Supply Strategies for Critical Medical Supplies during a Health-related Crisis

Exploring the impact of various PPE and ventilator supply strategies during a health-related crisis like COVID-19

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Executive Summary

In 2020, the world was hit by a global pandemic through COVID-19, causing millions of deaths worldwide. The last two years proved that a health-related crisis like COVID-19 strains us as a society and the capacities of health systems worldwide. Severe infections of COVID-19 require higher capacities of hospital beds and ICUs with ventilators. Simultaneously, the need for Personal Protective Equipment (PPE) reached its highest levels, as health care workers need to be protected from possible infections. For health systems, the question arises of how to secure enough PPE and ventilators before and during a health-related crisis like COVID-19, given that current supply strategies and supply chain structures are vulnerable to shocks.

This research explores how health systems can create responsive and prepared supply strategies to meet the rising demand for critical medical supplies during health-related crises. Concerning the availability of critical medical supplies, preparedness entails stockpiling as a supply strategy. Prepared supply strategies are applied in the long-term and aim to absorb the first decline in the availability of critical medical supplies during health-related crises. Furthermore, preparedness entails actions decision-makers in health systems can take to increase the effectiveness of responsive supply strategies. Such actions include implementing diverse supplier frameworks that focus on purchasing medical supplies from various countries and creating a higher domestic supplier base, as well as developing crisis frameworks that accelerate procurement processes and include a plan of action concerning the implementation of responsive supply strategies. On the other hand, responsiveness refers to supply strategies used at the beginning of a health-related crisis in the short term. Responsive supply strategies include ramping up domestic production, supporting innovations, loaning medical supplies, and purchasing medical supplies from the world market or through direct tender.

To explore how health systems can create resilient and responsive supply strategies, a System Dynamics model was developed, focusing on the English health system as an example for the Global North. The system captures the spread of a pandemic similar to COVID-19 within a society, its resulting demand for PPE and ventilators, and the different supply strategies the English health system used to secure enough PPE and ventilators. The most critical model outcome is the shortage of ventilators and PPE per day during a health-related crisis.

It stood out that the PPE stockpile exhibiting low inventory levels, high shipment times, and slow warehouse operations slowed down the health systems' response. Additionally, the focus on purchasing PPE and ventilators through direct tender and from the world market led to insufficient availability of PPE and ventilators, as ordered supplies were unusable or arrived late due to export restrictions and delayed shipments times. In contrast, loaning ventilators helped decrease the shortage, and increasing domestic production of supplies was impactful in the long-term, but not as an immediate response due to its significant setup time. Decision-makers in the English health system did not focus on innovative supply strategies, the implementation of crisis frameworks, or diverse supplier frameworks.

Given the deep uncertainties surrounding the supply chain of critical medical supplies, Exploratory Modelling and Analysis was conducted to identify candidate policies and explore their performance given the uncertainties. Promising candidate policies exhibited stockpiles with higher inventory levels than recommended and no delays concerning the operation within the warehouse or the delivery of the medical supplies. Furthermore, it stood out that short setup times were necessary for the responsive supply strategies of domestic production, innovation, direct tender, procurement from the world market, and loaning equipment. Concerning the supply of PPE, combining all supply strategies resulted in the most robust outcome. Due to their high production capacities, purchasing PPE and ventilators through direct tender and from the world market were the most prominent among candidate policies.

A scenario discovery explored what uncertainties and their combinations affected the availability of critical medical supplies given the candidate policies. Specifically, uncertainties affecting the success of purchasing supplies through direct tender and from the world market had the most impact on the availability of PPE and ventilators. The most prominent uncertainties include high shipment times, export restrictions, the performance of the supply chains (low initial production capacity or production delays), and the delivery of unusable medical supplies. These factors came into play during COVID-19. Hence, decision-makers need to decrease uncertainties and increase the preparedness and responsiveness of supply strategies.

The results of the analysis and the findings in the literature provide the following recommendations to decision-makers in health systems to create prepared and responsive supply strategies that ensure the availability of critical medical supplies during health-related crises. Concerning preparedness of health systems, decision-makers can implement (i) stockpiles exhibiting higher inventory levels than recommended, and no delays concerning the operation within the warehouse or the delivery of the medical supplies need to be implemented. To decrease the setup times of responsive supply strategies as a part of preparedness, it is suggested to (ii) implement diverse supplier frameworks and crisis frameworks that accelerate setup times by accelerating procurement processes and having a plan of action that explains how to implement supply strategies during a crisis, (iii) diversify supplier frameworks to decrease the uncertainties surrounding the responsive supply strategies direct tender or procurement from the world market, (iv) implement stocks of raw material for domestic production. Furthermore, it is useful for decision-makers to apply several responsive supply strategies simultaneously to increase the robustness of a policy. Hence, it would be relevant for health systems to investigate improvements to current supply strategies and new supply strategies, including (i) creating platforms to accelerate innovative supply strategies,(ii) loaning PPE, or (iii) creating a database with all available critical medical supplies within a country.

In this research, the English system is depicted as an independent actor of other national health systems, and it is assumed that collaboration is not relevant nor of interest. Hence, it would be interesting to explore the effect that sharing critical medical supplies between national health systems could have on the shortage of PPE and ventilators in the future.

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Glossary

Abbreviation	Definition
Coronavirus 19	Covid-19
CMS	Critical medical supplies
EMA	Exploratory Modelling and Analysis
HCWs	health care workers
MORDM	Multi-objective robust decision-making
PPE	Personal Protective Equipment
SD	System dynamics

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1
Introduction

In 2020, the world was hit by a global pandemic through the Coronavirus Disease 2019 (COVID-19), causing, so far, more than 485 million confirmed cases and 6.1 million fatalities worldwide (WHO, 2022). The following two years proved that a health-related crisis like COVID-19 could not only strain us as a society but also the capacities of health systems worldwide (Kontogiannis, 2021).

Through international travel, Covid-19 spread worldwide and put health systems under pressure. Given that approximately 20% of infected people require hospital care, thereby utilising hospital capacities (WHO, 2021a), health systems are put under pressure by a pandemic like COVID-19. Severe cases of COVID-19 reduce the availability of hospital beds and intensive care units (ICUs) with ventilators, as ICUs are needed for critically ill patients, and ventilators are required whenever a patient cannot meet their oxygen needs with natural breathing (Madekurozwa et al., 2021). To deliver the oxygen, invasive ventilation is needed to treat COVID-19 patients (Carter et al., 2020; Madekurozwa et al., 2021). Without a sufficient amount of ventilators available, healthcare professionals must make life or death decisions on which patients to whom they should provide medical attention (Fink, 2020; Kliff et al., 2020). Therefore, it is critical for health systems to have sufficient ventilators available during a health-related crisis like COVID-19.

With increasing pressure on health systems and hospitals, the need for protection of health care workers (HCWs) similarly increases. HCWs wear Personal Protective Equipment (PPE) to minimise exposure to hazards. PPE is essential for routine healthcare delivery and to contain local outbreaks of viruses, making it a critical tool in response to COVID-19. According to Gandrup-Marino et al. (2021), PPE is one of the most effective tools against COVID-19 that health systems have available as it prevents the depletion of an already limited healthcare workforce. At the end of 2020, 43% of all countries cited insufficient PPE as a leading cause of healthcare service disruptions (WHO, 2020b). Health systems require a sufficient amount of PPE to function. To prevent the spread of COVID-19, the WHO (2020c) recommends HCWs wearing the following PPE:

- Medical masks (respirators and surgical masks)
- Eye protection (face shield, goggles)
- Gloves
- Coveralls
- Gowns
- Aprons
- Scrubs

A health-related crisis like COVID-19 revealed that shortages of ventilators and PPE jeopardize the endless efforts of HCWs around the globe (Rebmann et al., 2021; Rowan & Laffey, 2020; Sharma et al., 2020). Furthermore, such a crisis puts health systems under immense pressure as decision-makers must expend limited financial resources to mitigate these resource shortages.

When COVID-19 hit health systems worldwide, it became clear how complex the organisation of PPE and ventilators for health systems is. Many health systems were overwhelmed with the task to provide their population with enough ventilators and their HCWs with enough PPE. The question then arose of how health system decision-makers can secure sufficient PPE and ventilator supplies before and during a health-related crisis like COVID-19. To answer this question, health systems must consider the production and supply chain context of PPE and ventilators. Today's supply chains are lean, focused on just-in-time deliveries and cost minimisation on the side of suppliers and health systems (Cohen & Rodgers, 2020; Miller et al., 2021). Products are usually sourced from single suppliers (Miller et al., 2021). Supply chains characterised by these factors increase the vulnerability of health systems to deficient inventory levels of PPE and ventilators, further increasing their susceptibility to uncertain events like COVID-19. Such disruptions can halt the procurement of raw materials or delay the delivery of critical medical supplies, which can lead to dire consequences during a health-related crisis like COVID-19.

To aid in this planning, decision-makers must consider the differences in the supply chains between ventilators and PPE when considering supply options. Ventilators are often made-to-order and are typically composed of hundreds of smaller parts produced by companies spread across the world (Kliff et al., 2020), making it difficult for suppliers to increase their production capacities within a short time frame. Furthermore, production centres of ventilators are located in wealthier countries (often referred to as the Global North). These factors contribute to the significant lead time it takes to fulfil ventilator orders. Conversely, PPE production is concentrated in a few countries around the globe. For instance, Chinese masks accounted for 77% of global PPE exports in 2020, with 60% of all PPE products produced in China and the USA (Gandrup-Marino et al., 2021; IFC, 2020). Compared to ventilators, PPE is relatively easy to produce and cheaper. Therefore, the increase in production capacities of PPE suppliers depends mainly on the availability of raw materials (IFC, 2020).

Additionally, health systems can maintain a stockpile of PPE or/and ventilators to counteract low levels of inventories and any risk of disruptions. Health systems may need to find different supply options for PPE and ventilators during a health-related crisis. They do not rely solely on their leading suppliers to provide sufficient healthcare equipment promptly.

COVID-19 is not the world's first pandemic and will not be the last one since the risk of virus outbreaks has increased rapidly in recent years (Marani et al., 2021; D. Meadows, 2020). Health systems need to be better prepared in the future to be able to provide sufficient PPE and ventilators during a health-related crisis. Currently, a knowledge gap exists regarding how health systems can be better prepared and quicker to respond, considering the different supply channels of PPE and ventilators. Consequently, the main research question for this master thesis is:

How can health systems create prepared and responsive critical medical equipment supply strategies during health-related crises?

1.1. Scientific Relevance

Answering this question is relevant for the future performance of health systems and scientific research. Based on the conducted literature review, answering this research question constitutes a novel contribution to the domain of healthcare supply chain systems. This research combines transmission models with the resulting demand and supply interaction of PPE and ventilators in hospitals, using system dynamics as a method. Thus far, research utilising a system dynamics approach has focused primarily on the spread of infections/diseases and their consequences for societies and the performance of supply chains within different fields. Thus far, combining both topics within a health system using a system dynamics approach has not yet been applied.

1.2. Objectives & Research Approach

To answer this research question, simulation modelling is a suitable method, as the provision of PPE and ventilators for health systems is a complex problem with multiple interacting components. Furthermore, simulation modelling provides the opportunity to test the performance of different supply strategies under various scenarios. Specifically, this master thesis uses system dynamics as a modelling method. System dynamics is characterised by its ability to model delays, feedback loops, and accumulation, all of which are present in the problem of interest. Delays are present in the delivery times of PPE and ventilators. Feedback loops exist: for example, as the PPE stock is emptied, more products are ordered, which replenishes the stock and decreases orders. Lastly, accumulation is present: the supply of critical medical supplies is present as stocks within the system, which can be refilled or depleted.

To feed the system dynamics model with realistic data and assumptions, a literature search is conducted. The literature search focuses on the different supply strategies available to health systems to prepare and respond in case of a health-related crisis to provide sufficient PPE and ventilators. Furthermore, Exploratory Modelling and Analysis is performed to explore the impact of assumptions on the shortages of PPE and ventilators and to discover bottlenecks.

In the focus of this research is the actions of health systems. Health systems act on a national level and are responsible for providing PPE and ventilators to hospitals during a health-related crisis. One of many health systems that failed to provide sufficient PPE and ventilators was the United Kingdom, more specifically England. More than one-third of HCWs claimed that PPE was scarcely available or not available at all during the first wave of COVID-19 (Ibbetson & Nolsoe, 2020). Additionally, the decision-makers were unsure about their ventilator availability (O'Dowd, 2020). At the same time, England is an interesting case as the government investigated how actors organised equipment through accelerated procurement processes and ramping up the production of ventilators domestically (Cabinet Office UK, 2020a; National Audit Office, 2020a). Therefore, I decided to use England's health system and its actions during COVID-19 to explain how health systems can provide PPE and ventilators during a health-related crisis.

At all times, it is necessary to remember that this research focuses on the provision of PPE and ventilators during a health-related crisis *like* COVID-19. Hence, this research is intended to apply to health-related crises in general and is not solely based on COVID-19. This is also visible in the developed system dynamics model.

1.3. Research Questions

To answer the main research question of this master thesis, the following sub-research questions were developed. Answers to the sub-research questions will help to give an informed and evidence-based answer to the main research question.

How do responsiveness and preparedness of health systems affect the availability of critical medical supplies during a health-related crisis?

