related products' daily consumption and respective weekly inventory levels in Excel for its own special area of responsibility
- Each special area of responsibility compiled that data into one report and sent it to the instructed contact person
- Data for all special areas of responsibility was then compiled into a single report which formed the national PPE consumption and stock levels regarding a specific week.
- This cycle was repeated until May 2021.

However, the reports were not in clean time-series format and the format itself varied in these files, so MS Excel Power Query data processing tool could not be utilized effectively in this case. As a consequence of that, combining these files into one report was time-consuming due to manual practices. However, there was little to no risk of negligence errors in manual work as the user would have noticed errors in the data immediately. It is noteworthy that the collection of considerable number of files into one dataset is essential as it includes the consumption and inventory levels of all hospital districts in Finland between April 2020 and May 2021, and thus helps to outline nationwide consumption and inventory levels during the COVID-19 pandemic. The one-year time period is due to that no further data has been collected or is available. In addition, similar national data is not known to exist elsewhere, but hospital districts only have data on their own consumption and stock levels.

4.2.2 Hospital districts

The second source of data from two hospital districts was relevant to the analysis as they provided currency-based data on purchasing transactions which was not available from the source of national data. Also, the time periods therein were longer and thus indicated the consumption levels beyond, especially to see how consumption and inventory levels evolved from May 2021. The time series intervals in these data sets were reported weekly and monthly, starting from January 2020, and ending in December 2021. The author estimates that the two hospital districts provided sufficiently reliable information in comparison with the national dataset to generate fair presumptions on national metrics. One source from a single hospital district would be too scarce and unreliable to generate assumptions on national consumption and inventory levels, but on the other hand, ten sources or more would be too laborious for the reliability to improve significantly especially if the correlations between the two hospital district's data were strong.

Excel Power Pivot was applied since it provided efficient and necessary tools for processing. The files included thousands of rows. Stock transactions and inventory levels could be organized on a weekly or monthly basis to see the development over time. Unit prices of purchase transactions were processed into a visual format, and these illustrated the development of unit prices over time. Part of the data was missing a few periods, mainly from the beginning because monitoring was not started back then. Summer holidays contributed to the lack of a few data points too. The absence of a few data points of consumption and inventory balances could be corrected by data manipulation: the missing data points were averaged over the previous and following data points. Figure 14 shows the graphical development of a product's consumption, inventory balance, and unit price as a time series form.

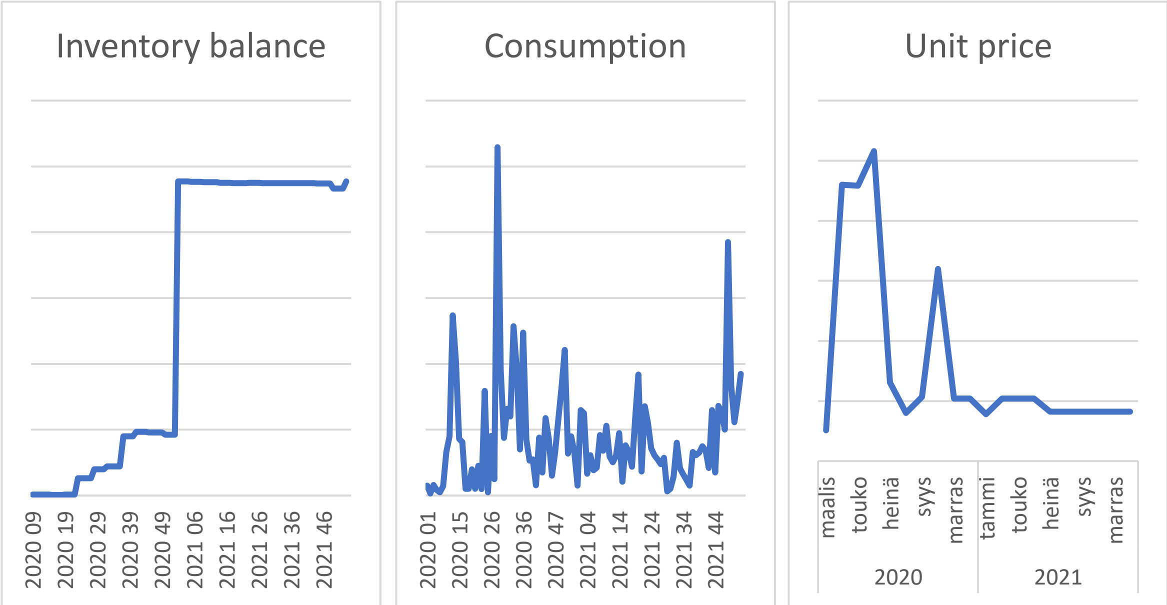

Figure 14. Graphical illustration of time series datasets of protective apron.

The same procedure was done to each category. Therefore, it was possible to see whether the data of hospital districts was correlated to both each other and national data (excluding differences in scale). See Appendix 3, 4, 5, and 6 for development of inventory and consumptions of the two hospital districts from 2020 to 2021.

4.3 Constructing the model

Data acquisition and collection was the first phase of model building. Thereafter the data was processed and consolidated together. As a result, relevant factors could be obtained for historical analysis. These were supply, demand, unit prices, and space requirement of PPE. At this point it was possible to analyze the historical events of the current decentralized SC structure (of time period June 2020 and May 2021). In order to make any comparison between the current and the new model, a certain metric, days-in-inventory (DII), that is an efficiency ratio that measures the time in days that the company holds its inventory before selling it (Hayes 2021), needed to be identified on which the new model is based on. This metric was evaluated by experts (more about this in the results). Then, inventory management (IM) equations, introduced in this thesis, were applied to calculate the current system's financial performance. The same equations were applied to the new model, with the exception of DII constraint that is constant. Due to this procedure, it was possible to see the differences between the models (space requirement, opportunity cost, etc.). See Figure 15 for step-by-step model building. Ordering cost, transportation cost, warehousing cost, and other costs are excluded from calculations, but are evaluated by ceteris paribus principle.

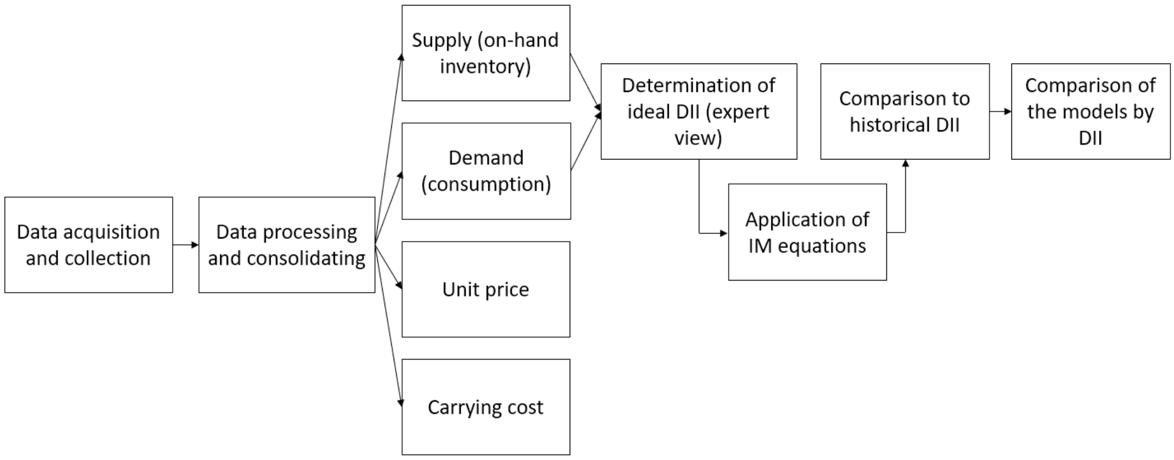

Figure 15. Model build-up. IM = inventory management, DII = days-in-inventory.

The dynamics between the models are similar with each other in a few aspects, i.e., these are easily compared if changes happen in inventory levels. For example, ordering and warehousing costs are likely to decrease when inventory levels decrease, and vice versa. Moreover, identical assumptions have been used for both models in particular cases such as the same unit prices and price levels of holding the inventories. However, there are exceptions too. Changes in transportation costs do not scale linearly between the models since structural changes in SCs affect transport routes in different ways. If there are significant economical differences between the models, transportation costs should be estimated at a later stage (through further research). Second, if the differences were insignificant, a structural change might not be considered necessary. Thus, no resources are allocated to examine transportation costs at this point.

4.3.1 PPE supply and demand

Since the national consumption and inventory levels for each category are known, inventory sufficiency levels for each PPE can be calculated. There are multiple ways in which one can choose to calculate days-in-inventory by using a single value or series of values within a min-max range. However, if the variation in supply and demand is volatile, it weakens the reliability of a single days-in-inventory value for the future. (Brewer et al. 2001, 198) Table 3 illustrates the min-max values of national daily consumption and the corresponding inventory balances. Previous four-month average values were included into the analysis too because these indicate how consumption and stock balance evolved over the time period (compared to one-year average).

Table 3. National PPE daily consumptions and inventory balances of time period 4/2020 – 5/2021.

Consumption

Product group	**Minimum**	**1-year avg.**	**Maximum**	**Prev. 4-month avg.**
Surgical masks	215 126	599 476	1 013 763	729 502
Face visors	4 321	8 608	21 787	6 476
FFP2 respirators	2 000	7 652	24 459	8 874
FFP3 respirators	1 255	2 925	6 933	3 092
Isolation gowns	8 397	15 787	87 789	12 747
Nitrile gloves	801 933	1 607 467	2 094 350	1 607 711
Vinyl gloves	254 841	446 961	640 335	496 731
Aprons	28 104	40 334	92 421	32 568

Inventory balance

Product group	**Minimum**	**1-year avg.**	**Maximum**	**Prev. 4-month avg.**
Surgical masks	10 611 146	113 530 571	196 402 835	184 959 465
Face visors	1 579 793	2 197 934	2 501 324	2 307 869
FFP2 respirators	1 029 798	4 291 570	6 978 867	6 223 867
FFP3 respirators	215 132	834 815	1 473 110	1 248 821
Isolation gowns	764 898	6 523 601	11 417 588	10 805 108
Nitrile gloves	44 844 092	125 321 321	210 838 943	178 291 878
Vinyl gloves	13 837 105	47 094 235	89 624 349	74 107 115
Aprons	1 441 377	13 167 010	23 702 935	22 956 207

Variations are immense regardless of the category. In the case of consumption of surgical masks, the maximum value is five-folded to its corresponding minimum value, and nearly two-folded to the average value. For isolation gowns, the maximum value is ten-folded to its minimum value, while the average value is almost two-folded to the minimum value. Therefore, the variation is not only high but also skewed in certain categories. To look for weekly development of consumption and inventories of PPE in a graphical format, see Appendices 1 and 2.