This question is intended to clarify the differences between responsiveness and preparedness concerning the availability of PPE and ventilators during health-related crises like COVID-19. Furthermore, this question helps to highlight how preparedness and responsiveness are related to each other and how their interaction contributes to the availability of critical medical supplies during health-related crises.

Considering the case of England, how did the prepared and responsive supply strategies affect the availability of PPE and ventilators during COVID-19?

Since this research focuses on a case study about England, it is essential to find out how the applied to supply strategies to organise PPE and ventilators affected the limited coverage of PPE and ventilators. To answer this question, I modelled the development of COVID-19 infections, the resulting demand for PPE and ventilators, and the supply of PPE and ventilators. With the help of simulation modelling, bottlenecks in the supply strategies can be identified while revealing other possibilities to increase PPE and ventilator coverage.

How can health systems like the English health system improve their supply strategies to organize PPE and ventilators considering existing uncertainties during health-related crisis?

Next to exploring how the applied to supply strategies affected the coverage of PPE and ventilators, it is essential to identify how health systems like the English health system can create more prepared and responsive supply strategies to organise sufficient PPE and ventilators. To answer this sub-research question, it is crucial to consider the arising uncertainties during a health-related crisis and their impact on the outcome of interest.

What additional supply strategies can health systems deploy to meet the demand of PPE and ventilators during crises?

The English health system, among others, was incapable of providing sufficient PPE and ventilators during the first wave of COVID-19 infections. Hence, it is necessary to identify additional strategies to organise medical equipment. Thus, this research question aims to explore available out-of-the-box solutions of other countries and innovative new solutions. The model analysis and literature search results can identify additional supply strategies.

1.4. Reader Management

This master thesis follows the following structure:

- **Chapter 2** focuses on the methods used to conduct this research and how they are related to each other.
- **Chapter 3** presents the results of the literature search.
- **Chapter 4** describes relevant assumptions used to develop the system dynamics model used in this research, as well as the experimental setups used for the Exploratory Modelling and Analysis.
- **Chapter 5** focuses on the results of the simulation model and the conducted Exploratory Modelling and Analysis.
- **Chapter 6** discusses the results of this research and positions it in the current literature.
- **Chapter 7** concludes this research by answering the research questions, highlighting the strengths of this research and opportunities for future work.

2
Methodology

This chapter focuses on the methods used to answer the main research question and sub-research questions – a literature search, system dynamics, and exploratory modelling and analysis (EMA). It shows how the different methods are related to each other, why the selected methods are suitable to answer the main research question, and how they are applied to answer the research questions.

Figure 2.1 explains what approach is taken to answer the main research question raised in Chapter 1. First, a literature review is conducted to disclose present knowledge gaps. This work uses the results of this literature search as input and as assumptions for developing a system dynamics model. Then, the system dynamics model is used to discover bottlenecks in the combination of supply strategies used by a health system. Since many variables are uncertain in the developed system dynamics model, it is suitable to use exploratory modelling to analyze the impact of uncertainties. Based on the Exploratory Modelling and Analysis results and the literature search, the question of how health systems can create prepared and responsive supply strategies for PPE and ventilators is answered, and policy advice is formed.

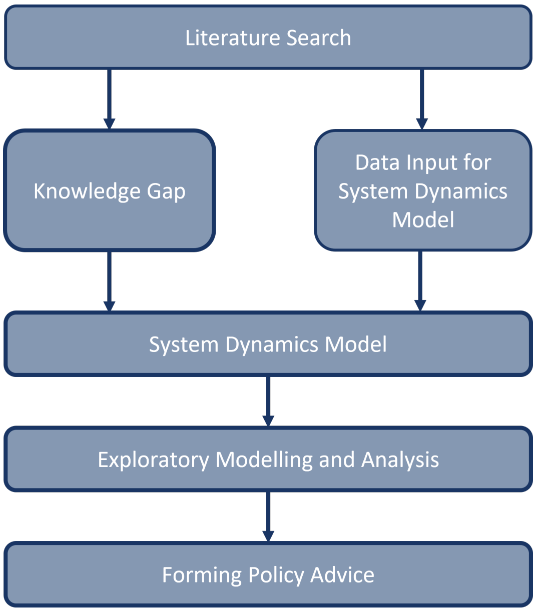


Figure 2.1: Research Approach used to answer the main research question.

2.1. Literature Search

The literature search aims to identify knowledge gaps in the current literature and critically assess the present information available in the field of interest. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram is used to organize the literature review. In this thesis, the literature review consists of four phases: *Identification*, *Screening*, *Eligibility*, and *Included* ("PRISMA", 2021).

According to Liberati et al. (2009), articles are first identified through searches in databases using applicable search terms. It is crucial to identify search terms that return relevant and fitting results during this phase. Afterwards, one screens the resulting articles and removes duplicates or irrelevant articles. Lastly, criteria are developed to decide whether articles are eligible for a full-text assessment. The criteria are applied to articles, which results in the number of articles included in the literature review.

Next to using search terms, I used the snowballing technique to identify valuable articles for this literature review and included recommended literature from experts. With that method, one identifies and reviews articles that are cited in other articles, which were particularly useful (Sayers, 2007).

2.2. System Dynamics as a Method

System Dynamics (SD) as a method was developed by Jay W. Forrester in the 1950s (Lane, 2008). His work, including his book Industrial Dynamics, is greatly dedicated to describing the core principles of system dynamics (Forrester, 1961). SD simulations focus on the behaviour of complex systems over a certain period. The method centres around the idea that a problem is present due to the interactions, feedback loops and delays among different components within a system. These characteristics cause the nonlinear behaviour of systems, which can be modelled with computer simulation models. Compared to other simulation modelling techniques, SD offers a whole system perspective, aiming to understand the internal structure rather than focusing on external factors affecting the performance of the system (Homer & Hirsch, 2006). Hence, SD is a suitable method for understanding problems situated within complex systems.

In SD, a system can be modelled with stock and flow structures. Objects move through flows and accumulate in stocks (D. H. Meadows, 2009). One can quantitatively report the status of variables with computer simulations. Feedback loops between objects and delays create a chain reaction throughout the entire system, which causes nonlinear behaviour (Homer & Hirsch, 2006; D. H. Meadows, 2009).

To simulate a SD model, one needs to create it using different building blocks. The building blocks can be grouped in the following categories when stock-flow structures are used in the modelling process: *stocks*, *flows*, *auxiliaries*, and *constants* (Pruyt, 2013).

Stocks are so-called state variables - as one can report the value of the variable at all times during a simulation run. Stocks have an initial value and their value changes depending on the inflow and outflow of the stock (D. H. Meadows, 2009). Stocks can be described with integral equations, as they are the accumulation of inflows minus outflows over time (Pruyt, 2013). Hence, for a stock variable x we have that:

$$x(t) = \int_{t_0}^{t} (Inflow - Outflow)dt$$

The corresponding stock-flow structure using the SD software Vensim can be found in Figure 2.2.

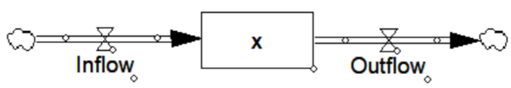


Figure 2.2: Stock-Flow Structure

The variables influencing the value of stocks are *flows* (Pruyt, 2013). Hence, the net flow equals the state changes of the stock over time. Furthermore, an outflow of one stock can act as an inflow into another stock. Variables affecting flows are either *auxiliaries* or *parameters*. The latter is not influenced by other variables and is mostly constant. Input data for parameters are, if possible, real data. Auxiliary variables can model real-world observations known as hard or soft variables. Soft variables are used to capture observations that are not well understood yet. For the modelling of soft variables, it is generally accepted to make use of assumptions (Homer & Hirsch, 2006).

Using the structural elements above, SD has been helpful for decision-makers to gain a better understanding and predict the dynamic behaviour of complex systems. SD offers the chance to find bottlenecks that cause problems within systems (Forrester & Senge, 1980). Furthermore, one can test policies under different scenarios, which allows decision-makers to explore possible futures before implementing policies in the real world (Homer & Hirsch, 2006). Hence, the essential advantages of SD are the ability to understand the inner workings of systems and help decision-makers learn and understand the problem at hand over time.

Modellers develop system dynamics models in an iterative process that consists of the following steps: scoping the problem, generating hypotheses, developing a causal diagram, quantifying the problem, testing the reliability of the model, and informing policy decisions about the model's implications (Sterman, 2000). The quality of the SD model can be improved through the involvement of stakeholders in the model building process.

2.3. Why System Dynamics?

SD has continuously proven to be a useful method to address the complexity of problems within health systems (Cassidy et al., 2019; D. J. Currie et al., 2018; Darabi & Hosseinichimeh, 2020; Davahli et al., 2020; Homer & Hirsch, 2006). An increasing interest can be observed in using SD for problems that involve health systems, as an increasing number of researchers support the use of system dynamics in health system contexts such as epidemiology, public health and health service delivery (Darabi & Hosseinichimeh, 2020; Homer & Hirsch, 2006). Furthermore, researchers focused on health care capacities and their fluctuations (Darabi & Hosseinichimeh, 2020; Davahli et al., 2020). The provision of PPE and ventilators is directly related to SD research focusing on increasing health care capacities, as the delivery of medical equipment affects the capacities of health systems. Furthermore, Homer and Hirsch (2006) points out that SD can be promising to model the interaction of diseases and risks, as well as the interaction of delivery systems and diseased populations. Additionally, it is important to know that SD has mainly been applied to health systems in high-income settings (Cassidy et al., 2019).

Next to the focus on health systems, modelling supply chains is relevant for this work. SD modelling in supply chain management often focuses on decisions regarding inventory levels, demand amplification, supply chain design, supply chain management, sustainability, as well as stock-outs of medicine (Angerhofer & Angelides, 2000; Bam et al., 2017; Rebs et al., 2019). Hence, SD can be used to model supply chain issues, which is also an interest of this work.

The provision of PPE and ventilators during a health-related crisis like COVID-19 is a complex problem within health systems, as different components are interrelated. SD can be used to improve the timely provision of PPE and ventilators, as the current literature shows. Furthermore, it is essential to point out that the characteristics to model this problem using SD are apparent. Health systems can be characterized by *accumulation phenomena* (such as the stockpiling of PPE and ventilators and the production capacity of PPE or ventilators), *delays* (such as the procurement processes, or the time between the production and delivery of PPE), as well as *feedback phenomena* (such as meeting the demand for PPE with new deliveries). For this master thesis, supply strategies of PPE and ventilators and their performance need to be represented. Hence, SD is a suitable method to model the complex problem outlined in this master thesis.

2.4. Modelling COVID-19 as a SEIR Model

As Darabi and Hosseinichimeh (2020), Davahli et al. (2020), and Homer and Hirsch (2006) identified in their literature reviews, SD was heavily applied to epidemics and diseases. To model the spread of infectious diseases, such as COVID-19, researchers have applied deterministic epidemiology modelling since the 20th-century (Hethcote, 2000). This kind of modelling can be useful to test the impact of different policies and understand infectious diseases better. Deterministic epidemiology models often use compartments to classify the different stages of the disease and the resulting flow between compartments. The number of compartments depends on the nature of the epidemic. One classical model to represent the spread of virus infections is the *SEIR* structure. Its four compartments are *S*usceptible, *E*xposed, *I*nfected, and *R*ecovered (He et al., 2021). The system's total population equals to $N = S + E + I + R$. The SEIR model structure can be extended or reduced, e.g. compartments for quarantine or self-isolation can be added. Within an SD model, the different compartments are treated like stocks, as shown in Figure 2.3.

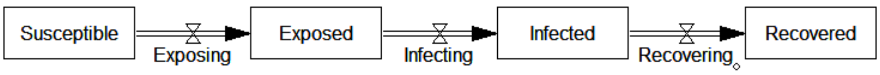


Figure 2.3: SEIR Structure

Researchers, such as Aggarwal et al. (n.d.), Jia et al. (2021), Mutanga et al. (2021), and Rubin et al. (2021), developed SD models to analyse the spread of COVID-19 infections and the impact of different policies. C. S. Currie et al. (2020) point out that SD and other simulation modelling methods can be beneficial to support decision-makers. Furthermore, other researchers applied SEIR structures using deterministic mathematical models different from SD, such as the mathematical models developed by He et al. (2020) and Prem et al. (2020). Hence, applying the SEIR structure to model the spread of COVID-19 and other infectious diseases has been proven applicable and useful based on published work. Furthermore, the SEIR structure can easily be applied to SD modelling and extended with additional stocks, which is very useful for modelling hospitalizations and the resulting demand for PPE and ventilators.

2.5. Exploratory Modelling and Analysis

A health-related crisis like COVID-19 creates numerous uncertainties regarding the functioning of health systems, including the supply of critical medical equipment (Allain-Dupré et al., 2020; Gifford et al., 2021). Given the uncertainties in health systems and supply chains during crises, various parameters of the developed SD model are assumptions built on best guesses or are unknown. Hence, it is relevant to analyze the influence of parameters on the model outcomes under different assumptions and scenarios. A method to explore the impacts of different uncertainties and hypotheses regarding the model structure is exploratory modelling (Bankes, 1993). For such an exploration, computational experiments covering the range of values of uncertainties in the model are used. The Exploratory Modelling and Analysis Workbench (EMA Workbench), an open-source library for Python, is a tool suitable to run a series of computational experiments considering the uncertainties of the model (Kwakkel, 2017). Furthermore, the EMA workbench can be used to find candidate strategies and to evaluate the robustness of policies (Kwakkel, 2017). Given the uncertainties regarding the supply strategies of PPE and ventilators and the abilities of the EMA workbench, it is appropriate to explore the developed SD model with the EMA workbench. Using this analysis method for this master thesis aims to identify the uncertainties affecting the model's outcome significantly and identify successful policies' characteristics. Reaching both goals is possible by applying Many Objective Robust Decision-Making (MORDM).

MORDM allows decision-makers to identify the most critical uncertainties in a model. In the case of this work, the developed SD model, in an understandable manner (Kasprzyk et al., 2013). Before the MORDM process is applied, an open exploration is conducted. The open exploration aims to explore how the different suggested policies behave over the range of uncertainties and to check whether the suggested policies could be robust. The results of the open exploration are visualized using different kinds of graphs. The possible range of outcomes is mapped using a Kernel Density Estimation (KDE) over time to explore possible outcomes given the uncertainties. KDE is a method for density estimation and provides the opportunity to visualize the "shape" of data (Conlen, n.d.). Furthermore, feature scoring is applied to identify the differences in impact uncertainties can have on the outcome (Kwakkel, 2017).

The MORDM process consists of four different steps: problem formulation, generating alternatives, uncertainty analysis, and a scenario discovery (Kasprzyk et al., 2013).

The *problem formulation* contains the definition of uncertainties, levers (decision variables), and the model outcomes, which can also be described as measures of performance (Kasprzyk et al., 2013). For this step, it is vital to identify the range of values uncertainties and decision levers can take. The problem formulation follows the XLRM framework introduced by Lempert et al. (2003).

After the problem is defined, the *alternative generation* takes place, which generates a set of candidate policies based on a specific state of the world. The state of the world considered for the MORDM process in this work is the worst-case scenario identified in the open exploration. Candidate policies are found using multi-objective optimization by identifying the best policies given the worst-case scenario. The optimization uses Latin hypercube sampling as suggested by Bryant and Lempert (2010) since it provides an efficient sample of a model's behaviour.

Afterwards, an *uncertainty analysis* is conducted by running experiments over the set of candidate policies and different scenarios (Kasprzyk et al., 2013). A scenario is a system state that is defined by uncertain variables. The range of values for the uncertainties needs to be reasonable but does not always have to be possible (Kasprzyk et al., 2013). Considering the PRIM algorithm used in the scenario analysis, the number of uncertainties must not exceed a threshold value. The uncertainty analysis results are then used to base the next step. Additionally, the robustness of candidate policies can be compared and identified using box plots. Box plots display the maximum and minimum outcomes and the interquartile range and median of the outcomes of interest. Outcomes are considered more robust if the interquartile range is small and the maximum and minimum values are less spread out.

Lastly, a *scenario discovery* is conducted to identify combinations of uncertainties that have the most significant impact on the outcomes of the model. Scenario discovery uses clustering analyses to find combinations of uncertainties that best predict an outcome of interest (Kasprzyk et al., 2013). The outcome of interest is low coverage of PPE and ventilators for the case at hand. For the scenario discovery, the EMA workbench deploys a PRIM algorithm (Kwakkel, 2017). For the application of PRIM, it is necessary to identify cases of interest that are considered for scenario discovery. Then, the user can choose a scenario based on its coverage and density value. Ideally, a case with a high percentage of coverage and density is chosen. A high coverage indicates that the selected scenario can explain a high share of outcomes of interest, whereas a high value in density indicates the certainty in the prediction (Kasprzyk et al., 2013). The scenario discovery entails a plot that considers the most relevant uncertainties affecting the outcome of interest, as well as the range of values of the uncertainties affecting the outcome of interest (Kasprzyk et al., 2013). To further analyze the impact of uncertainties, dimensional stacking is applied. Dimensional stacking identifies the combination of uncertainties that have the most impact on the outcome of interest.

3

Literature Search

This literature search focuses on providing PPE and ventilators for health systems during health-related crises. First, an overview, including the criteria and search terms, is presented. The first part of the literature search focuses on health systems' strategies to provide sufficient PPE and ventilators and the role of responsiveness and preparedness in this context. The second part of the literature review concentrates on simulation modelling techniques used to model the use and provision of PPE and ventilators during health-related crises.

3.1. Overview of Literature Search

The body of literature about crisis management and crisis resilience has developed considerably since the appearance of COVID-19. Since crisis resilience is a rather broad topic, this review focuses on the preparedness and responsiveness of health systems for health-related crises. Hence, its objectives are to analyze preparedness and responsiveness in health systems and identify countries' strategies to prepare and respond to sufficient PPE and ventilators. Furthermore, I critically assess the literature regarding global disruptions and their effect on the provision of PPE and ventilators. Lastly, I aim to identify knowledge gaps in simulation modelling literature about the provision and use of PPE and ventilators.

For this literature search, the databases PubMed, which focuses on biomedical and life sciences literature, and Scopus, which provides critical research from different scientific fields, were used. For both platforms, the following search terms were used for title and abstract:

Table 3.1: Search terms for Literature Search

”supply chain*” AND (”ventilator*” OR ”PPE” OR ”Personal protective equipment” AND (”pandemic” OR ”emergenc*” OR ”crisis” OR ”disaster*”)
”procur*” AND (”ventilator*” OR ”PPE” OR ”Personal protective equipment”) AND (”pandemic” OR ”emergenc*” OR ”crisis” OR ”disaster*”)
”prepar*” AND (”ventilator*” OR ”PPE” OR ”Personal protective equipment”) AND (”pandemic” OR ”emergenc*” OR ”crisis” OR ”disaster*”) AND ”supply*”

In total, 409 documents were found in Scopus, and the search resulted in 254 articles on the database PubMed. More than 200 studies were removed as they were duplicates, and 158 studies were excluded since they did not fit the overall topic of the literature search. The criteria applied to determine whether a study should be included in the full-text assessment were:

1. Studies must be written in English.
2. The context of studies was the Global North.

3. Studies were included if the preparedness and responsiveness focused on the hospital/local, regional or national level. Studies focusing on the preparedness of specific units within hospitals were excluded.
4. Studies focusing on the supply of other medical equipment than PPE and ventilators were excluded.

Applying these eligibility criteria resulted in 74 articles for the full-text assessment. Additionally, articles were added through snowballing and based on expert recommendations. A graphical representation of the literature search is shown in Figure 3.1.

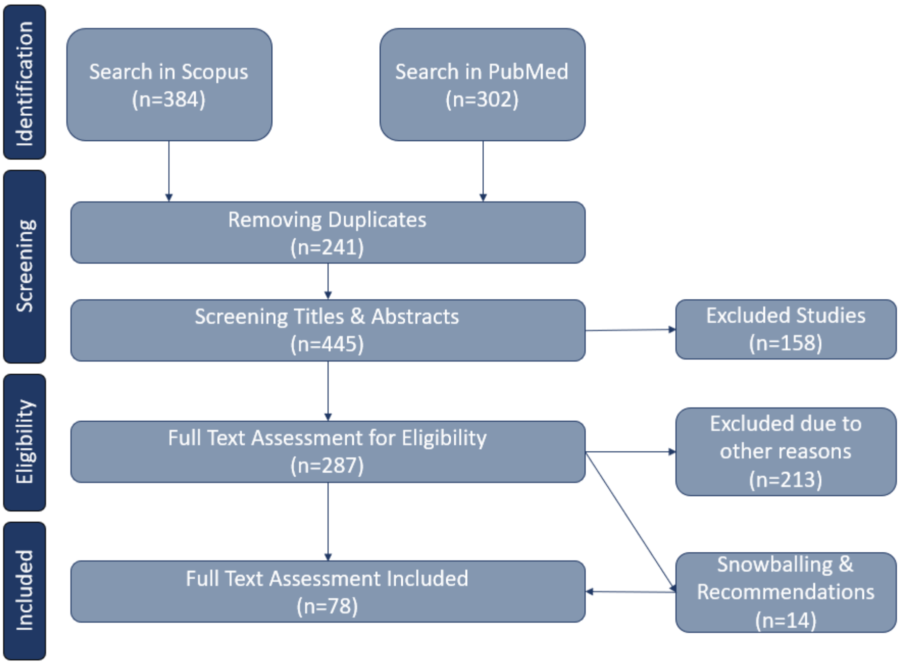


Figure 3.1: PRISMA Diagram - graphical representation of the literature search

It stood out that most of the collected studies focused on COVID-19 as a health-related crisis and were published in the previous two years (2020 & 2021). A few studies focus on the preparedness for influenza pandemics concerning the provision of ventilators. The provision of PPE was not an issue in previous crises in the Global North and did not spark as much interest and need for research before COVID-19.

Next to studies collected in this literature search with Scopus and PubMed, grey literature was included in the literature search. Many governments and non-governmental organizations (NGOs) published reports in the last two years about PPE and ventilator provision, procurement actions, and papers about potential bottlenecks and other topics.

3.2. Being Prepared and Acting Responsive in Health-Related Crisis

Before digging deeper into how a health system can be prepared and respond to a crisis, it is essential to define what "crisis" means in the context of this report. The term *crisis* is sometimes used interchangeably with the terms *emergency* and *disaster*, as no standard definition exists for either term (Al-Dahash et al., 2016; Shaluf et al., 2003). For instance, COVID-19 has been labelled as a public health emergency and a public health crisis (UNICEF, n.d.; WHO, 2020d). Likewise, competing views exist for how the terms *crisis*, emergency, and disaster are related. The literature review conducted by Al-Dahash et al. (2016) identified that an emergency could lead to a crisis, and a crisis could lead to a disaster. On the other hand, Shaluf et al. (2003) concluded that a disaster could lead to a crisis based on his collected definitions of disaster and crisis. Often, disasters are defined as unforeseen events that develop instantly, causing significant damage and requiring management to maintain the functioning of the system(Alexander, 2005; UNISDR, 2009). *Crises* are often associated with a time of intense difficulty and in which challenging decisions need to be made (B. A. Turner & Pidgeon, 1997).

Even though the term *crisis* is ill-defined, its characteristics have been determined by several researchers (Al-Dahash et al., 2016; Shaluf et al., 2003). A *crisis* is associated with a time when a difficult decision has to be made quickly that can affect a large group of people and is, therefore, considered a complex situation (Shaluf et al., 2003). Moreover, a *crisis* is characterized through its unexpectedness and uncontrollability (Alexander, 2005; Robert & Lajtha, 2002). It is important to note that crises occur in different contexts (Shaluf et al., 2003), and the focus in this work is a *crisis* affecting health systems. According to Pauchant and Mitroff (1992), a *crisis* is a "disruption that physically affects a system as a whole and threatens its basic assumptions, its subjective sense of self, its existential core, ... and it triggers a public policy change." This definition is fitting for the context of this work, as COVID-19 can be seen as a crisis that physically affects the provision of PPE and ventilators, questions the preparedness of health systems, and lastly, triggers decision-makers in health systems to implement policies to accelerate the provision of PPE and ventilators.

As a crisis can affect a system as a whole and threatens basic assumptions, it is relevant for countries to be prepared for crises in different sectors and to be able to act in that situation. The WHO (2020d) 's Director General stated at the beginning of COVID-19: "This is not just a public health crisis, it is a crisis that will touch every sector – so every sector and every individual must be involved in the fight." Decision-makers in the health system have, therefore, a special role, as they can take action to prepare and respond in time, allowing health systems to bounce back quickly to their normal performance. To describe this process, the term resilience is often used. According to Capano and Woo (2017), resilience is a term that has been widely used over the past years in various scientific fields: climate change, health systems, supply chains, and others. Capano and Woo (2017), Hohenstein et al. (2015), and Linkov et al. (2018) associates this term with being prepared, responding quickly, or "bouncing back" from an unexpected event/disruption/shock. Currently, researchers and the media use the term resilience extensively and in different contexts. Hence, various definitions and approaches to capture resilience developed over the years (Linkov et al., 2018; Scala & Lindsay, 2021; Turenne et al., 2019; Wiig & O'Hara, 2021). Turenne et al. (2019) concluded in their scoping review that the concept of health system resilience "remains highly confusing." Hence, it is important to define what it means for a health system and its supply chains to be resilient in the context of this research. Resilience is often referred to as a goal, but it describes a long-lasting, iterative process consisting of four characteristics (Bryce et al., 2020; Day, 2014; Hohenstein et al., 2015; Turenne et al., 2019) that requires investments on many ends. The four common characteristics of resilience can be summarized as and are visualized in Figure 3.2 (Day, 2014; Hohenstein et al., 2015):

- Readiness: being prepared for unexpected events
- Response: a period of quick reaction
- Recovery quickly to potential disruptions, in our case a crisis, and returning to the original situation
- Growth: moving to a new, more desirable state

A resilient health system can minimize the public health impact of crises on humans and aims to achieve SDG 3 "good health outcomes" before, during, and after crises (WHO, 2017). Sufficient provision of PPE and ventilators during a health-related crisis contributes to the resilience of health systems, as it enables a quick response and ensures the readiness of health systems for an unexpected health-related crisis. The provision of PPE and ventilators does not directly affect the system's recovery. Hence, a health system needs to have sufficient capacity beforehand or can quickly increase its capacities when a crisis hits (Nuzzo et al., 2019).