To figure out sufficiency ratio between consumption and on-hand inventory at a certain point in time, days-in-inventory was applied to each PPE category. The equation for DII is the following:

$$DII = \frac{average\ inventory}{COGS} * 360\ days \qquad (3)$$

where COGS is cost of goods sold during the time period (Ganesan 2007; Hayes 2021b). Monetary values of a product or quantities of products can be applied in the formula, but not crosswise. DII is applicable for other time periods too (time scale), such as for four-month length, under the condition that the time period must be the same for each component in the formula. Therefore, the average inventory and COGS can be calculated using the four-month time period, where 360 days must be replaced by 120 days, for example.

4.3.2 Inventory size and cost factors

Space capacity and costs associated with it were recognized. EUR-pallets were considered to estimate the need for total space. Other pallet sizes were not considered because they can be scaled to match the same volume to price. The necessary information was to estimate the number of units per EUR-pallet for each category. The metrics may differ slightly in the real world because there are substitute PPE in the same category, having an impact on package sizes. Market value of a pallet and monthly holding cost of a pallet are known.

Unit prices of the purchases are known and by that data, value of inventories was assessed for a given time. Options were to use lowest, highest, average, or some other value such as weighted average. Prices varied significantly, however. Furthermore, the mean values were not considered suitable because they considered the price averages, not quantities. Weighted average cost method of inventory valuation (WAC) solves this problem since it includes quantities too, and thus calculates the purchase transaction expenses quickly and accurately (Peterson 2003, 178). The equation for WAC is as follows:

$$WAC = \frac{Cost\ of\ goods\ available\ for\ sale}{Units\ available\ for\ sale} \tag{4}$$

WAC is good in that it avoids the impact of decreasing or increasing prices that FIFO or LIFO does not consider (Peterson 2003, 178). As mentioned, remarkable variation in unit prices existed. Therefore, this method was selected for inventory valuation. Two parameters were used:

1) one-year weighted average unit price (between June 2020 and May 2021)
2) four-month weighted average unit price (between February and May 2021)

Technically, the weighted average of a non-empty finite multiset of data $\{x_1, x_2, \dots, x_n\}$ with corresponding non-negative weights $\{w_1, w_2, \dots, w_n\}$ is derived as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

In this case, weights have the identical value with the exception of the parameter that is used (specific time periods vary depending on parameter). The first parameter was chosen because it considers the weighted average for all purchases during the pandemic. The second parameter indicates the development of purchasing unit prices and reflects the value of inventories at a time when the times series of national reports was no longer continued. The time period is also narrower. As the parameters for weighted average unit prices and quantities are known, equation for purchasing cost (PC) can be derived as follows:

$$PC = P * D * (1 - \propto_u) \tag{6}$$

where P is unit purchase cost, D is annual demand, and $\propto_u$ is percentage of discount per unit. In this work, discount per unit is replaced by economies of scale. Last, holding costs (HC) must be determined. HC is linear and depends on order quantity (assuming lead time is constant), i.e., a higher inventory costs more to carry (Cargal 2003). The equation for it is as follows:

$$HC = \frac{H*Q}{2} \qquad (7)$$

where H is annual cost to hold a unit and Q is quantity being ordered, divided by 2 because the inventory is half full throughout the year on average. Alternatively, carrying costs can be derived by the summation of individual components such as capital costs, service costs, space costs, and risk costs that relate holding the goods (Cargal 2003). Thereafter the total inventory value, or total cost (TC) can be estimated as with the following formula:

$$TC = PC + OC + HC = P * D + (\frac{D*O}{Q}) + (\frac{H*Q}{2}) \qquad (8)$$

where OC is order cost and O is cost of one order. Unfortunately, order cost is excluded from this research due to lack of data, but the formula is still applicable with this delimitation. On the other hand, order cost can be estimated to decrease since the number of orders decrease as order volumes increase in the centralized model when demand is assumed to be equal in both models.

4.3.3 Development of consumption and inventories

The last data points were recorded May 2021 of the national reports. Therefore, a survey of the two hospital districts was included to this study to obtain observations of the development on consumption and inventory levels. This illustrated the development of the situation and consumptions and inventory levels until December 2021. Figure 16 shows the development over time in the case of surgical masks of a hospital district.

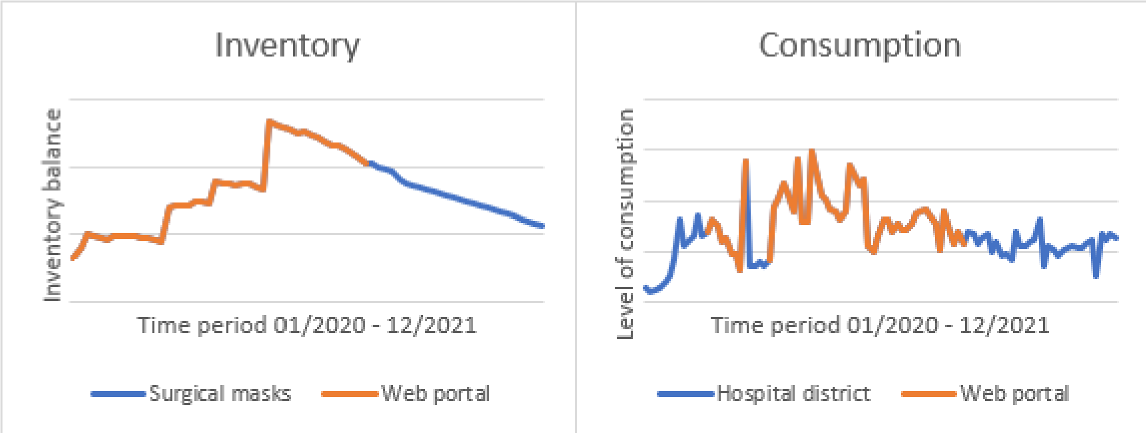

Figure 16. Development of inventory and consumption of surgical masks of a hospital district. Y-axis values are removed for non-traceability.

The orange line shows time series of a hospital district (obtained from national data) whereas the blue line represents time series of the same hospital district. It can be seen that inventory balances for surgical masks have decreased over time while consumption has remained fairly stationary.

The same monitoring has been done for each product group of the two hospital districts' data, and these are shown in Appendices 3, 4, 5, and 6. However, it is difficult to establish an accurate current state based on data from two hospital districts since there are twenty of them overall. Consequently, it can only be stated that for some product groups inventory balances have started to decrease, but for some categories these levels are still close to the May 2021 situation. On the other hand, the point is to analyze the previous situation on whether a resilience strategy could be more efficient in the future.

Another issue to show is that unproper method selection does not support decision making. The last datapoint of national data was recorded May 2021 and the last datapoint of a hospital district was December 2021. These datapoints were compared to see whether changes in consumptions appeared. Obviously, variation was extreme. Furthermore, May 2021 consumption of national data was compared to two-year average consumption of a hospital district, but even though the variation was remarkably high. Table 4 points out the percentual change in consumption levels.

Table 4. Variation in consumptions.

Product group	Week 20/2021	Week 52/2021	Change (%)	2-year average	2-year average, change (%)
Surgical masks	314 210	172 710	-45 %	195 496	-38 %
Face visors	712	4 991	601 %	1 269	78 %
FFP2 respirators	30	1 048	3393 %	1 251	4070 %
FFP3 respirators	1 484	5 092	243 %	1 252	-16 %
Isolation gowns	5 633	10 213	81 %	5 859	4 %
Nitrile gloves	692 060	627 280	-9 %	635 595	-8 %
Vinyl gloves	192 600	157 500	-18 %	212 542	10 %
Aprons	2 710	3 700	37 %	1 745	-36 %

It is quite clear how enormous percentual differences in consumption have been in different product groups by this method. Thus, forecasting the future demand in this way could cause severe problems. The data is acquired from one hospital district and the case is similar for the other hospital. For the rest of hospitals, the situation is probably the same. Therefore, this approach was not proper.

4.3.4 Economies of scale

Inquiries of quotation prices for different order quantities were included to the study to identify potential economies of scale. Tenders were sought from three suppliers. Assumption concerning economies of scale was made based on summation of the results. The purpose was to know the realistic market prices for different order volumes to achieve potential cost savings from bulk purchasing. The offers were made on the basis of consumption levels: for PPEs that have less consumption lower order quantities were requested and vice versa. For example, consumption on surgical masks has been significantly higher than for FFP3-ventilators and thus, a higher order quantity sizes were inquired for surgical masks, nitrile gloves, and vinyl gloves than for the other categories.

Offers were compared to hospital districts' historical average unit prices. Percentual values on economic of scale were used for analysis. All three suppliers responded to the inquiry and averages from offers were formed for each order quantity on that basis. However, the answers were not consistent with each other, because one supplier provided the offerings based on container capacity while the others on order size. Further, one product category itself may have extensive catalogue and the prices of the products within it may differ significantly.

5 Results

NESA has previously discussed preparedness level planning with hospital districts. Thus, four-month preparedness level for on-hand stock was used in this work as a basis. The sufficiency levels of PPE categories were examined and compared. It turned out that these levels have been remarkably unbalanced between categories. For better readability, DII was scaled to months in inventory. The results are shown in Figure 17.

In addition, days-in-inventory equation was applied to previous four-month averages of the time series to analyze whether a trend between consumption and inventory balances could be seen. Interpreting the figure below reveals that the inventory size to consumption is remarkably higher at the end of the time period in comparison with the one-year average in each of the product groups. These indicate increased inventory levels while consumption has remained quite the same during the review period.

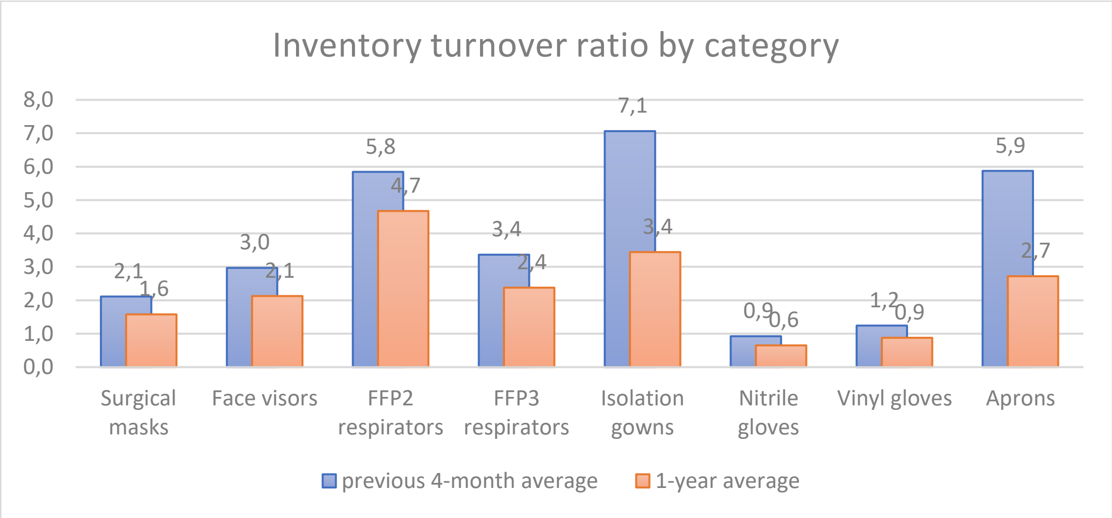

Figure 17. Months-in-stock with 4-month preparedness level.

Hospitals have had enough surgical masks to last for over eight months measured by the previous 4-month average consumption indicator. Ideally, all bars would be at level 1.0. If the value is less than 1.0, there are less PPE in the inventories than for four-month sufficiency, and if the value is higher than 1.0, there are more medical equipment in the inventories than necessary. On the other hand, it is challenging or even impossible to maintain precise inventory levels due to high uncertainty in demand. Analyzing further, three categories have been close to ideal DII level: surgical masks, nitrile gloves, and vinyl gloves. The reason for this might be that the overall volume for these products is much higher and thus, estimating the total demand may had been easier. As a contrary, isolation gowns have not been high-volume products, thereby estimating demand for these has probably been challenging during the pandemic. Figure 17 shows there were protective gowns for 28 months on-hand using the previous four-month average consumption and the four-month average inventory in estimations.

5.1 Holding costs

As DII is known for each category, holding costs can be solved. First, pallet costs are calculated. Since inventories require pallets for at least four months at a time, pallets tie up capital during that period. Again, two parameters were used for estimates: quantities of yearly averages and the previous four-month averages. As deducted from results of DII scenarios, one-year average method ties up less capacity and expenses due to reduced inventory size. Figure 18 shows the structure of pallet costs by using one-year average method.

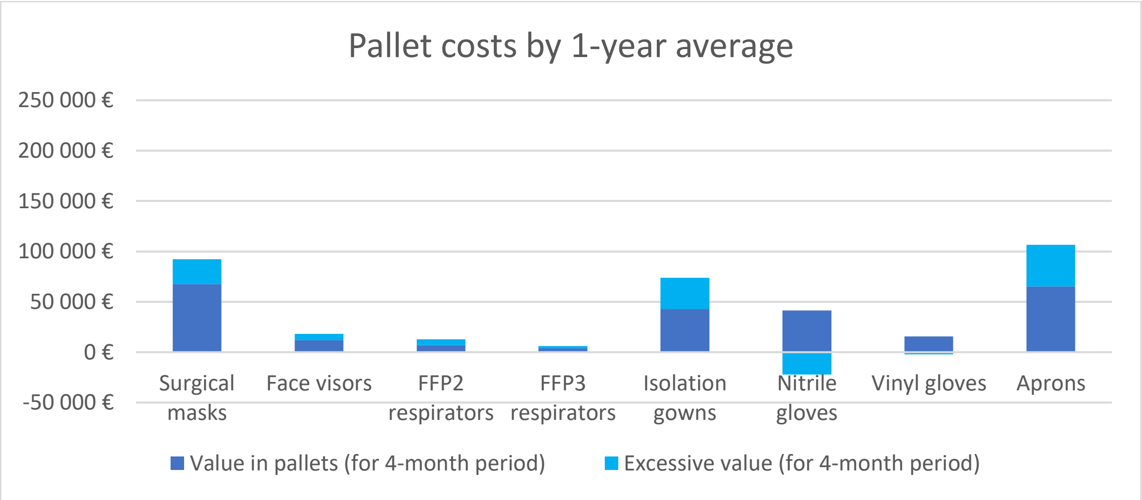

Figure 18. One-year average method.

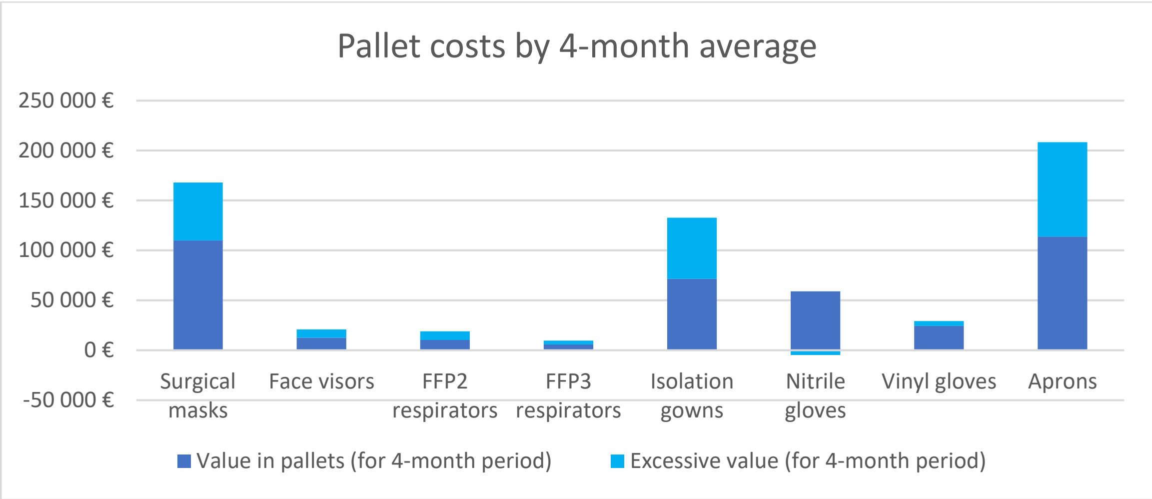

Figure 19. Previous 4-month average method.

Figure 19 shows the pallet cost structure on four-month average method. Monthly inventory holding cost per EUR-pallet is set to 6,00 € and purchasing price of EUR-pallet is set to 11,90 € (based on market price estimates). The results of the two figures above line up with each other (except from scaling), but the differences are apparent, when it is a comparison of space need versus sufficiency of an item. For example, pallet costs of FFP2 respirators are one of the lowest (Figure 19), but from the DII view, they represent the top sufficiency among categories (Figure 17).

Figures 18 and 19 show that aprons, gowns, and surgical masks tie up most capital due to highest space need. Nitrile gloves are almost at the same level as the first mentioned PPE in terms of required capital, but these do not accumulate unnecessary value (blue vs. cyan bars). Therefore, it is likely that attention has not been paid to the holding costs of surgical masks, isolation gowns, and protective aprons. For the rest of categories, the situation has been quite tolerable.

The second source of holding costs come from rental (or owning a warehouse). It is estimated that one-day holding cost of a pallet is 0,20 €. Assuming there are 30 days in month, the monthly cost of holding EUR-pallet is 6,00 €. In this case, monthly holding cost of a pallet is approximately half of the market price of a pallet. Thus, the holding cost is linear to the price of the pallet, and four-month period holding cost is twice the value of the EUR-pallets

(24,00 € vs. 11,90 €). Note that rental levels can differ as well as pallet prices, but the levels mentioned in this work are certainly indicative.

5.2 Purchasing costs and comparison of models

From sensitivity analysis perspective, inventory value (SKUs in inventory) is the most sensitive variable of inventory cost structure. Since the unit prices differed due to purchasing transactions within the time period, two parameters of weighted averages were used: one-year weighted average unit price and the previous four-month weighted average unit price. Then, an additional discrete-event Monte Carlo simulation was incorporated to the study. In this way two different approaches using the same data could be utilized effectively. First, results by traditional inventory management equations are shown, and results from the MC simulation runs thereafter.

5.2.1 Current state and “what-if” -scenario

The necessary input values for the current state inventory valuation were unit prices and the corresponding quantities. The estimated value could be obtained by PC equation. Also, two time periods were used for the review: one-year and the previous four-month. Weighted average unit prices were obtained based on the length of specific time period. Both the current state and “what-if” scenarios included the same unit prices. The results of one-year period are shown first.

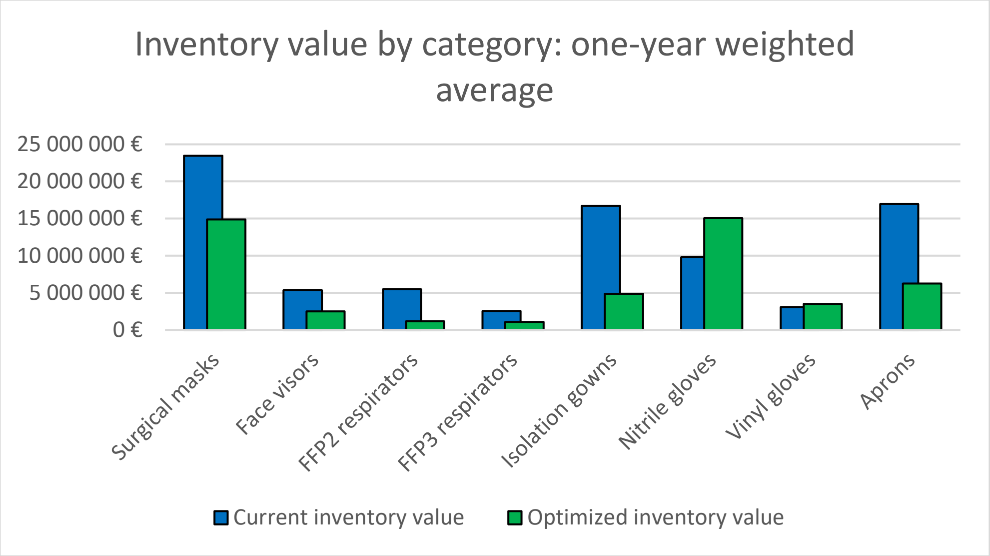

Figure 20. Inventory value by category by one-year weighted average unit prices.

Comparison between the models was done in a way where the current model considers the actual stock levels (blue bars) while the new model uses quantities based on the four-month preparedness level (green bars) that in turn is based on the one-year average consumption. The inventories value was estimated at circa 83,4 M€ whereas the optimal level would be at 49,3 M€. Thus, the excessive cost was 34,1 M€ from this approach. Next, Figure 21 shows the results when the four-month time period was used.

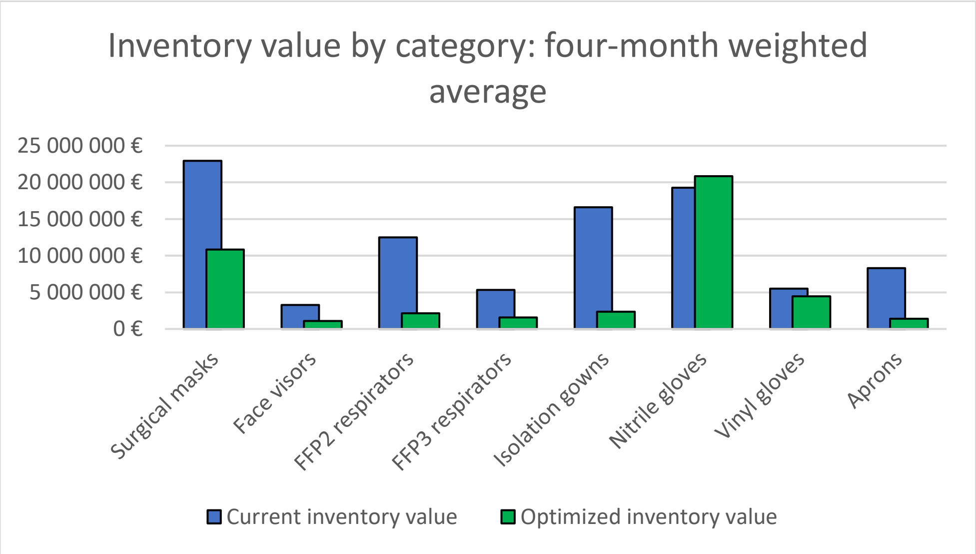

Figure 21. Inventory value by category by the previous four-month weighted average unit prices.