3.2.1. The Role of Health Systems during health-related crises

The system of interest for this work is health systems. The most widely accepted definition of health systems was developed by the WHO (2000) and entails: A health system comprises all organizations, institutions, and resources that produce actions whose primary purpose is to improve, maintain, or restore, health. Health actors need to resolve crucial and complex issues with their available resources

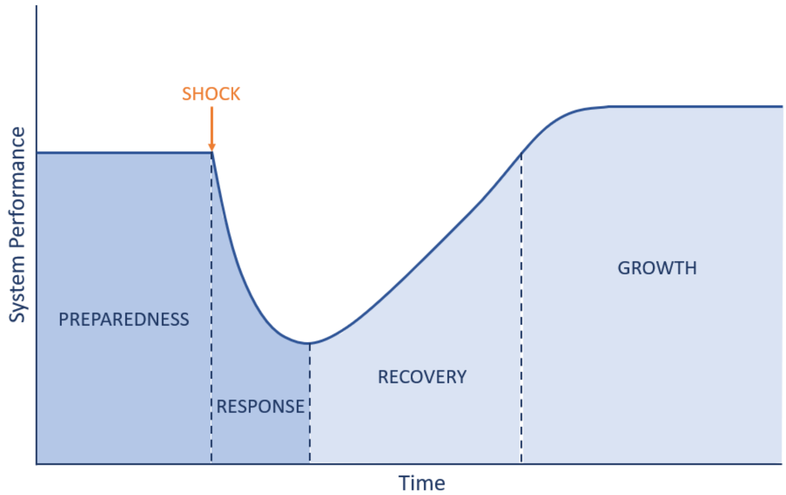


Figure 3.2: Resilience over time adapted from Linkov et al. (2014)

to reach this goal. Daily, they need to make choices involving trade-offs, for instance, investing in pandemic preparedness with it being uncertain when or whether a pandemic will happen vs investing in research and development for a disease that affects a significant percentage of a population. Therefore, the OECD (2020d) considers responsiveness and preparedness to be ”global public goods”, as a pandemic in one country can spread to other countries, and unprepared health systems contribute to the transmission of diseases.

During health-related crises, health systems should be resilient. A literature review conducted by Nuzzo et al. (2019) and Turenne et al. (2019) showed that resilience in health systems is still not clearly defined, but definitions refer to the four phases of resilience. A widely used definition to describe resilient health systems was developed by Kruk et al. (2015). They describe a resilient health system as one that is ”integrated with existing efforts to strengthen health systems”, can ”detect and interpret local warning signs and quickly call for support, provide care for a diverse population, isolate threats, maintain core functions, and adapt to health shocks”. Similarly, later work by Kruk et al. (2017) defined health system resilience as ”the capacity of health actors, institutions and populations to prepare for and effectively respond to crises; maintain core functions when a crisis hits; and, informed by lessons learned during the crisis, reorganize if conditions require it”. That also means that a resilient health system can coordinate responses in times of crisis, carries a special role in risk and crisis communication with the population, and can increase its capacities, including infrastructure, personnel and medical equipment such as PPE and ventilators (Hanefeld et al., 2018; Nuzzo et al., 2019; Therrien et al., 2017). Managing a crisis within a health system is complex, as various actors are involved, and health actors can make decisions on different levels (Wiig & O’Hara, 2021). Decisions regarding the provision and management of medical equipment can occur on a national or local level. During a crisis, decision-makers often centralize tasks to smooth working flows (Bhaskar et al., 2020; OECD, 2020c).

Regarding the COVID-19, the OECD (2020d) concluded that the preparedness and response were insufficient by health systems worldwide. It is also evident that efforts to increase capacities during previous health crises such as H1N1 influenza and the Ebola virus pandemic occurred to be challenging (Kruk et al., 2015; Yorio et al., 2019). It appeared that the provision of healthcare and pharmaceutical products and their supply chains were critical components for responses of health systems during such crises (Patel et al., 2017). Even though these crises showed the importance of preparedness and responsiveness, Bell and Nuzzo (2021) and Frutos et al. (2021) established that the preparedness of health systems is still insufficient, almost two years after COVID-19. Therefore, it is essential to provide further research concerning the provision of medical equipment and the role of health systems during health-related crises. Literature regarding the role of health systems during health-related crises proves that health systems are at the centre of acting and shows that unpreparedness combined with slow responses are challenges for health systems.

3.2.2. Providing Sufficient Equipment on Time

As mentioned above, it is relevant for health systems to have access to medical supplies and equipment, including PPE and ventilators, during a health-related crisis. Thus, relevant actors within the health system need to be able to supply enough products to HCWs and patients in hospitals. During a global crisis, the provision and organization of PPE and ventilators can be more difficult for health systems as resources are scarce, and countries compete for limited resources.

Medical supply chains are essential for a well-functioning health system, as without functioning supply chains, the provision of critical medical supplies cannot be guaranteed (Francis, 2020; Miller et al., 2021). Concerning PPE and ventilators, they must be delivered to the correct location and comply with the national quality standards (National Audit Office, 2020b; Pecchia et al., 2020). However, COVID-19 showed how fragile manufactured systems and medical/healthcare supply chains are (Helmold et al., 2020). One observed significant delays in healthcare supply chains, endangering the sufficient provision of PPE and ventilators. Researchers criticized that in the centre of supply chains are cost minimization, the reduction of inventory, and the maximization of utilization across the entire supply chain (Bryce et al., 2020; Cohen & Rodgers, 2020; Miller et al., 2021). On the opposing side of a Just-In-Time (JIT) strategy is the Just-In-Case (JIC) strategy, which focuses on diversification of suppliers and higher inventories levels to buffer possible disruptions (Folkers, 2019; Jiang et al., 2022). A supply chain focusing on JIT exhibits a lower preparedness, as low inventories do not allow for sudden increases in demand. The reliability of JIT highly depends on the stability of raw material suppliers. On the other hand, JIT allows suppliers to be efficient and reduce any waste. Hence, suppliers need to find a balance between the efficiency of JIT and the preparedness of a JIC strategy.

Today's healthcare supply chains, including PPE and ventilator supply chains, are placed in a globalized and interconnected world (Dai et al., 2021), where supply chain steps are spread around the globe, and countries depend on each other for the export and import of products. These developments strengthened the effect of COVID-19 on the performance of supply chains for PPE and ventilators. Additionally, COVID-19 caused health systems to implement export bans, travel bans, as well as taking part in panic buying and hoarding of PPE and ventilators (Bradsher & Alderman, 2020; "Germany bans export of medical protection gear due to coronavirus", 2020). These actions by health systems caused a surge in demand for PPE and ventilators, which overwhelmed the global production capacities and created raw material shortages. Consequently, delays in deliveries in health systems occurred more often, increasing their shortage of PPE and ventilators (Boiko et al., 2020; Chowdhury et al., 2021). The spike in demand reinforced competition on the market, causing health systems to purchase products with lower quality over the market price and leaving countries with less financial means behind (Miller et al., 2021). The tremendous demand for PPE caused price increases of up to 500% and lead times to up to nine months in 2020 (Gandrup-Marino et al., 2021). Such price increases caused a competitive advantage for countries with more financial resources.

According to Asian Development Bank et al. (2020), various factors surrounding the supply chain contribute to the global disruption in the supply chain of PPE and ventilators. Production capacity has been an issue for suppliers of PPE and ventilators, as it is challenging for them to increase the production capacity quickly, and research suggests that already in previous years, not enough equipment was produced (Asian Development Bank et al., 2020). Furthermore, raw materials shortages can pressure the production capacity of supply systems (Asian Development Bank et al., 2020). On the other hand, health systems have problems with their quality and procurement processes, as they are often not fast and accurate enough (Gandrup-Marino et al., 2021). Gandrup-Marino et al. (2021) points out that even though the provision of PPE and ventilators affects health systems worldwide, NGOs, like the WHO, have not been able to create global coordination systems as it is the case for vaccines and diagnostics.

Hence, global disruptions in combination with supply chains that are prone to uncertainties can significantly affect health systems' performance. Health systems need to organize PPE and ventilators differently if medical supply chains are interrupted, as COVID-19 showed. Hence, it is essential to reflect on available strategies to respond and prepare for the PPE and ventilator provision during health-related crises. The following sections present and review such researched and applied solutions within health systems.

3.2.2.1 Preparing for Crises

Worldwide health systems were unprepared for a pandemic like COVID-19 (Kaye et al., 2021). Preparing for a health-related crisis involves distribution plans for vaccines, medications, or medical equipment and the chance to achieve a sufficient capacity in hospitals and clinics. Health systems have various opportunities to prepare for a sufficient provision of PPE and ventilators during a health-related crisis. For instance, they can stockpile PPE and ventilators, implement sustainable supplier frameworks or crisis procurement frameworks.

Stockpiling PPE and ventilators in centralized or decentralized warehouses can provide health systems with the chance to be prepared for health-related crises constantly. The primary purpose of stockpiles is the ability to absorb demand shock in the beginning stage of a health-related crisis (Dow et al., 2020; Patel et al., 2017). Adelman (2020) points out that stockpiles can provide health systems with an early start and with the chance to already prepare for the near future. Even though stockpiles allow health systems to be prepared for health-related pandemics, many health systems do not apply this solution. An often mentioned argument against stockpiling are high costs compared to the uncertainty around the occurrence and strength of health-related crisis. Hence, the goal for the management of stockpiles is to determine the correct amount of PPE or ventilators, to find the balance between costs and preparedness (Chen et al., 2017; Huang et al., 2017). According to Greenawald et al. (2021) and Huang et al. (2017), the costs of stockpiling compromise the costs for products, maintenance, monitoring of stockpiles, and uncertainty planning. Maintaining stockpiles allows health systems to have reliable products available during a crisis (Greenawald et al., 2021; Mehrabi et al., 2018; Yorio et al., 2019), while also allowing changes in the composition of products over the years, as the risk for different kinds of crises may shift (Greenawald et al., 2021; Wilgis, 2008). For instance, the stockpile of England was designed for an influenza pandemic and not for a coronavirus pandemic (Public Accounts Committee - House of Commons, 2021a). Next to the composition and management of stockpiles, distributing the products in times of a health-related crisis is a challenging task. Decision-makers need to consider different factors for the distribution of medical equipment, such as the ability of facilities to make use of the additional products (Kontogiannis, 2021; Koonin et al., 2020). Furthermore, it is important to mention that health systems in the Global North did not have the chance to form an evidence-based preparedness approach, specifically for stockpiles, in the past(Branson et al., 2008).

Another way to prepare the provision of PPE and ventilators during health-related crises is for health systems to create sustainable supplier frameworks and supply chains. The performance of health systems highly depends on the performance of medical supply chains. Similarly to other industrial fields, the supply chains for PPE and ventilators are lean. Products are often sourced from one supplier, even though diversifying the supplier network can help to ensure deliveries during times of crisis (Handfield et al., 2020; Sodhi et al., 2021). Lean supply chains are prone to uncertainties but can be improved through sharing responsibilities, improving Just-In-Time systems, and using innovative communication channels (Rowan & Laffey, 2020). As mentioned in the introduction, the production of PPE and ventilators is focused on a few areas worldwide. To ensure the provision of ventilators and PPE, health systems could increase the number of local suppliers (Cohen & Rodgers, 2020; Vecchi et al., n.d.). So in times of crisis, deliveries are not dependent on rules in other countries. Health systems have little opportunity to change suppliers' supply chains but can improve parts of the supply chain that are their direct responsibility. Currently, the monitoring of PPE use and orders, as well as the distribution of PPE, is insufficient in many health systems (Finkenstadt & Handfield, 2021).

Next to improving the supply chains, including the supplier network, health systems can accelerate and improve procurement processes and other governance processes during health-related crises (Bhaskar et al., 2020; Frauscher et al., 2020; Okeagu et al., 2021; Vecchi et al., 2020). This can include clear coordination frameworks, accelerations by including direct awarding of contracts, speeding up procurement processes or setting up collaboration frameworks. During COVID-19, many countries, such as the UK, Germany, the US, or Italy, applied these changes in their procurement strategies to ensure the provision of PPE and ventilators (OECD, 2020c).

3.2.2.2 Responding Quickly to Crises

Health systems need to obtain the ability to respond quickly in times of a health-related crisis to be still able to serve all patients at all times (WHO, 2000). Time is one of the most critical factors to evaluate such a crisis response. Additionally, each possible response requires decision-makers to interact with stakeholders and need to foresee the consequences of a solution. Hence, choosing fitting responses is a complex problem for decision-makers and requires interdisciplinary expertise (Wilgis, 2008).

Health systems can apply a wide range of solutions to increase the capacity of PPE and ventilators to respond quickly during a health-related crisis. Health systems' actions during COVID-19 and research showed what responses are possible and successful in a crisis. Many health systems in the Global North applied ”quick” fixes that focus on reducing the time to organize equipment. For instance, the procurement of PPE and ventilators can be centralized in order to obtain a better overview of the demand (Best & Williams, 2021; Winkelmann et al., 2021). Additionally, centralizing procurement processes can decrease the competition between actors within health systems (Cabinet Office UK, 2020b) and increase the purchasing power of a health system. When this solution is applied, health systems still depend on the performance of suppliers.

”Ramping up” the domestic production of PPE and ventilators was another strategy by countries in the Global North to increase the production of PPE and ventilators (Best & Williams, 2021; Winkelmann et al., 2021). To achieve this response, health systems needed to find businesses that could change their production line and retool machinery to produce PPE or ventilators. For instance, the fashion sector in Italy started producing face masks in 2020 (OECD, 2020c). Choosing reliable providers is one of the factors affecting the success of domestic productions (Sodhi et al., 2021). Furthermore, decision-makers can implement collaborations between the public and private sectors to achieve this supply strategy promptly (Dai et al., 2021; OECD, 2020c; Vecchi et al., n.d.). A quicker response (that is only applicable to the provision of ventilators) than increasing domestic production is using ventilators from other sectors (OECD, 2020c). For example, health systems in the US made use of ventilators in veterinary hospitals, and England loaned products from the private health sector (National Audit Office, 2020a).

Times of crisis force people to question basic assumptions and think outside the box (Kelley et al., 2021). For the development of quick responses, innovative minds play a relevant role, as they can develop solutions with the available time and financial resources. Therefore, health systems can support innovative supply strategies by providing a framework, resources, or a platform to develop innovative supply strategies(Bhaskar et al., 2020; Dubey et al., 2021; OECD, 2020c). Among other health systems, the US decided to leverage innovative technologies by cooperating with companies they usually do not cooperate with but offer promising technologies (OECD, 2020c). Furthermore, researchers focused on the use of additive manufacturing and 3D printing for the production of PPE and ventilators (Arora et al., 2021; Ibrahim et al., 2021; Iyengar et al., 2020; Kumar & Pumera, 2021). Local initiatives can also help to meet any shortages (Kieslinger et al., 2021; Krause et al., 2021). Regarding the provision of PPE, enabling the reuse of PPE was a topic of interest for researchers and health systems (Cumbler et al., 2021).

A response often called for by the WHO, the OECD and researchers (Dey et al., 2020) were international collaborations to ensure the provision of PPE and ventilators worldwide. Additionally, Dubey et al. (2021), Friday et al. (2021), and Wilgis (2008) point out that the scientific collaboration between different fields is necessary to develop sound and new solutions. A first step could be to share knowledge through open knowledge platforms (Best & Williams, 2021). Currently, health systems' collaborations with other systems or other systems are still limited. For instance, the WHO was able to create an international network for the distribution of vaccines and not PPE or ventilators, even though both products are relevant for the performance of health systems worldwide (Gandrup-Marino et al., 2021).

3.2.3. Preparedness and Responsiveness in the Context of Health Systems during a Health-Related Crisis

In times of crisis, decision-makers in health systems do everything to fulfil the system's primary purpose: being able to serve their patients. To provide sufficient PPE and ventilators during a health-related crisis, they need to be prepared and respond quickly, as both characteristics contribute to the resilience of health systems. The conducted literature search resulted in the following differences between preparedness and responsiveness. Preparedness focuses on the time frame before a shock hits the health system and involves actions health systems can take before a crisis. Such solutions take place in the long term. Furthermore, it is relevant to realise that preparedness contributes to the responsiveness of systems, and involves next to supply strategies policy recommendations.

On the other hand, responsiveness focuses on the time window when the crisis first occurred, when the health system's performance is heavily affected or will be heavily affected soon. Therefore, actions taken in this period focus on quickly enabling a change. This thesis concentrates on the different supply strategies health systems have available before and at the beginning of a health-related crisis affecting the sufficient provision of PPE and ventilators. In table 3.2, a comparison between the characteristics of preparedness and responsiveness is presented, including the available strategies. The content of the table is based on the conducted literature search.

Table 3.2: Characteristics of Preparedness and Responsiveness

	Preparedness	**Responsiveness**
Time period	Before crisis	At the beginning of crisis, first response
Time Window	Long-Term	Short-Term
Supply Strategies & Recommended Actions	• Preparing Crisis Frameworks • Diverse Supplier Frameworks • Higher domestic production base • Stockpiling	• Collaboration with Other Sectors and Health Systems • ”Ramping up” Domestic Production • Loaning Equipment • Focus on Innovation • Increasing purchases from world market • Using Direct Awards

3.3. Modelling of Strategies to Provide Sufficient PPE & Ventilators during Crises in the Context of the Applied Literature Search

The provision of PPE and ventilators during health-related crises is a complex problem for health systems. Simulation modelling is a valuable method to solve complex problems like the provision of PPE and ventilators for health systems. According to Means et al. (2020), simulation and modelling is one building block to strengthen crisis responses, among others such as process mapping, micro-planning, or stakeholder engagement. The results of simulation modelling research can be used to inform decision-makers about their possible actions (Koonin et al., 2020). However, simulation modelling should not be underestimated when discussing preparation for health-related crises. Modelling the depletion of stockpiles can inform decision-makers about potential needs in a future crisis. Furthermore, modelling can be used to develop decision frameworks. Even though health-related crises are unlikely to happen, health systems need to be prepared for such to fulfil their primary purpose. In order to test their preparedness, health systems can conduct real-life exercises with different stakeholders. Such exercises allow testing parts of the system but not the entire system. Simulation modelling can be used to forecast needs, the depletion of stockpiles, and other purposes.

The following section focuses on the previous modelling and simulation work conducted by researchers in this literature search. Literature and reports found via this search were included in this review. An additional search focused on modelling was not conducted, as these search terms provided a good overview of the modelling techniques applied regarding the supply strategies of PPE and ventilators in times of a health-related crisis. The work in this chapter critically assesses literature about the modelling of procurement processes for PPE and ventilators, simulation modelling of stockpiling, and the modelling of estimated needs.

3.3.1. Modelling of Procurement Strategies

In response to COVID-19, procurement strategies and their outcomes have been given more attention in academic research, as they were relevant for health systems during the start of COVID-19. So far, frameworks to improve procurement processes and identify issues in the procurement process have focused on research regarding procurement strategies. For instance, Handfield et al. (2020) researched how procurement processes have developed over time and developed a framework that positions procurement in the supply chain. The game theory research conducted by Salarpour and Nagurney (2021) does not focus directly on procurement processes but the competition between governments for products. Their research results indicate that the ability to adapt processes during a crisis significantly impacts meeting the demand for N95 respirators. Simulation modelling has not been a focus of the research. Furthermore, research and strategies applied by governments focus on how procurement can be accelerated. Simulation modelling could be applied to identify the role of time in procurement processes.

3.3.2. Modelling of Stockpiling & Distribution Strategies

As explained in section 3.2.2.1, stockpiling is a solution for health systems to prepare for a health-related crisis. Stockpiles can be used to store PPE and ventilators. In the past, simulation modelling work has been conducted by researchers regarding the stockpiling of PPE and ventilators. The stockpiling of ventilators has been a topic of interest before COVID-19, whereas the optimal stockpiling of PPE became a topic of interest with COVID-19. The objectives of such models have been to minimize costs and maximize the number of products stored.

Simulation modelling work regarding stockpiling has focused on different issues and levels. Stockpiling is an issue in hospitals, on a local and a national level. For instance, Abramovich et al. (2017) focused on the allocation of hospital beds at a hospital level, and Huang et al. (2017) compared different storage options on a state level considering a range of scenarios, including an allocation framework. Chen et al. (2017) focused on developing a PPE stockpiling framework to maintain a minimum stockpile while meeting the demand for PPE. On the other hand, Mehrotra et al. (2020) researched how sharing stockpiled ventilators can help to mitigate shortages using a stochastic optimization model. Real-time needs were considered in some research to decrease the uncertainty regarding future needs. Another important topic for stockpiling research is the optimal distribution of medical products and the optimal scheduling of orders among health care facilities. Abedrabboh et al. (2021) points out that optimized distribution strategies can help to develop proper management strategies on a national level for health systems.

3.3.3. Estimation of needs

COVID-19 caused the development of a wide range of tools that can be used to estimate the use of PPE and other resources used in hospitals. The developed tools have different aims. Whereas some tools aim to calculate the burn rate of medical equipment (CDC, 2021), other tools aim to make accurate predictions for the future use of PPE and ventilators (Chertok et al., 2021; Kam et al., 2021; Locey et al., 2021; Meltzer et al., 2015; Pfenninger & Kaisers, 2020; WHO, 2022). The developed tools mainly focused on the need for PPE or ventilators for hospitals and were not designed to be used locally or nationally.

Predictions are based on different factors, for instance, the number of patients in a hospital ward, the COVID-19 epidemiology, institutional parameters, or the rate of reusing PPE. Hence, tools can be used in a country-specific context. One of the organizations developing a country-specific tool to estimate PPE use was the WHO. The developed tools can make prediction based on past data and/or different scenarios (Barrett et al., 2020; Cupp & Predmore, 2020; Meltzer et al., 2015). Kam et al. (2021) points out that the accuracy of estimations improves with more data available.

Since estimations are needed by health systems during a health-related crisis, and the tools need to be applicable for different settings. Estimation tools developed by organizations like the WHO or CDC are easily applicable spreadsheet models. On the other hand, models developed by Chertok et al. (2021), Cupp and Predmore (2020), and Mosallanezhad et al. (2021) are more sophisticated as they include forecasting or planning mechanisms. The objective of such models is to minimize shortages and total costs.

research about the estimation of needs for suppliers of PPE and ventilators is limited. Daniele and Sciacca (2021) and Paul and Chowdhury (2020), for instance, developed an optimization model that aims to satisfy the quickly arising demand of PPE. Simulation modelling research by Salama and McGarvey (2021) aims to identify what a resilient supply chain looks like for suppliers. They also point out that the supply chains for socially critical products like ventilators are different from regular supply chains. On the other hand, Li et al. (2021) takes a more ”outside perspective”, as they analyzed the interaction between COVID-19 as a supply chain disruption and the COVID-19 dynamics to find out how to better balance pandemic control and economic losses.

3.3.4. Identified Simulation Modelling Knowledge Gaps in the Applied Literature Search

Simulation modelling can be seen as a building block for decision-makers in health systems to make informed decisions regarding the stockpiling, procurement, and planned use of PPE and ventilators. Hence, simulation modelling can be a valuable tool for preparedness and response to health-related crises. Research about simulation modelling is rich regarding stockpiling of PPE and ventilators and when it comes to the estimation of its needs. On the other hand, simulation modelling work was limited to the procurement processes of health systems during health-related crises. That may be because procurement processes are an administrative task and are not seen as relevant for modelling research. The objectives for stockpile modelling or the estimation of needs are minimizing shortages of PPE and ventilators, minimizing costs for health systems, and achieving an optimal distribution. Furthermore, data collection can help to improve the accuracy of the forecasted need for PPE and ventilators Kam et al. (2021). It stands out that research regarding the optimization of stockpiling was already a topic of interest before COVID-19. In contrast, the amount of research regarding the estimation of needs has increased since COVID-19 tremendously. The estimation of needs often focuses on a hospital/local level, as procurement processes of PPE are not centralized in many countries. Furthermore, it was essential to researchers that their results/frameworks are applicable and easy to use for practitioners in health care organizations and systems. Modelling research focusing on suppliers' points of view was mainly interested in how suppliers can meet the increasing demand under the given disruptive circumstances.

A critical question to raise regarding modelling research is: Whom are you modelling for? Almost all research mentioned in this chapter focuses on the needs of health systems at different levels, and little research focuses on the suppliers of PPE or ventilators. Furthermore, it stands out that most of the current research does not focus on a whole system perspective but focuses in more detail on specific parts of the system. This means that the current research focuses on different components of the provision or demand for PPE and ventilators, for instance, *stockpiling* or *distribution*, but the combination of different steps is limited. The combination of these components is specifically relevant for health systems. They need to decide how to diminish the shortage of PPE and ventilators, taking into account all parts of the system and the interactions between the different parts of the system. Given the conducted literature search, no simulation modelling research is present that combines procurement processes, stockpiling, distribution, and forecasting of PPE and ventilator usage, as well as the modelling of the supplier side of PPE and ventilators. Hence, a knowledge gap is present in that regard that is relevant to be filled for decision-makers in national health systems.

3.4. Summary of the Literature Search

The literature search's objectives were to analyze the effect of preparedness and responsiveness on the availability of critical medical supplies in health systems, identify countries' strategies to prepare and respond to provide sufficient PPE and ventilators and identify knowledge gaps in simulation modelling literature about the provision and use of PPE and ventilators. Hence, this literature search helped to answer the following sub-research question:

How do responsiveness and preparedness of health systems affect the availability of critical medical supplies during a health-related crisis?

The literature search results suggest that responsiveness and preparedness jointly contribute to the resilience of health systems. It is essential to realize that preparedness can be considered a prerequisite for the responsiveness of a health system.

Concerning the availability of critical medical supplies, preparedness includes stockpiling as a supply strategy and various frameworks/policy recommendations that can be implemented to improve the responsiveness of health systems in times of crisis. On the other hand, responsiveness entails supply strategies that can be applied to increase the availability of critical medical supplies by either starting to purchase or produce medical supplies. The characteristics of the relevant supply strategies can be used as an input for the development of the SD model in Chapter 4.

The second part of this literature helped identify current gaps in the modelling literature in the context of this literature search. It was evident that current modelling and simulation work did not focus on the combination of procurement processes, stockpiling, distribution, and forecasting of PPE and ventilator usage, as well as the modelling of the supplier side of PPE and ventilators. Hence, a knowledge gap is present in that regard that is relevant to be filled for decision-makers in national health systems.