Using the four-month time period, the inventories value was estimated at 93,7 M€ while the optimal level would be at 44,8 M€, meaning 49,0 M€ of excess capital was tied up. The optimal level of inventory was quite close in both scenarios, but potential savings vary significantly, being approximately 14,9 M€. This is due to two factors: changes in unit prices and quantities. While the inventory levels increased over time, the average unit prices decreased. Therefore, potential cost savings are higher in the example of the previous four-month period.

In comparison with one-year average prices, prices were higher for FFP2 and FFP3 respirators while cheaper for the rest of PPE during the previous four-month time period. The differences in unit price development were remarkable in a few categories, implying an uncertain environment even after the epidemic has been ongoing for almost two years.

Approaching inventory value estimation from a different angle, an additional hypothesis was made. The constant of four-month inventory level was changed to a discrete, monthly level of sufficiency. The range was between one month to twelve months and the one-year average inventory value was used as a benchmark. The scenario is shown below.

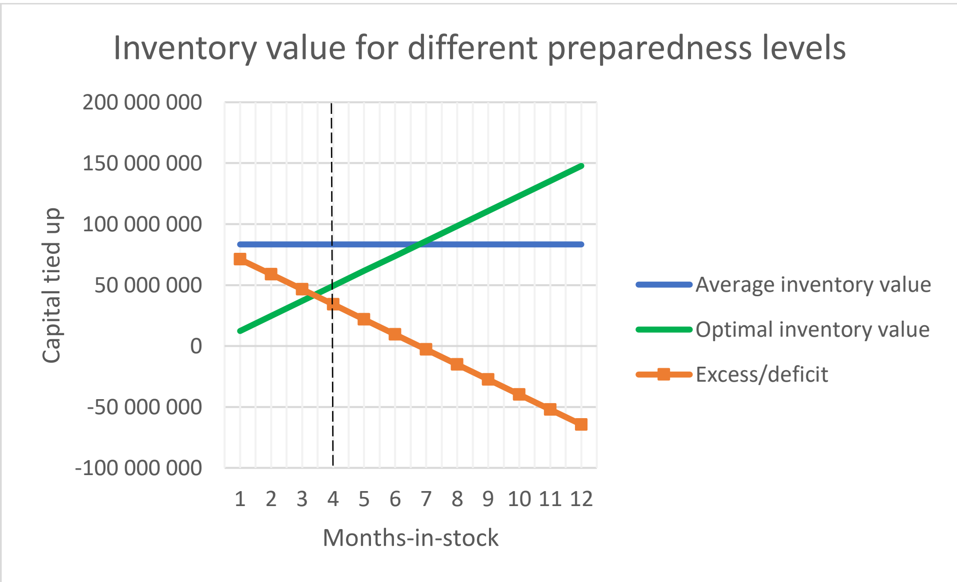

Figure 22. Inventory turnover as an explanatory factor.

First, note that a change in preparedness level does not affect the current model's inventory value. The quantities are linear to the preparedness levels. The lower the level is, the less material is needed for storing, and vice versa. The figure above shows how a longer or shorter preparedness level affects the inventory value. If the level of preparedness were decided to be set at one-month, the savings would be substantial. On the other hand, the possibility of product shortage is higher. By contrast, if the preparedness level would be twelve months, there would be no risk of product shortages, but the tied-up capital would be enormous. Therefore, the four-month preparedness level seems to be quite tolerable from an economic view (as it is being compared to the current model). At best, the new centralized model could utilize seven-month preparedness level as a break-even to the current model. After that level the new model would be less cost-effective.

Finally, economies of scales were added to the analysis. A 10% discount for bulk purchases was used for analysis, based on suppliers' answers. In each PPE category, the percentual discount was reported quite similar. The exact value for economies of scale was very difficult to determine because suppliers have different pricing methods, order volumes vary, and usually due to large order sizes the price is formed after negotiations on a case-by-case contract. In addition, constantly changing environment increases the complexity on price levels.

Table 5. Saving estimates for inventory level optimization.

	One-year average	**Four-month average**	**Maximum consumption***
"As is" model			
Purchasing cost	83,36	93,70	142,15
Holding cost	0,52	0,82	0,89
"To be" model			
Purchasing cost	49,26	44,72	103,68
Holding cost	0,34	0,35	0,66
Economies of scale	4,93	4,47	10,37
Estimated savings (M€)	**39,20**	**53,92**	**49,06**

Table 5 reveals the estimated yearly savings by parameter, ranging from 39,2 M€ to 53,9 M€. It can be seen that HC appears to be a small factor compared to PC in every case. This well illustrates the cost structure of PPE logistics regarding these, and total logistic costs were evaluated on this basis. According to Tuovila (2020), HC accounts for 20% - 30% of total logistic costs. Therefore, transportation costs, warehousing costs, and other costs were assessed to be between 1,7 M€ – 4,5 M€. For the new model, these costs are estimated to be within 1,1 M€ - 3,3 M€. Note that economies of scale for the centralized model are approximately from 4,5 M€ to 10,4 M€, depending on the scenario, outweighing total logistic costs. In the light of the results, economies of scale could bring significant added value to logistics.

A scenario of maximum consumption was added to the analysis to see how the situation would change compared to the averages. For both models, PC was remarkably higher, but the centralized SC structure generated savings, nonetheless. Thus, regardless of the parameter, the estimated savings were high. For the big picture, potential advantages of intangible resources should be considered, such as technological advances and benefits of collaboration. Next, estimates for future PPE inventory levels are evaluated with MCS since traditional IM equations are restricted of building multiple scenarios at once.

5.2.2 Future guidelines by Monte Carlo simulation

Hugos (2018, 66) says that when consumption is notably below or above expectations, this should be brought to the attention of the parties so that the causes can be studied, and adequate actions taken. Therefore, consumption to demand is examined by means of a Monte Carlo simulation to analyze their relations. Historical consumption is known and hence, the lower and upper thresholds for the minimum and maximum 4-month consumption by category were determined. This was done by converting minimum and maximum daily demand to the corresponding 4-month minimum and maximum demand. Table 6 presents the range of consumption for both lower and upper threshold values of each category.

Table 6. Historical min max consumption and the corresponding stock levels.

Product group	Consumption min	Consumption max	Lower stock threshold value	Upper stock threshold value
Surgical masks	215 000	1 014 000	25 800 000	121 680 000
Face visors	4 300	22 000	516 000	2 640 000
FFP2 respirators	2 000	24 500	240 000	2 940 000
FFP3 respirators	1 250	7 000	150 000	840 000
Isolation gowns	8 500	40 000	1 020 000	4 800 000
Nitrile gloves	800 000	2 100 000	96 000 000	252 000 000
Vinyl gloves	250 000	640 000	30 000 000	76 800 000
Aprons	28 000	55 000	3 360 000	6 600 000

The maximum consumption is of attention (resiliency view). The upper stock thresholds are compared to the actual inventory in May 2021. Table 7 illustrates this. The second column shows the actual inventory in May 2021, and the third column the maximum stock thresholds for the new model. Green-colored cells represent quantities that are sufficient to meet demand on a min-max scale and red-colored cells illustrate an abundant stock level. The keynote is that there has been an abundant quantity of PPE in inventories, with the exception of visors and nitrile gloves.

Table 7. Comparison of May 2021 actual inventories of hospital districts and a calculated sufficient amount.

Product group	Inventories in May 2021	Upper stock threshold value
Surgical masks	196 400 000	121 680 000
Face visors	2 501 000	2 640 000
FFP2 respirators	6 980 000	2 940 000
FFP3 respirators	1 473 000	840 000
Isolation gowns	11 417 000	4 800 000
Nitrile gloves	210 840 000	252 000 000
Vinyl gloves	89 624 000	76 800 000
Aprons	23 700 000	6 600 000

In order to generate estimates for proper PPE quantities, MCS is applied. Upper thresholds would be sufficient already. On the other hand, it is irrational to consider maximum consumption at all times even from the resiliency strategy, but it works as a benchmark. As the minimum and maximum consumption of each category and the maximum required quantity to meet consumption is known, the model set-up is straightforward. MS Excel's RAND -function was applied on consumption. Thus, in the model it was assumed that consumption was stochastic (not deterministic) and evenly distributed. The formula was derived as follows:

$$DII_1 = \frac{\min consumption + (\max consumption - \min consumption) * RAND}{upper\ threshold\ value} \quad (10)$$

Moreover, a for-loop was built in MS Excel VBA to consider multiples scenarios. Three examples were created: no risk, high risk, and low risk. The number of bins was 100 and the number of simulation runs was set at 20 000 for each example. Of PPE categories, surgical masks were taken to visualize the results. Figure 23 shows the first example of probability distribution of DII of surgical masks when the upper threshold is the denominator (constant value). Thus, there is no chance that surgical masks would be on-hand for less than 120 days when demand is volatile (no risk scenario). The minimum DII is 120 days while the maximum is 566, with an expected sufficiency period at 237 days.

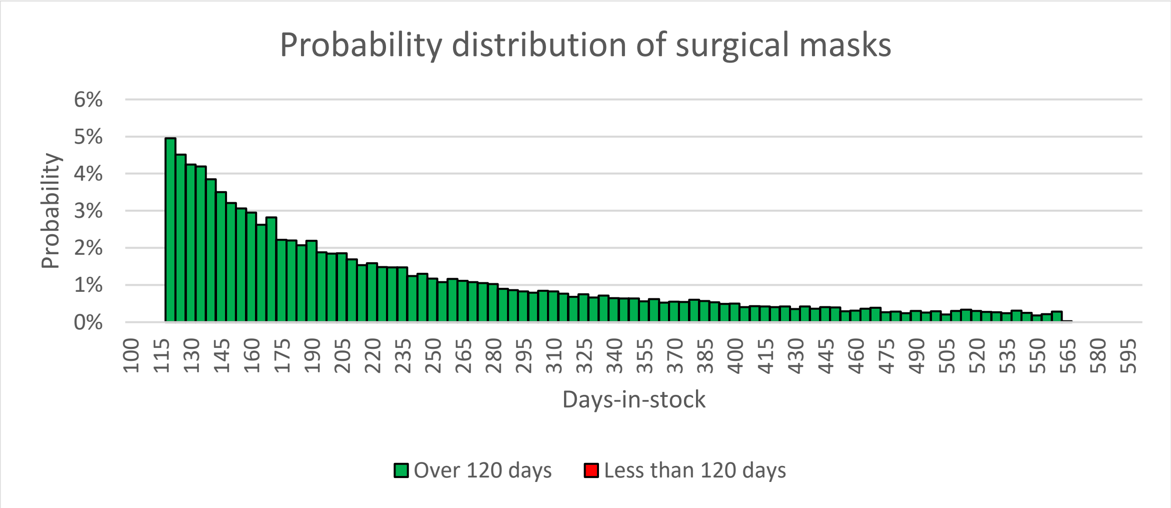

Figure 23. Histogram for the probability of sufficiency of surgical masks.

In order to proceed to the second example, a range of inventory of stock quantities was formed. RAND -function was set in the nominator too. Now both numerator and denominator resulted in 20 000 random outcomes for scenario making, and the formula was the following:

$$DII_2 = \frac{\min consumption + (\max consumption - \min consumption) * RAND}{\min inventory + (\max inventory - \min inventory) * RAND} \quad (11)$$

In the second example, the lower inventory thresholds were included to the calculations, and these were obtained by multiplying the minimum consumption of a category by 120 days. The figure below shows the outcome.

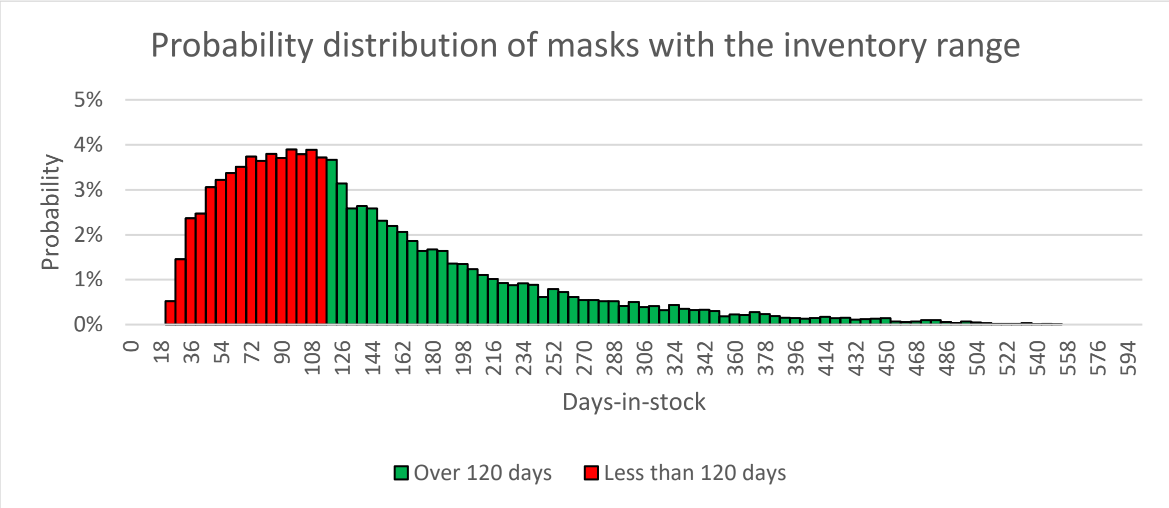

Figure 24. Probability distribution of surgical masks when lower inventory threshold value is included.

Red bars illustrate the probability of surgical masks being sufficient for less than 4 months and green bars beyond that. The probability distribution was more normal than in the first example although both are right skewed. Table 8 shows the output values for this scenario. Although the risk is high, the maximum DII is quite the same as in the previous example (557 vs. 566). The expected DII value of 143 is higher than the four-month inventory level and implies that surgical masks are likely to meet demand, but on the other hand, the number of red bars is 50%. In addition, the minimum DII is far away from the ideal (94 days). Thus, the risks are too high in this example.

Table 8. Results with 50% probability that surgical masks are for less than 4 months in stock of surgical masks. The unit of measurement is days, except for the two lowest rows.

Min	26
Max	557
Expected	143
St. Dev	89
% of negative	50 %
% of positive	50 %

Lastly, the breakdown was made in a way where approximately a fifth of DII was less than 120 days and the rest suffice longer than for 120 days (20 % - 80 % breakdown) by consumption. This required an iteration for lower inventory threshold quantities since consumption and inventory range of surgical masks are not normally distributed with each other. Figure 25 shows the scenario of lower-level risk.

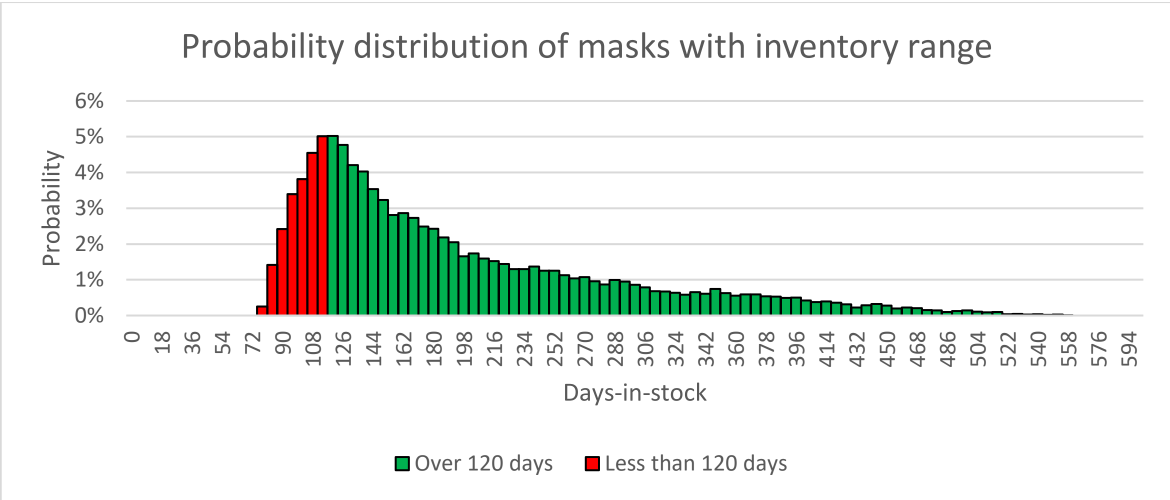

Figure 25. Probability distribution of surgical masks when lower inventory threshold value is modified.

In the third example, the minimum DII is 84, thus only 36 days away from the ideal sufficiency level. Also, the on-hand range of surgical masks is approximately between 80 million and 122 million units. In the second example (high risk) the range was wide, varying between 26 million and 122 million units (see the range of values of other PPE categories in Appendix 7). Therefore, the responsiveness is much greater in the third example, and the risk is mitigated. Table 9 shows the comparison of results of the three examples.

Table 9. Results of the three MCS examples. The unit of measurement is days, except for the two lowest rows.

	Example #1: no risk	**Example #2: high risk**	**Example #3: low risk**
Min	120	26	84
Max	566	557	558
Expected	237	143	193
St. Dev	109	89	92
% of negative	0 %	50 %	21 %
% of positive	100 %	50 %	79 %

In each example, the expected DII is higher than the 4-month inventory level (i.e., 120 days). The maximum DII did not differ significantly between examples, but the variation was high on minimum and expected days-in-stock. Moreover, the first example (no risk) proved that cost savings can be achieved by analyzing the relations of consumption and inventory stock quantities, even though the maximum consumption was used as a constant. Thereby, it is more about a decision on which the right amount to hold stocks is in inventories, and what level of risk to take. But clearly, the historical stock levels have proven out that the risk is close to zero while the costs of acquisitions and product carrying have been quite expensive. Appendix 7 illustrates the range of quantities of each PPE category for similar epidemics that can be used for analysis and decision-making[4].

5.3 Result analysis

Normally, most of the logistics costs arouse from transportation (Kantasila and Ojala 2012). In the healthcare sector, inventory represents the largest asset in pharmacy practice and its value is estimated to rise due to complex and expensive products and the product range growing (Ali 2014). Unfortunately, distribution of healthcare logistic costs by function was difficult to find out, but Figure 26 illustrates the distribution of logistics costs of manufacturing and trading companies in Finland as a benchmark.

[4] Based on historical PPE consumption during COVID-19 pandemic in Finland.

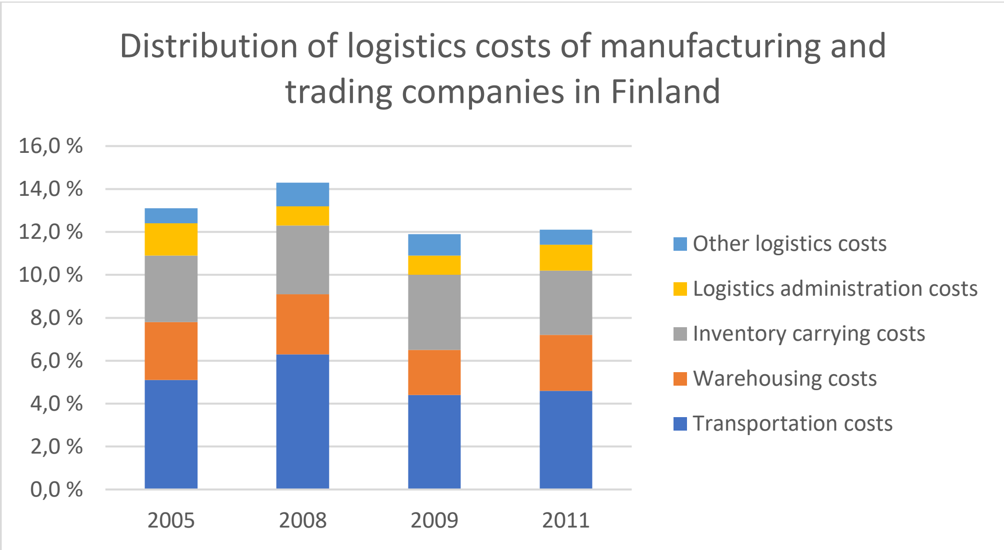

Figure 26. Cost structure distribution as a share of turnover (Ministry of Transport and Communications 2012).

Generally speaking, transportation costs individually outweigh inventory carrying and warehousing costs (and other logistic costs). However, radical generalization should be avoided as logistics costs vary a lot depending on the industry. For example, transportation costs are clearly highest for businesses that conduct import and export activities, whereas inventory carrying, and warehousing costs outweigh transportation costs in manufacturing industry. (Ministry of Transport and Communications 2012; Kantasila and Ojala 2012) Further, COVID-19 changes the logistics toward a more prepared level, thus increasing inventory carrying and warehousing costs. Consequently, the distribution of logistics costs is at abnormal level.

Nevertheless, the centralized SC structure affects the transportation routing system. Therefore, centralizing PPE can result in some-level centralization or collaboration of transportation as hospital districts do not need their own suppliers for these products to the same extent. Perhaps the transportation system would be more efficient due to interconnected coordination and co-operation.