4
Model Description

The content of this chapter concentrates on the description of the model, its essential assumptions and relationships, and the setup used to analyze the uncertainties within the system. The created SD model aims to be helpful to investigate the effect of different supply strategies on the availability of PPE and ventilators during crises.

4.1. Overview of System

The developed SD model focuses on supply strategies used by the English health system to organize PPE and ventilators for the arising demand in hospitals at the beginning of a health-related crisis similar to COVID-19. It aims to aid decision-makers in providing an overview of the effectiveness of available supply strategies. The effectiveness of the combination of supply strategies, of a policy, is measured by reporting its normalized shortage of critical medical supplies. In their decision-making, actors also need to consider costs. However, they were of a lower priority during Coivd-19 and were not considered as an outcome of interest (National Audit Office, 2020a). The English health system was chosen as a case, as it acted similarly to health systems in the Global North and experienced a shortage of PPE with 126 deaths and more than 8000 COVID-19 cases among HCWs according to employers (Iqbal & Chaudhuri, 2020; Mantelakis et al., 2021; National Audit Office, 2020b). Furthermore, the actions of the English health systems to organize PPE and ventilators were investigated by National Audit Office (2020a, 2020b, 2021). Hence, the information by these reports were used for the model development. It was assumed that the information presented applied to the English health system. The SD model focuses on England rather than the UK, as regions in the UK acted independently.

The causal loop diagram (CLD) in Figure 4.1 captures the most critical components of the model and helps to grasp the relationships between the variables within a system. Arrows with (+) or (-) indicate the nature of the relationship. Furthermore, the CLD highlights the feedback loops in a system, which either balance or reinforce the behaviour over time. Based on the CLD in Figure 4.1, one could follow the following train of thought to explain the behaviour of the system.

As COVID-19 spreads throughout the population, the pressure on hospitals and the demand for PPE and ventilators increases. A shortage of PPE and ventilators can appear if the demand for critical medical supplies (CMS) exceeds its supply. To counteract a future lack of CMS, decision-makers can order CMS with or set up various supply strategies: they can purchase CMS from the world market or through direct tender, reach out to companies to adapt their production to assemble CMS, support innovative supply strategies or loan ventilators from the private sector (National Audit Office, 2020a, 2020b, 2021). Decision-makers can decide about the combination of supply strategies to apply. How many CMS end up reaching England depends on factors affecting the success of a supply strategy, such as export restrictions or the risk of unusable products being delivered. As more CMS are provided, the shortage of CMS decreases in England, causing fewer orders to be placed.

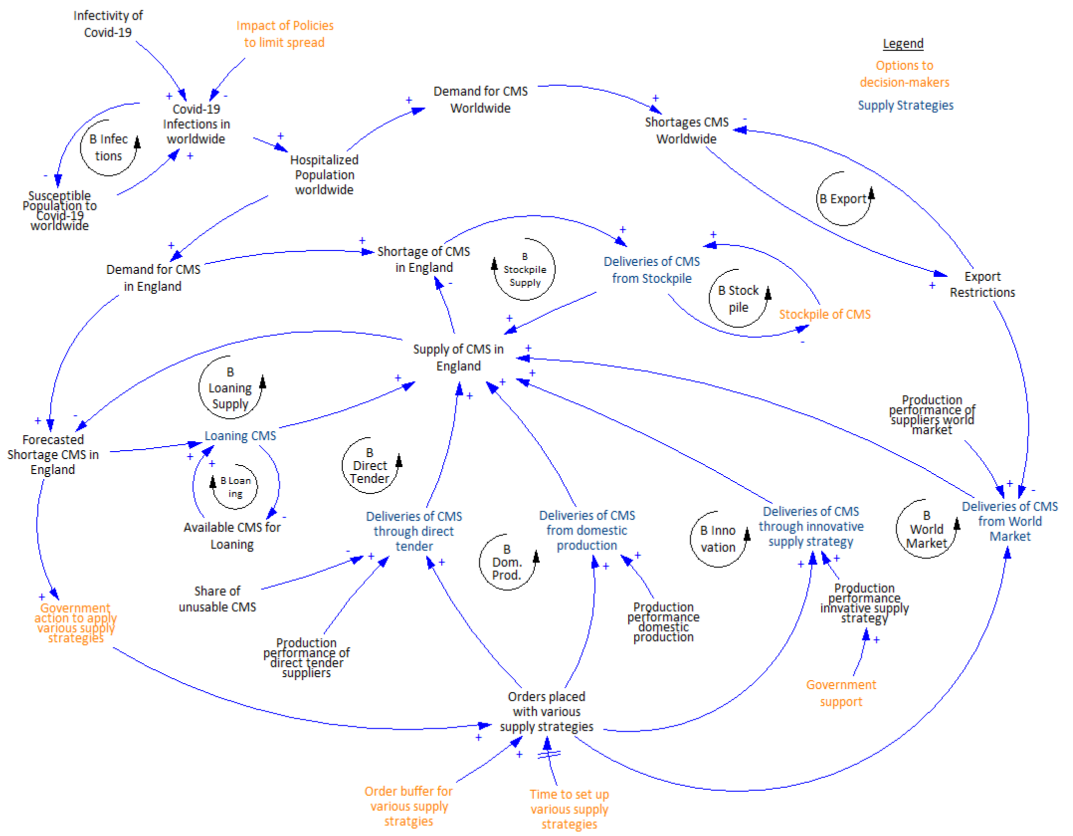


Figure 4.1: Causal Loop Diagram focusing on the impact of supply strategies on shortage of CMS in England.

4.2. Focusing on Sub-Systems and Underlying Assumptions

To effectively analyze the developed SD model, it is critical to understand structures and choices during the modelling process. The following sections point out essential aspects of a virus outbreak like COVID-19, how shortages and demands are forecasted, relevant differences between supply strategies of interest in the system, and how decision-makers can decide to place orders. Appendix B and Appendix C provide further details about the model structure and used parameters.

4.2.1. Modelling COVID-19 as an SEIR Model

As mentioned in Section 2.4, an SEIR model structure is useful to model the transmission of infectious diseases such as COVID-19. To model the spread of COVID-19 and report the hospitalized population, additional stocks to Susceptible, Exposed, Infected and Recovered are needed as highlighted in Figure 4.2. Once a person is exposed to COVID-19 through the close contact an with infectious person - asymptomatic, symptomatic, or pre-infectious, they can develop a *symptomatic* or *asymptomatic* infection (WHO, 2021c). Symptomatic infections are characterized by dry cough, fever, and fatigue along with other complaints in non-severe cases WHO (2021c). People infected asymptomatically can still infect others. COVID-19 pressures the capacities of health systems, as 15% of infected people require oxygen treatment and around 5% become critically ill and require intensive care treatment.

As COVID-19 pressured health systems, the number of available ICUs and hospital wards decreased with a higher number of infections. The model assumes that patients can be declined from being admitted to an ICU or regular ward if no beds are available. In that case, they are either sent home or stay in general hospital wards. The number of available ICUs can increase through additionally purchased ventilators. The choice was made to exclude arsing HCW shortages due to COVID-19 as this SD model focuses on PPE demand for HCWs, assuming that they can serve all admitted patients.

Worldwide, governments introduced measures to limit the spread of the virus. Such measures can include quarantine and self-isolation guidelines, different levels of lockdowns, as well as contract tracing systems (WHO, 2021b). Rules and restrictions differed among countries. For simplicity, it is assumed that the same contact restrictions are applied worldwide once COVID-19 spreads. Furthermore, it is assumed that approximately 80% of infected people followed the call to self-isolate (Steens et al., 2020). Many countries applied contact tracing to identify asymptomatic or pre-symptomatic infections (Kretzschmar et al., 2020). In the context of this model, it is assumed that contact tracing has almost no impact due to its use of resources.

The assumptions and data used to model the spread of COVID-19 can be found in Table C.1.

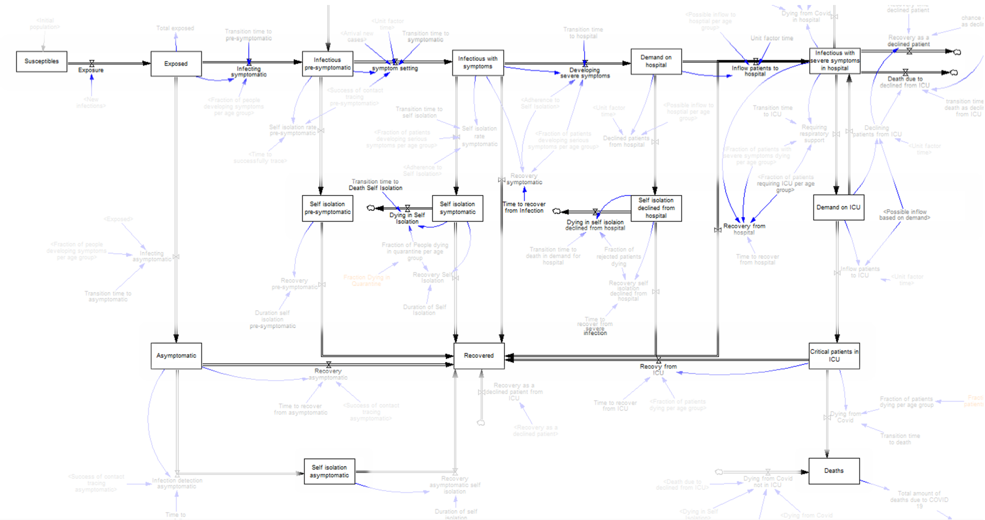


Figure 4.2: Relevant stocks in the SEIR Model to represent a health-related crisis like COVID-19

4.2.2. Demand for PPE and ventilators

As Figure 4.1 shows, the hospitalized population affects the demand for CMS. If more people are admitted to ICU or general wards, the need for CMS increases. The CMS considered in this model are gloves, simple face masks, respirators, gowns, eye protection, and ventilators for ICUs.

To estimate the demand for different PPE, the usage assumptions developed by Johns Hopkins Center for Health Security (2020) were considered (Table C.4). The number of declined persons from intensive care was considered for the demand estimation for ventilators. The number of declined persons decreases with the arrival of new ventilators.

To forecast the PPE and ventilator shortage, it is necessary to forecast their demand. In this system, the forecasted demand for PPE and ventilators builds upon the derivative of their current demand. In reality, estimations were also based on possible outcomes of infection models (National Audit Office, 2020a). Decision-makers can choose the forecast horizon for the forecasted demand. With a higher forecast horizon, the forecast's accuracy decreases as less knowledge is available for the far future.

4.2.3. Supply Strategies of PPE and Ventilators

Like 3.2.2 shows health systems can apply a range of supply strategies to diminish the shortage of PPE and ventilators. In England, the Department for Health& Social Care, the Department for International Trade, the Foreign Commonwealth Office, and the Ministry of Housing, Communities & Local Governments collaborated to increase medical equipment as quick as possible (National Audit Office, 2021). Their actions to organize additional PPE and ventilators served as assumptions for this model.

In that process, decision-makers need to consider that PPE and ventilator supply chains differ, as ventilator supply chains are more complicated than PPE supply chains (Kliff et al., 2020). Furthermore, ventilators are complex to purchase as they are usually made-to-order, and the production is time-intensive (National Audit Office, 2020a). Hence, lower production capacities and a more extended period to set up production facilities are considered for ventilators to implement the differences between PPE and ventilator supply chains.

The coming subsection defines the characteristics and highlights the differences between supply strategies for PPE and ventilators applied in the context of the Global North (and highlighted in blue in the CLD in Figure 4.1). Table 4.1 and Table 4.2 provide an overview of each supply strategy, including their definition, information about the production capacity, shipment times, vulnerabilities, and the influence of decision-makers on the supply strategies. The latter is further explained in Section 4.2.4.Detailed information about the variables can be found in Table E.4 and Table E.5.

Table 4.1: Relevant characteristics of the supply strategies domestic production, innovation, and loaning critical medical supplies.

	Domestic Production	**Innovative Supply Strategy**	**Loaning Critical Medical Supplies**
Definition	Decision-makers reached out to companies to start the production of critical medical supplies (National Audit Office, 2020b).	Individuals or companies produce critical medical supplies in small batches, such as highlighted in the article by Pagliacolo and Pavka (2020).	Decision-makers can loan critical medical supplies from other sectors if they fit in the context. In England limited to ventilators from private medical sector (National Audit Office, 2020a).
Production Capacity	Assumption that production capacity equals 60% of suppliers reached through direct tender for PPE. Concerning ventilators, "ventilator challenge" in England is used as a base (National Audit Office, 2020a). The initial production capacity is 0 and increases over time.	Production capacity is small per project and increases over time as more products are approved. Assumptions based on information about single projects (Dixon, 2020; Pagliacolo & Pavka, 2020) or on information on the "ventilator challenge" (National Audit Office, 2020a).	Limited to the availability of critical medical supplies in other sectors. In England, 1200 ventilators were loaned private medical sector (National Audit Office, 2020a).
Shipment Time	Shipment within 5 days. Based on information about PPE delivery times by the Department of Health and Social Care (2020)	Shipment within 5 days	Shipment within 5 days
Input of Decision-Makers	Set-up time Order Buffer	Set-up time Government support Order buffer	Set-up time

Table 4.2: Relevant characteristics of the supply strategies direct tender, purchasing products from the world market, and stockpiling.

	Direct Tender	**Purchasing Critical Medical from World Market**	**Stockpiling**
Definition	Decision-makers can place orders with suppliers using accelerated processes and without competition (National Audit Office, 2020b).	Decision-makers can order products from suppliers from the world market. The English health system is in competition with other health systems (National Audit Office, 2020b).	Decision-makers can implement and operate stockpiles with critical medical supplies. In England, Public Health England created a PPE stockpile designed for an influenza (National Audit Office, 2020b) .
Production Capacity	Assumption that production capacity equals 5% of production capacity of suppliers reached through world market. Production capacity can be increased with increasing demand (IFC, 2020).	Highest production capacity compared to other supply strategies. Production capacity is based on sources where possible. Production capacity can be increased with increasing demand (IFC, 2020).	Limited to the inventory stored in the stockpile. Initial values were derived from (National Audit Office, 2020b).
Shipment Time	Shipment time is assumed to be 1.5 months, varies between 1 and 3 months (Gandrup-Marino et al., 2021).	Usual shipment time between 3 weeks. During height of COVID-19, shipment times of up to 9 months (Gandrup-Marino et al., 2021).	Shipment within 5 days (Department of Health and Social Care, 2020).
Vulnerability	Share of unusable critical medical supplies purchased(National Audit Office, 2020b).	Export restrictions Delayed shipment times (National Audit Office, 2020b)	
Input of Decision-Makers	Set-up time Order buffer	Set-up time Order Buffer	Equipment of stockpile Operations of stockpile

Critical medical supplies can be purchased through *domestic production*. To quickly build up production capacities, decision-makers reached out to businesses to adapt their production lines (National Audit Office, 2020b). Since the businesses do not produce such products regularly, the maximum production capacity is assumed to be lower than the production capacity of direct tender suppliers and is assumed to increase over time.

Additionally, the government support the development of *innovative supply strategies* (Bhaskar et al., 2020; Dubey et al., 2021; OECD, 2020c). It is assumed that factors affecting the success of innovative products include the perceived urgency and the ability to reach people to develop innovations. The development time of products takes time, but urgency can decrease this time. Decision-makers in England decided to focus less on innovative solutions for PPE (National Audit Office, 2020b). They conducted a challenge for businesses to increase the domestic production of ventilators (National Audit Office, 2020a), which is assumed to be an innovation example as well.

Stockpiling provides health systems with the chance to respond quickly during a crisis, as they exhibit, together with domestic production and innovation, the shortest shipment times. The preparedness of a stockpile depends on the quality of maintenance, the stored products, and the operations within warehouses (e.g. preparing deliveries), as the report and research by Boiko et al. (2020) and National Audit Office (2020b) show. Hence, the maintenance of the products was modelled, and delays were implemented to model insufficient operations within a stockpile. In the UK, only PPE was stockpiled. In contrast, *loaning products* from other sectors, such as the private sector, was only possible for ventilators (National Audit Office, 2020a; OECD, 2020c).

To respond to COVID-19, health systems purchased critical medical supplies using *direct tender*, where decision-makers accelerated procurement processes (Cabinet Office UK, 2020b). This leads to a higher risk of ordering unusable products as actors may choose to purchase products from unknown suppliers without checking (Boiko et al., 2020; McKee, 2020; Sodhi et al., 2021). An assumed advantage of purchasing products through direct tender is its high production capacity, the second-highest among the supply strategies. Shipment times are assumed to be lower compared to purchasing products from the world market, as products are transported via air freight (Harvey, 2020).

Concerning the production capacity *purchasing products on the world market* is the most promising, but its performance is affected export restrictions (Bradsher & Alderman, 2020; "Germany bans export of medical protection gear due to coronavirus", 2020; National Audit Office, 2020b) and delayed deliveries by several months (Gandrup-Marino et al., 2021). To represent the competition between countries, it is assumed that a country's purchasing power depends on its GDP. This assumption may misrepresent the situation of some countries, as the GDP does not capture health spending (Kapoor & Debroy, 2019). Compared to purchasing supplies through direct tender, it is assumed that the set-up time takes longer.

After the PPEs' and ventilators' delivery, it is relevant to review them. Hence, it is assumed that all products are checked and then delivered to hospitals. No delay is assumed to present in the delivery to hospitals, as the model considers a shipment time with each supply strategy. Furthermore, it is assumed that products can be stored until needed.

4.2.4. Decision Framework

Before critical medical supplies can be delivered, they need to be ordered by decision-makers. The variables highlighted in orange Figure 4.1 indicate where decision-makers can act. It is assumed that decision-makers can decide which supply strategies to apply, the order date and order size. Like, in the English health system, procurement activities are assumed to be centralized.

It is assumed that decision-makers can decide which supply strategies they would like to deploy and which incoming orders of supply strategies to consider. When incoming orders of a specific supply strategy are considered, it leads to placing fewer orders earlier. If decision-makers decide to focus on a particular supply strategy, they have the chance to give a higher priority to this supply strategy by increasing the order buffer. In this way, more orders are placed with a specific supply strategy.

To determine when orders are applied, the forecasted demand for PPE and ventilators is compared to the deliveries of PPE and ventilators per day. If the difference exceeds a certain threshold, for instance, a stock of seven days to serve COVID-19 patients, orders are placed. Since the products' delivery and the point of time of the delivery is uncertain (National Audit Office, 2020a), not yet delivered supplies are not considered when new orders are placed.

The order size equals the difference between the forecasted demand for that day and the deliveries incoming on that day. Hence, the forecasted shortage equals the forecasted demand minus the deliveries on the day the forecast is made. Decision-makers stop placing orders once the forecasted shortage does not exceed the threshold. Furthermore, orders can be placed every day since decision maskers in England ordered as many products as possible (National Audit Office, 2021). The stockpile for PPE can be depleted at all times.

4.3. Implementation of Policies

The following subsection focuses on implementing different supply policies decision-makers can apply to decrease the shortage of PPE and ventilators. A policy consists of a combination of supply strategies, decisions regarding the forecast type, the threshold to order PPE, the time it takes to set up a policy and the state of the equipment and operation of the PPE and ventilator stockpile.

Four different policies were developed to explore their impact on the shortage of ventilators and PPE. The developed policies have different focus points and aim to represent the preparedness spectrum and focus on domestic production and innovative solutions versus purchasing products from the world market. Figure 4.3 presents an overview of the suggested policies. Further details about each policy can be found in Appendix D.

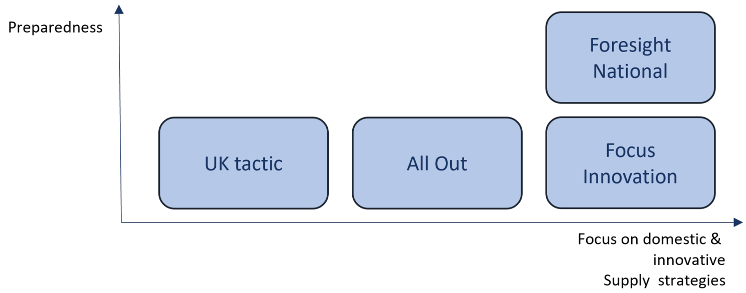


Figure 4.3: Overview of policies on spectrum preparedness and focus on innovative and domestic supply strategies

The policy *"UK tactic"* aims to represent the tactic taken by the English health system, as they prioritized purchasing PPE and ventilators through direct tender and from the world market. PPE was depleted from the stockpile as shortages arose. A stockpile for ventilators was not in place. Ventilators were loaned from other sectors. The domestic production of ventilators of PPE and ventilators is applied with a lower priority. The innovative strategy is not applied for PPE and has a lower priority for ventilators. Furthermore, the English health system decided to produce ventilators and PPE domestically.

Compared to the policy "UK tactic", the policy *"AllOut"* aims to represent the tactic of a health system that is unprepared and acts without thinking. Hence, decision-makers apply all available supply strategies without prioritizing one over another. The stockpile is in the same state as the " UK tactic policy".

The policy *"Focus Innovation"* prioritizes the innovative supply strategies the most among the suggested policies. Additionally, PPE is depleted from a national stockpile, and ventilators are loaned from other sectors. Furthermore, they focus on producing PPE and ventilators domestically as a higher priority. The lowest priority is to purchase products on the world market or through direct tendering.

In contrast, the policy *"Foresight National"* implements a stockpile for all PPE and ventilators, with a 150% of the recommended value. Furthermore, the stockpile's logistics are faster. Similarly to "Focus Innovation", decision-makers focus on domestic production and support innovative suppliers more than on purchasing products through direct tender and from the world market. Additionally, decision-makers consider a higher forecast horizon and a lower threshold to order products.

4.4. Model Settings

To build and simulate the created System Dynamics model, the software *Vensim DSS* was used. The model is run for 210 days. This timeframe was appropriate as it allows to model an entire wave of infections, the resulting demand for PPE and ventilators, and incoming supplies. Furthermore, a longer time frame is not used as it focuses on the preparedness and responsiveness of health systems to a pandemic. The most minor time step (0.0078125) is chosen to achieve the most accurate results, and the integration method is Euler as IF THEN ELSE statements are included in the model.

4.5. Model Verification & Model Validation

Before a model can be validated, the model needs to be verified. During the verification process, the modeller answers the question: "Is the model correctly?". Answering this question helps to identify any errors and to check whether the created model represents the conceptual model (Balci, 2013). This process takes place during model building. In the case of this master thesis, I verified the created

Vensim model as no errors were identified with the option model check, and it contains the outcomes and structures of interest.

The model validation process, on the other hand, focuses on building confidence in the usefulness of the developed model (Forrester & Senge, 1980). During the model validation process, the researcher aims to answer the question: ”is the model consistent with the slice of reality it tries to capture?” (Richardson & Pugh, 1994). The model aims to depict the difference between PPE and ventilator demand resulting from a health-related crisis and the supply that can be organized. It aims to aid decision-makers in selecting supply strategies available for PPE and ventilators. To increase the confidence in a system dynamics model, model structure and model behaviour tests are commonly used (Forrester & Senge, 1980). According to Forrester and Senge (1980), model structure tests focus on comparing the model structure to the real system. In contrast, model behaviour tests focus on comparing the model to the behaviour of the real system. Where applicable, the impact of EMA is considered for the conducted validation tests.

Based on the suggestion regarding validation testing by Forrester and Senge (1980), the following model structure tests were applied:

- Structure verification test
- Parameter verification test
- Extreme conditions test
- Boundary adequacy structure test
- Dimensional consistency test

To increase the confidence in the model behaviour and policy implications, a behaviour reproduction and anomaly test was conducted. Sensitivity tests were not explicitly considered as the open exploration in the EMA can be seen as a sensitivity test.

The goal of the structure verification test is to compare the structure of the model with the structure of the system in the real world (Forrester & Senge, 1980). An SEIR model was used to represent the spread of COVID-19, which is suitable as other modellers have used it to model the spread of COVID-19 and other infectious diseases. Furthermore, the different supply chains, including capacities and shipment times, were implemented in the model. Order backlogs were created to represent reality, so orders are delivered once enough stock is available. To illustrate the competition in the world market, the purchasing power of the UK and other countries depends on the GDP of a nation. Using the GDP as a metric may misrepresent some countries, as GDP does not reflect the inequality within countries (Kapoor & Debroy, 2019), but provides a good picture of the overall situation. Next to the model structure, parameters can be verified. Parameters are where possible and when data was available based on sources (see Appendix C), and uncertain parameters were considered as they could be insightful for the EMA. As the performance of the supply chains is specifically uncertain, a broad range of uncertainties was considered here.

Another way to test the model structure is testing its behaviour under extreme conditions. First, the infectivity of the virus is set to its extreme values, 0 and 1. If the infectivity equals 0 and the arrival of new cases is set to 0, the virus does not spread across the community, and no shortage of products occurs. If the infectivity equals 1, not enough ventilators are available to serve declined patients. Once enough ventilators arrive, the shortage of ventilators can be diminished in Figure 4.4. Similarly, the shortage of PPE reaches its maximum at an earlier point in time. It decreases gradually as deliveries with longer shipment times and set up times arrive in Figure 4.5. The initial experiments conducted with the EMA workbench also can be seen as extreme conditions tests, as the uncertainties considered in the model are very broad (Auping, 2018). The model also tests if the outcomes are logical given the wide range of uncertainties.

Furthermore, a boundary adequacy structure test is conducted. This test determines whether the model includes all necessary structures (Forrester & Senge, 1980). A hypothesis related to the proposed model structure is developed to carry out this test. A competing model structure for a stable population

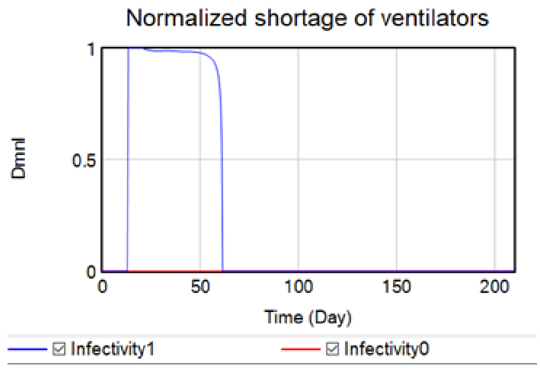


Figure 4.4: Extreme condition test: Shortage of ventilators if infectivity = 1 or 0

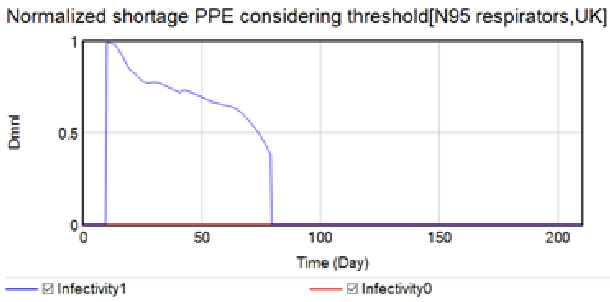


Figure 4.5: Extreme condition test: Shortage of N95 respirators if infectivity = 1 or 0

is implemented. The proposed population model includes the birth and death rates over the simulation. The proposed model structure does not return possible values as the susceptible fraction of the population exceeds one at some points. Hence, using the initial population for this simulation is preferred over using a non-constant population structure. Furthermore, the open exploration showed that the most critical uncertainties were included in the model. The open exploration can give insight into whether the most relevant perspectives were included (Auping, 2018). Additionally, a unit check is conducted to check whether the dimensions used in the model are consistent, which was the case.