5.4 Short-term future

According to the trendlines of the two hospital inventories, inventory levels have decreased steadily from the beginning of 2021 while consumptions have remained close to the one-year averages. This implies inventory balances have started to recover from the time of high uncertainty. If consumption was to increase unpredictably, the situation may change at a fast pace, possibly causing challenges, but hopefully, lessons have been learned from the past few years. Considering new epidemics, the current SC structure is not as cost-efficient or flexible for similar market disruptions as the more centralized SC structure, if the same response of non-cooperative preparedness happens again. The current model of hospital districts to lean on their own PPE safety stocks must be discussed especially from economic viewpoint.

The end of COVID-19 is not a foregone conclusion, and no exact date can be set for it. We should not make presumptions that the situation will only improve after hospitals and residents are faced with the reality of the epidemic but prepare ourselves with a holistic point of view for possible future epidemics or such crises. It is necessary that strategic (proactive) plans are being considered and suggested beforehand to avoid reactive actions which can be costly, demanding, and slow to fix. It is certain that new epidemics will emerge, and it is just a matter of time.

6. Conclusions and discussion

The study reviewed inventory management of critical personal protective equipment among Finnish hospital districts and proposed an alternative way of conducting it. The purpose of this study was to compare the present decentralized SC structure to the centralized SC structure from an economic viewpoint. This study has shown that there is a significant difference between the two models as the centralized SC would tie up remarkably less capital. This can be explained mostly by information management: as monitoring takes place in a bigger picture, uncertainty would reduce while cooperation increase in the centralized model. Previous research supports this. In times of crisis decentralization does not appear to be beneficial although it could be sub-optimal during normal circumstances. (Aghion et al. 2021) Rangavittal and Sohn (2009) found that centralizing strategic functions and decentralizing operational functions is a key to lower SC costs.

The objective of this work was to gather knowledge about the comparable models and reflect these for the future. The first research question was the following:

1. *According to the literature, how the economic feasibility of different SCM-policies of centralization and decentralization can be evaluated using computational models?*

Literature revealed various computational models to exist on the subject. A research by Suryawanshi and Dutta (2022) that addressed optimization models for SCs under risk, uncertainty, and resilience found mixed integer linear programming (MILP), linear regression (LR), multi-criteria decision-making (MCDM), analytical, and simulation the most adopted techniques. MILP and MCDM have been used for supplier selection, regression analysis for sales forecasts. Stochastic programming has been identified the most popular against SC disruptions and demand uncertainty (Chowdhury et al. 2021; Suryawanshi and Dutta 2022). Thus, a discrete-event MCS was applied to this study. However, only 4% of industry-wide applications addressed healthcare SCs overall, implying that less research has been done in this sector.

Answer to the first research question introduced the second research question on whether the adequate computational method existed. The second question that was the following:

2. *How to model centralized procurement of personal protective equipment in the Finnish hospital system and what would be the estimated amount of savings compared to the current situation?*

In this study, traditional inventory management equations along with the MCS analysis provided economic insights, the feasibility of different SCM policies was assessed, and the author estimates the findings to be reliable. Moreover, the research method of this work was concluded adequate, based on the literature and the needs of this case. Traditional inventory management equations were fundamental of this study to which MCS was able to be applied upon. The majority of potential savings resulted from product purchases, economies of scale, and a marginal portion from holding costs. Transportation costs were not examined extensively, but from a sensitivity perspective this seemed to not have a remarkable impact in this particular case of high stock levels. These estimates were mathematically computed and related to procurement for the most part. Centralization may also have other advantages, such as technological advances and collaboration. These can be reflected in labour productivity and a reduction in human error, for example. The insight is that there are both tangible and intangible benefits to aim for.

According to previous literature, SC resilience strategies can be divided into two concepts that are extra inventory or backup supplier, in which the first costs more but leads to higher resilience (Moosavi and Hosseini 2021). However, this requires that the extra inventory must be determined accordingly. In this work, the new model suggests alternative ranges of quantity for PPE products for the future pandemic disruptions on a national level which are based on historical consumption. Therefore, procurement can be made based on mathematical equations and models. National data about PPE consumption did not exist before 2020 nor estimates for advisable quantities in preparation for natural epidemics. Decision makers may utilize this information to form estimates on future procurement as learning from last pandemic has proven out to be beneficial (Sharma et al. 2021).

6.1 Delimitations

This is the first centralization focused study of PPE that compares SC structures of hospital districts in Finland from an economic approach during an epidemic. Normal market conditions are left out from the study, and therefore there is room for further research from this perspective since the comparison between decentralized and centralized models are unknown in between epidemics. Further, potential savings from economies of scale should be considered in all seriousness as it has the fundamentals for more cost-effective logistics during and between crises in the future.

Even though the study consists of a great amount of data, all costs were not included in calculations. Collecting data from transportation costs, ordering costs, administration costs, stockout costs, and warehousing costs would have been too laborious to process since 20 hospital districts are considered. Moreover, it is unlikely to acquire data with such information as resources of the hospital districts are very limited under the current environment. However, it is good to note that a few of these costs may decrease while others increase, if the new SC model would be executed. For example, cost-savings would take place in labor, insurances, package materials, services, and in maintenance fees as overall inventory balances decrease. On the other hand, new or additional costs would include technology and engineering costs, implementation costs, administrative costs, and other costs. Iannone et al. (2014) experienced similar results when they examined SC centralization for medical equipment.

Purchasing unit price transactions were obtained from two hospital districts and generalizations were made on this basis since the prices could not be obtained from national level data. Thus, attention should be paid to this as the total number of hospital districts in Finland is 20 and unit price is one of the most sensitive factors in this study. The same assumption for consumption and inventory from May 2021 onwards was used for trend-tracking. Also, prices of substitute PPE vary (among category), thereby having an impact in the accuracy of the results.

6.2 Further research

From a simulation approach, further research could utilize Gaussian distribution or possibilistic distribution (fuzzy numbers) for the same issue as what was studied in this work and compare whether the results differ. In addition, research on Finnish healthcare projects such as most critical medical equipment within Finnish hospital districts could be studied in the future. Also, data standardization issues regarding medical equipment among hospital districts have been noticed as a challenge which can be examined in the future for example from the viewpoint of process efficiency and collaboration. There is room for research addressing public hospitals' IT applications since studies have shown that there is potential for improvement. (AbuKhousa et al. 2014; Amrami et al. 2021; Beaulieu and Bentahar 2021; Bhaskar et al. 2020; Chowdhury et al. 2021; Mathew et al. 2013; Sharma et al. 2021; Syahrir et al. 2015). All these represent resilience strategies. Resilience is an inclusive subject, not a solo concept to be examined in isolation. In times of crises, the necessity of cooperation emphasizes as research has proven out.

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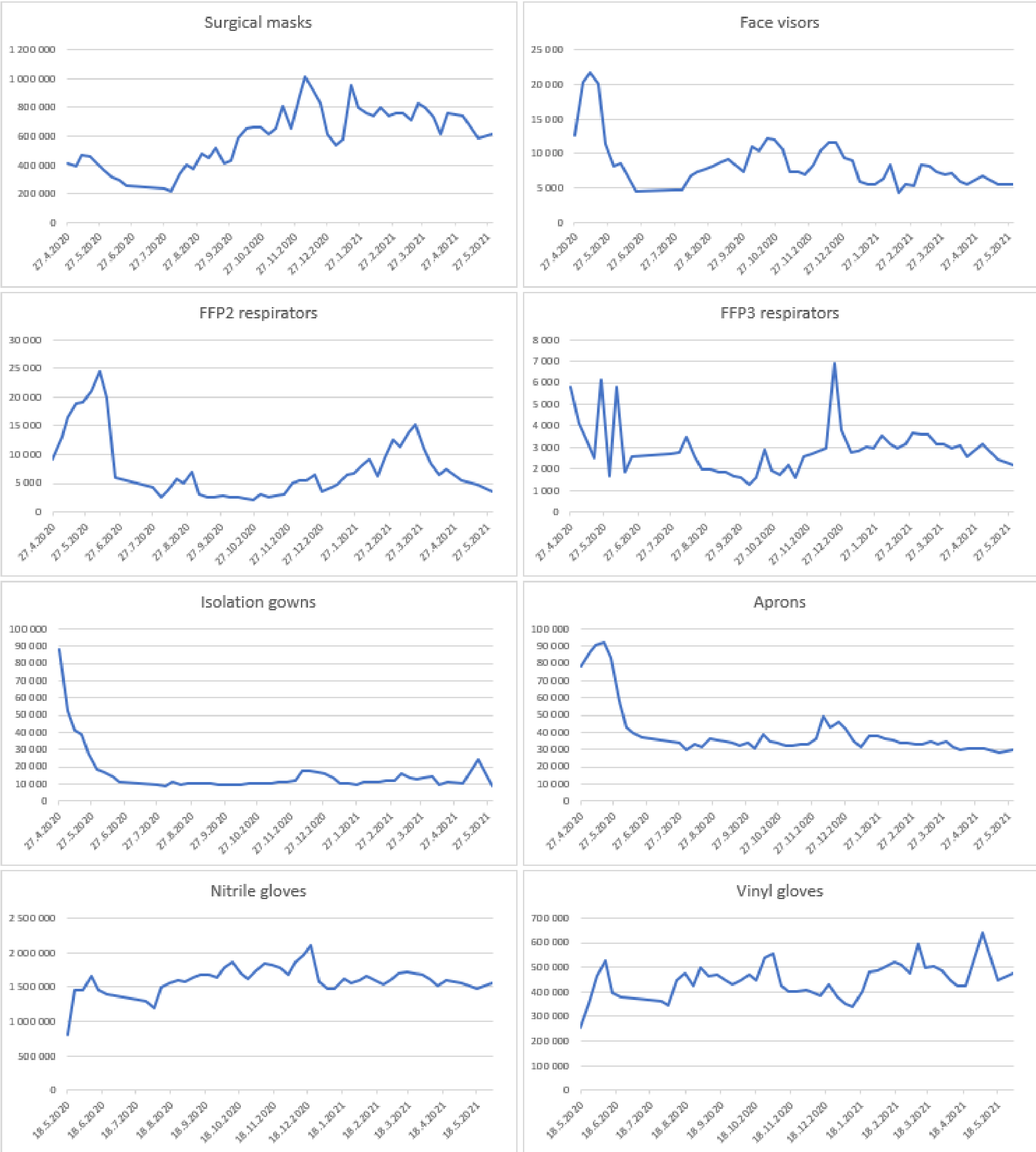
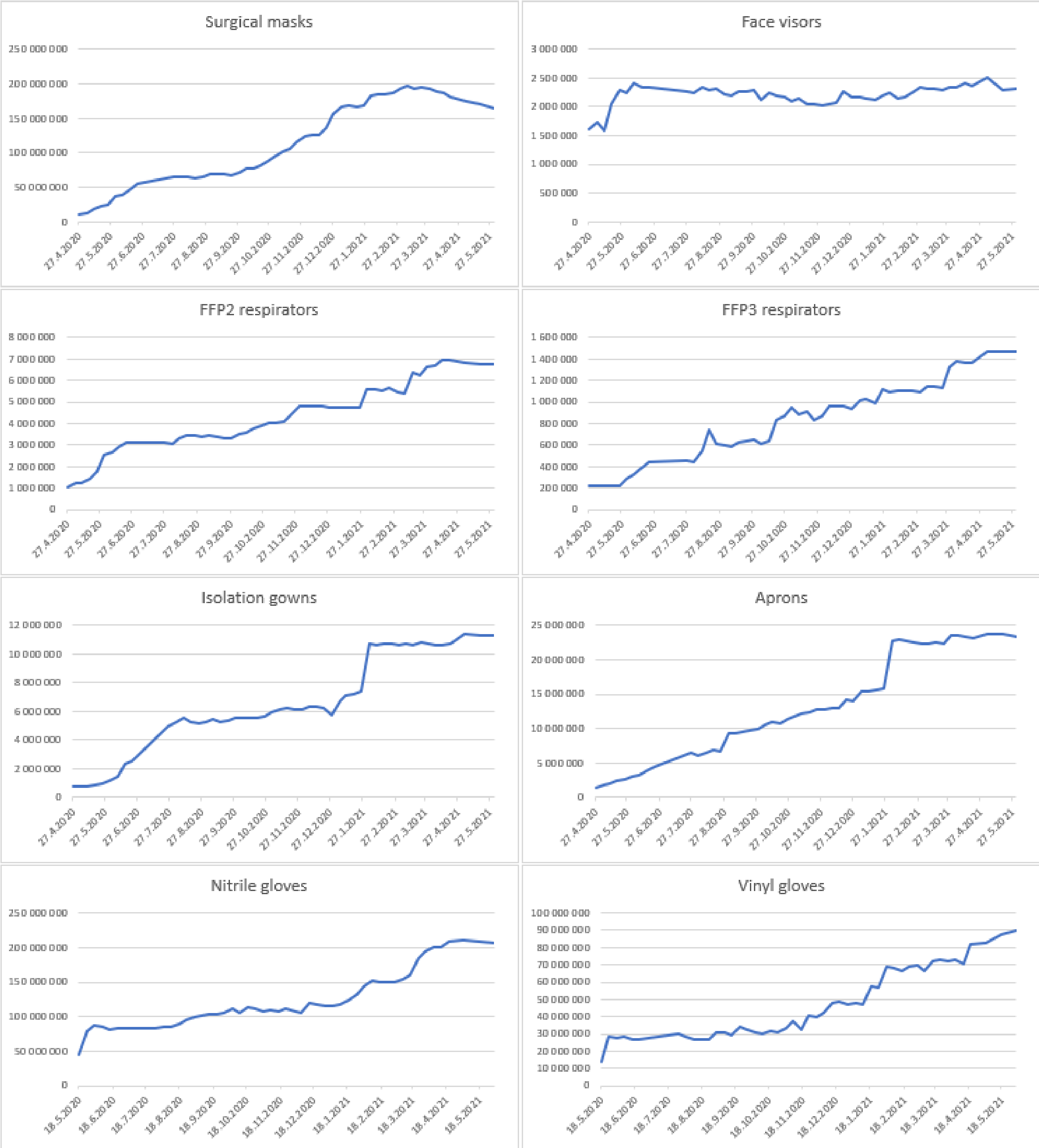
Appendices

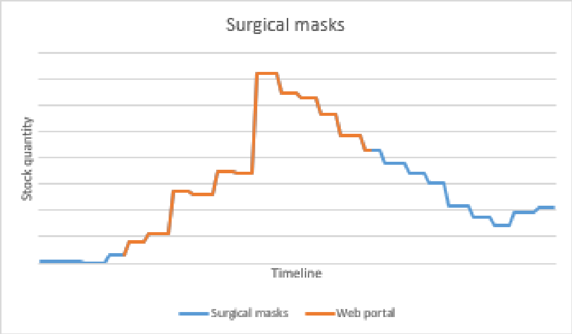
Appendix 1. Development of hospital districts consumption from April 2020 to May 2021.

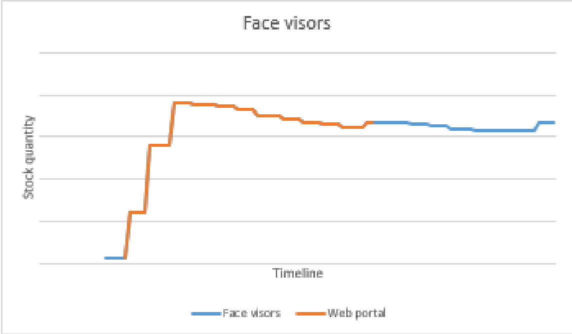


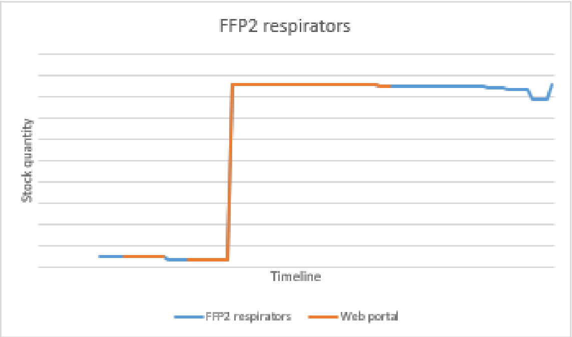
Appendix 2. Development of hospital districts PPE inventory balance from April 2020 to May 2021.

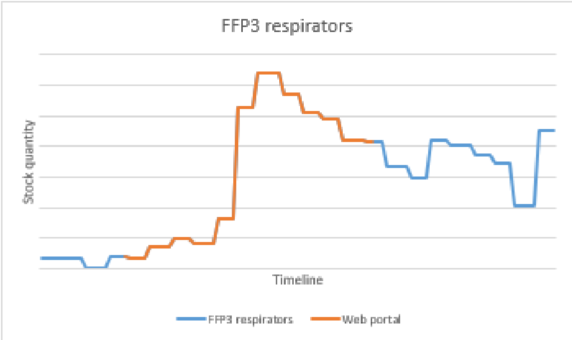


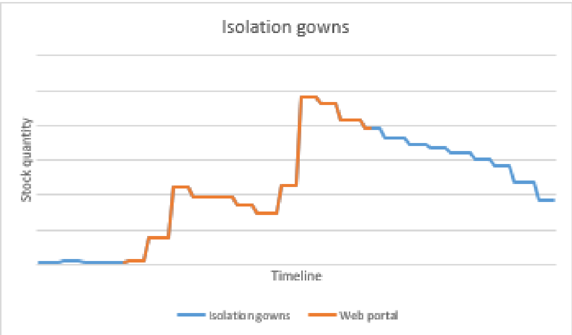
Appendix 3. Inventory balance, the first hospital district.

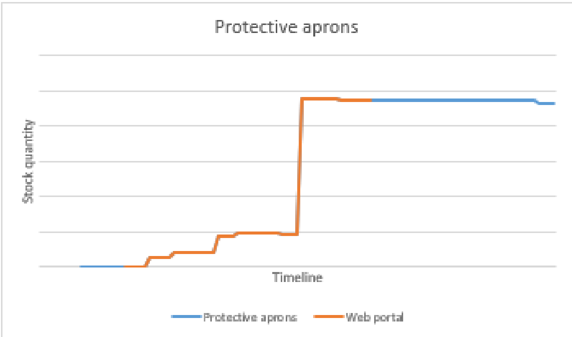


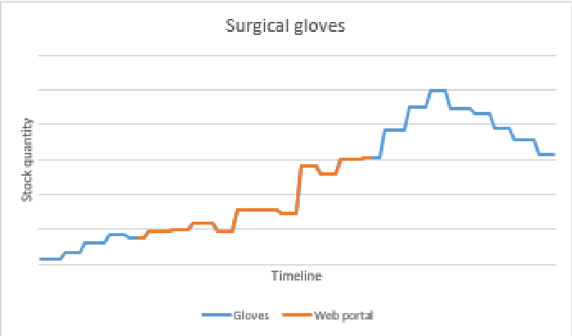




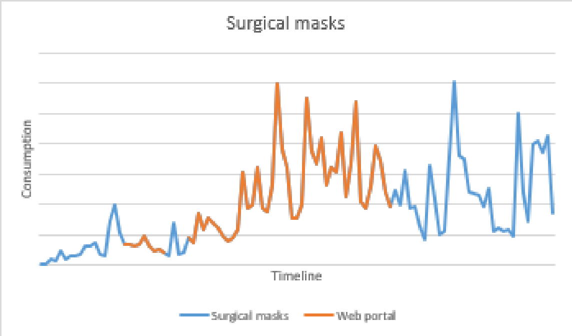


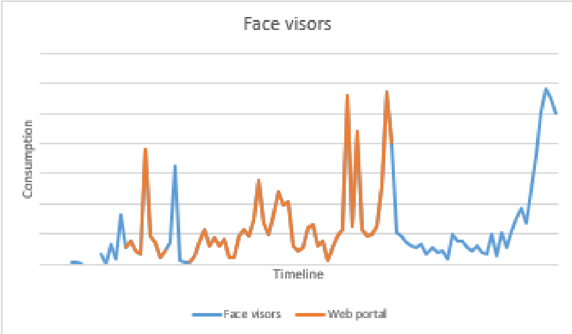


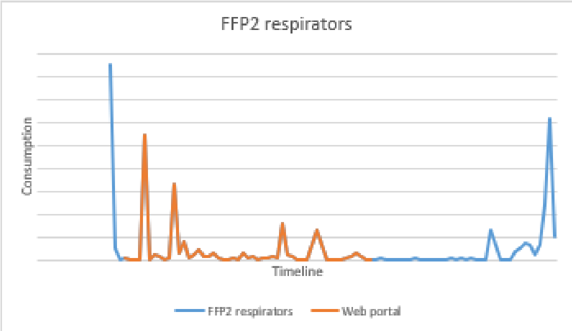


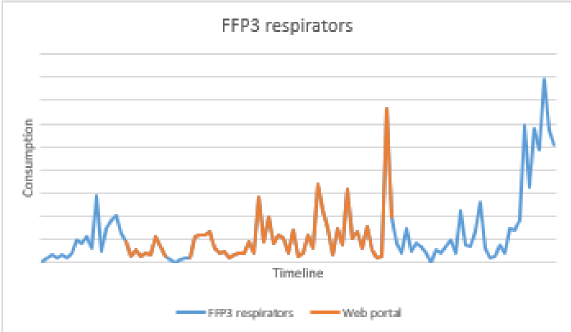


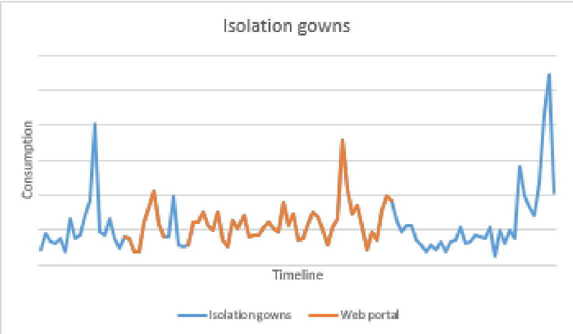
Appendix 4. Consumption, the fist hospital district.

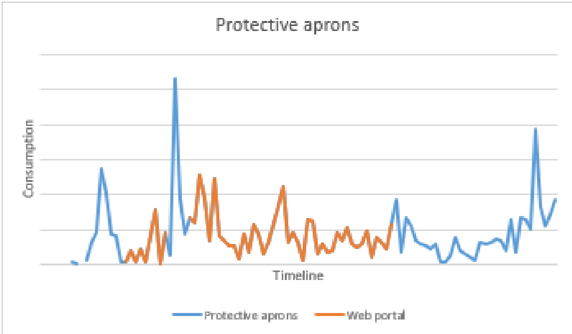


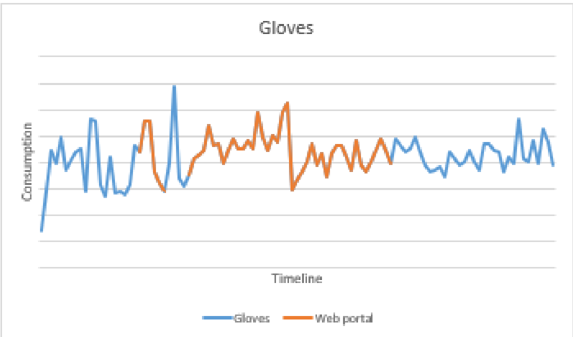




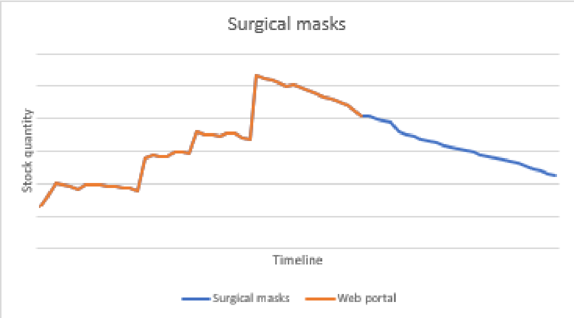


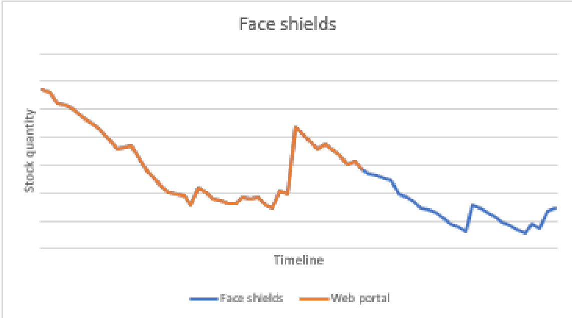


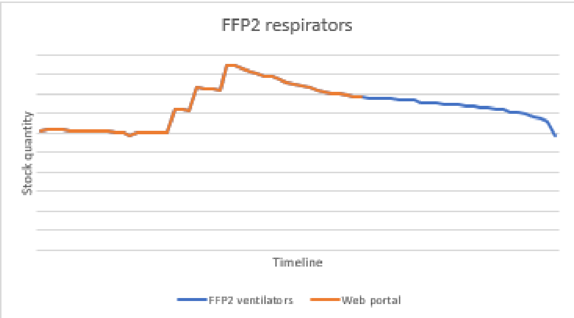


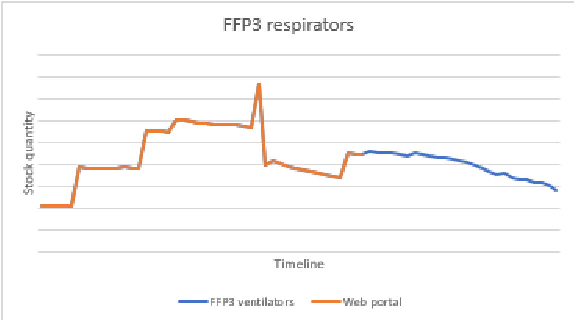


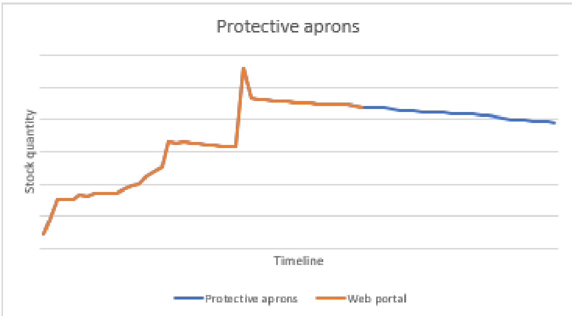
Appendix 5. Inventory balance, the second hospital district.

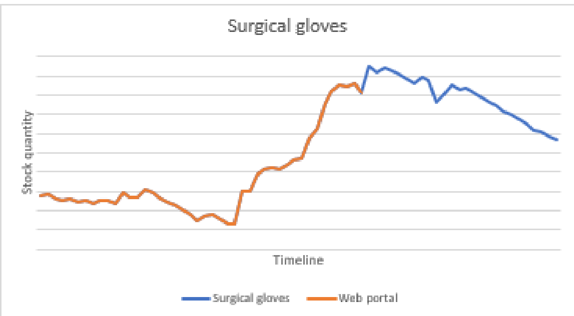




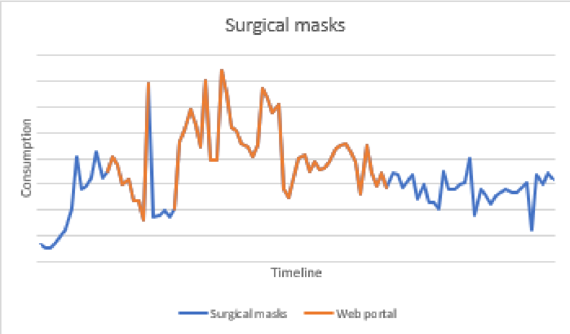


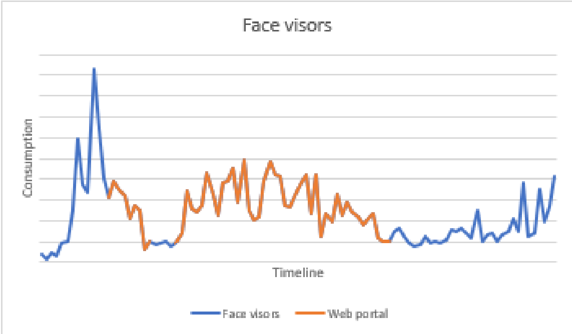


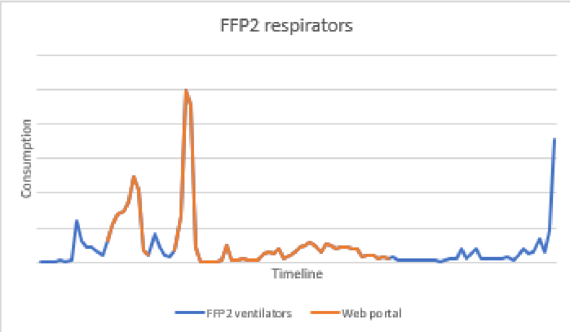


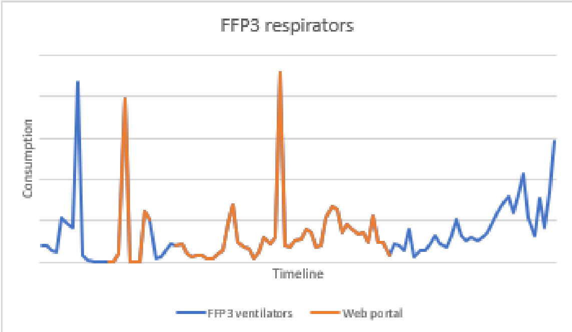


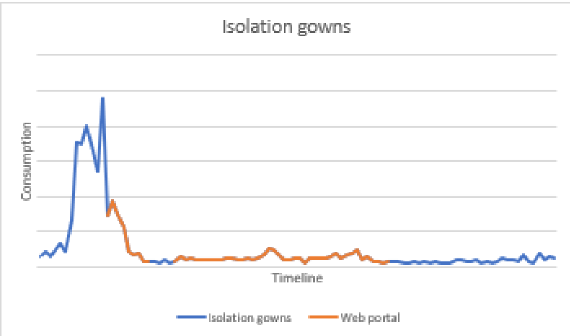
Appendix 6. Consumption, the second hospital district.

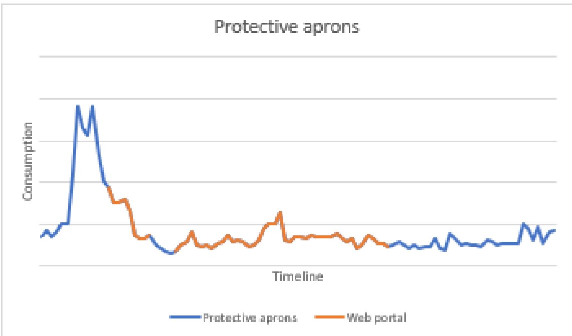


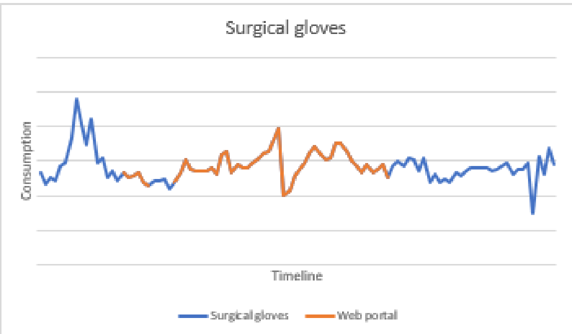












Appendix 7. Values used to simulate PPE quantities.

Product group	Consumption min	Consumption max	Lower threshold value	Upper threshold value	(Lower) threshold values for lower risk example
Surgical masks	215 000	1 014 000	25 800 000	121 680 000	81 112 000
Face visors	4 300	22 000	516 000	2 640 000	1 760 000
FFP2 respirators	2 000	24 500	240 000	2 940 000	1 960 000
FFP3 respirators	1 250	7 000	150 000	840 000	560 000
Isolation gowns	8 500	40 000	1 020 000	4 800 000	3 200 000
Nitrile gloves	800 000	2 100 000	96 000 000	252 000 000	188 000 000
Vinyl gloves	250 000	640 000	30 000 000	76 800 000	58 200 000
Aprons	28 000	55 000	3 360 000	6 600 000	5 300 000