To test the model behaviour, a behaviour reproduction test and a behaviour anomaly test are conducted. The behaviour reproduction test shows that the model at hand generates the same problems as in the real world. A shortage of PPE arises with the spread of COVID-19. In the base run of the simulation, patients were declined from ICUs, which was not the case in reality. A probable reason for this difference is that the public behaviour and the impact of policies regarding contact restrictions are simplified. The behaviour anomaly test asks the modeller to explain certain assumptions (Forrester & Senge, 1980). In the model development, DELAY FIXED functions were used to model the delay regarding the placement of orders over other delay functions. Other delay functions reduced the number of orders placed but did not delay them far enough. Furthermore, the choice was made to calculate the forecasted demand for PPE and ventilators based on the derivative of the current demand. This choice was made over using the Vensim built-in function FORECAST, as the latter returns less accurate values. The open exploration in EMA also contributes to the validity of this test as it shows whether different future scenarios are plausible (Auping, 2018).

As the results of the conducted tests show the model passes the model behaviour and structure tests. Based on the conducted validation tests throughout the modelling process, the confidence in the model's usefulness is increased.

4.6. Uncertainties, Decision levers, and Outcomes for Exploratory Modelling and Analysis

During crises, all systems in society, including the health system, have to act in a context of radical uncertainty (Allain-Dupré et al., 2020). Gifford et al. (2021) points out that health care organizations operate in complex, uncertain environments that intensified with COVID-19. Material resources contribute to these uncertainties. The supply of PPE and ventilators was disrupted by COVID-19, leading to an increasing uncertainty around the performance of supply chains. The sensitivity analysis showed that changing parameter values could significantly impact the outcomes. Hence, it is essential to identify to what extent different variables, uncertainties, and decision levers, can affect the shortage of ventilators and PPE. This section focuses on the definition of uncertainties, decision levers and the outcomes of interest that are the input for the *directed search* of the MORDM.

4.6.1. Outcomes of Interest

As the research question and the content of this master thesis indicate, the outcome of interest for this system is to minimize the shortage/maximize the coverage of ventilators and PPE. The outcome of interest can be formulated as the coverage per day or the total coverage cumulated over the simulation run. For the analysis, it is appropriate to choose the *total coverage of PPE or ventilators* as an outcome of interest, as it can be formulated as a scalar outcome. The disadvantage of choosing only this outcome is that the behaviour cannot be investigated over time. Hence, other outcomes were included where computational resources allowed it. These outcomes were reported as time series outcomes and included the normalized shortages of PPE or ventilators, total costs or the supply ready to be shipped. An overview of the outcomes of interest can be found in Table E.1.

4.6.2. Relevant Decision Levers

The literature search and the developed SD model revealed that decision-makers have different levers available to mobilize the organization of PPE and ventilators. The suggested policies presented in section 4.3 demonstrate already which possibilities exist, such as implementing a particular supply strategy, prioritizing specific supply strategies, or changing the composition or logistics of the stockpile. Furthermore, decision-makers can change procurement or supplier frameworks to decrease the set-up times of different supply strategies. It is necessary to mention that the range of values considered for the decision levers is possible but necessarily realistic. The goal is to identify the characteristics of a policy rather than the exact value in this work; therefore, it is reasonable to choose more extreme ranges for possibilities. An overview of decision levers regarding the provision of PPE and ventilators is shown in Table 4.3, a detailed description of decision levers can be found in Tables E.2 and E.3.

Table 4.3: Overview of decision levers

Decision levers	Definition
Switches for supply strategies	These variables determine whether a supply strategy is applied or not. Stockpiles are assumed to be always in place
Order buffers for supply strategies	Order buffers are applicable to supply strategies, excluding stockpiling PPE or ventilators. Order buffers determine to what extent a supply strategy is prioritized. Higher-order buffers trigger higher-order sizes.
Set-up times for supply strategies	Set-up times determine how quickly orders can be placed with a specific supply strategy. Set-up times are not considered for stockpiles. More effective procurement and supplier frameworks can reduce the set-up times for supply strategies.
The effectiveness of innovative supply strategies	Decision levers in this category affects the impact of the supply strategy innovation. Levers in this category include, for instance, government support.

The composition and operation of stockpile	Decision levers in this category focus on the logistics of the stockpile and its equipment.
Operational levers	In the developed system, it is assumed that products are stored centrally before being delivered. These variables focus on the effectiveness of these processes.
Levers affecting forecast and order point	Levers in this category include the forecast horizon and the threshold value to order PPE.

4.6.3. Uncertainties Affecting the System

Throughout this research, it became apparent that the values of parameters used to describe the performance of different supply strategies were often challenging to identify. Hence, parameters regarding the production capacity of PPE and ventilators are uncertain. Furthermore, uncertainties regarding supply chains are apparent during crises causing export restrictions or delayed shipment times. Additionally, the knowledge about the crisis may not be complete initially. Variables like the infectivity of COVID-19 are uncertain. All these uncertainties need to be considered in the MORDM cycle and for the outcome of this work. A summary of the most critical uncertainties for PPE and ventilators can be found in Table 4.4. All uncertainties considered for the analysis of ventilators, simple masks, and gloves with assumed values can be found in the appendix in the tables E.4 and E.5.

Table 4.4: Overview of uncertainties

Category	Uncertainty	Source
Supply Chain	Base raw material & production capacity for PPE and ventilators Increase in production capacity over time for PPE and ventilators	Assumptions made based on sources where possible. For instance, information by HisoMedical (2020), IFC (2020), OCED (2020), and Pagliacolo and Pavka (2020)
Supply Chain Disruption	Shipment times Export Restrictions Delays in the production & procurement of products	Gandrup-Marino et al. (2021) and National Audit Office (2020b)
Crisis	Infectivity	Madewell et al. (2020) and Qiu et al. (2021)

4.7. Experimental Design for EMA workbench analysis

The following section focuses on the experimental design used to analyze the suggested policies and uncertainties within the system with the EMA workbench. The experimental design follows the MORDM structure introduced in 2.5.

First, an *open exploration* was conducted. On the one hand, the open exploration aims to help understand the model behaviour and was part of the validation process. On the other hand, the open exploration helped to identify the potential impact of the suggested policies in Section 4.3. The four suggested policies were tested over 800 scenarios resulting in 3200 experiments considering the uncertainties. The behaviour of the open exploration was explored using different kinds of visual analyses. Additionally, the worst-case scenarios for PPE products and ventilators were identified. The worst-case scenarios were different among PPE. Due to computational and time resources, only two PPE products (with the same worst-case scenario) and ventilators were considered in the directed search.

For the directed search, the uncertainties, outcomes, and decision levers needed to be formulated, as shown in section Section 4.6. Only uncertainties relevant to the directed search of PPE products or ventilators were included to reduce the number of uncertainties. Other PPE than gloves and simple masks were still considered. Furthermore, the decision framework, which determines the point of order, was adapted in the Vensim model to decrease the number of orders in the long term as it did not have a relevant impact (shown in Section 5.1.2).

A *directed search* is then conducted for PPE and ventilators to generate a set of candidate policies that perform best considering the worst-case scenario identified in the open exploration. The worst-case scenario is chosen over the best-case scenario. It is more relevant for decision-makers to find policies that perform well under disadvantageous conditions since unforeseen events characterize crises. The directed search was run over 4000 Number of Evaluations (nfe) for ventilators and 5000 nfe for gloves & simple masks aiming to maximize the total coverage. To track the convergence of the optimization process in the directed search, the ϵ-progress, using an ϵ-value of 0.05, is tracked. The ϵ-progress showed that better-performing policies could have been found, but the ϵ-progress was sufficient. Due to time resources, the process was not repeated. The directed search resulted in only one candidate policy for ventilators and six policies for simple masks &gloves.

Afterwards, an *uncertainty analysis* was run using the candidate policies identified in the directed search and the defined uncertain variables. The defined uncertainties had to be reduced, as PRIM's scenario discovery can only consider up to around 30 uncertainties. Uncertainties associated with a specific supply strategy not relevant to the candidate policies and uncertainties affecting the spread of the virus were eliminated. The feature scoring of the open exploration showed that uncertainties affecting the spread of COVID-19 had a significantly higher impact and outshone uncertainties relevant to supply strategies. The uncertainty analysis considered 1000 different scenarios. Hence, for the case of ventilators, 1000 experiments and in the case of simple masks & gloves, 6000 experiments were run. The uncertainty analysis results were used as an input for the scenario discovery.

Lastly, a *scenario discovery* using PRIM was applied to identify the variables that have the most impact on the changes in performance, considering the conducted for the case of ventilators. To do so, one must define performance measure thresholds regarding the outcomes of a model. The performance threshold was chosen to focus on values lower than 35% of worst cases regarding the total coverage regarding ventilators, simple masks, and gloves. PRIM returned the uncertainties most likely to contribute to the outcome and their range of values. Furthermore, dimensional stacking was applied to expose any patterns regarding the combination of uncertainties affecting the outcome of interest. For dimensional stacking, the values were separated into two bins.

The GitHub repository, including python notebooks, Vensim files, and data files, can be found here: https://github.com/pmgoetz/MasterThesis.

4.8. Summary of Model Description

This chapter focused on describing the developed SD model, highlighting the SEIR model structure used to model the spread of a pandemic similar to COVID-19, the resulting demand for PPE and ventilators, and the supply strategies used to provide sufficient PPE and ventilators. The applied supply strategies are:

- Stockpiling
- Domestic production
- Innovative supply strategies
- Purchasing critical medical supplies through direct tender, and
- Purchasing critical medical supplies from the world market.

Furthermore, this chapter focused on the experimental design used for the EMA. Hence, relevant decision levers and uncertainties and the setup for the MORDM were presented. This chapter allowed me to implement and reflect on the supply strategies used by the English health system to increase the availability of PPE and ventilators during the beginning of COVID-19 and reflect on what combination of policies could be implemented instead. Hence, the research needed to construct the model helped to partly answer the following sub-research question, as the research results will fully answer this question.

Considering the case of England, how did the preparedness and responsive supply strategies affect the availability of PPE and ventilators during COVID-19?

5 Results

This chapter focuses on the results provided by the Exploratory Modelling and Analysis. It presents results regarding the behaviour of the system given the uncertainties, the results of the search for better performing policies, as well as the impactful scenarios resulting from the scenario discovery process.

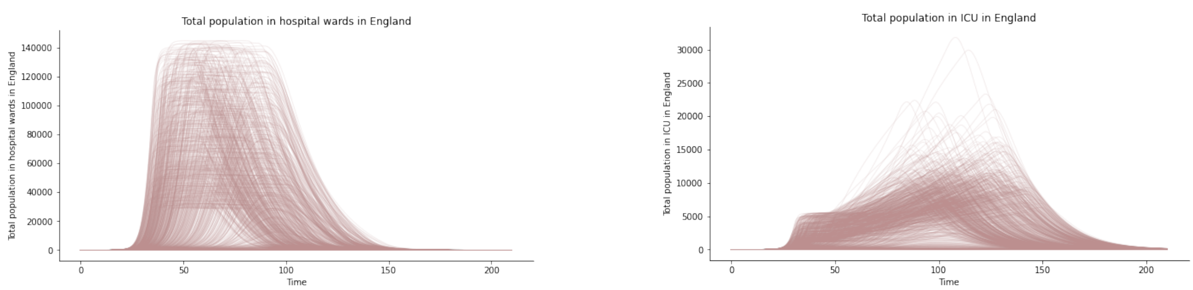
5.1. Model Behaviour

This section centres around the model behaviour observed in the open exploration, reporting relevant results regarding the infection development, observed impacts of the decision framework and pointing out the differences between the different supply strategies and the suggested policies.

5.1.1. Infection Development

The SD model presents the first wave of a health-related crisis like COVID-19. It is important to note that it is not the aim to model COVID-19 exactly. For instance, the system does not fully represent the reality of the spread of a virus infection, as public behaviour and policies implemented by policy-makers were modelled simplistically, which in this case led to a higher number of infections compared to COVID-19. This, combined with the data resources used for the assumptions, resulted in more infections amongst the middle-aged / younger population and a higher share of middle-aged people in hospitals. One can find the range of possible model outcomes regarding the total amount of people hospitalised (excluding ICU) in Figure 5.1a and the total population in ICU over time Figure 5.1b. It is visible that the hospital population reaches its maximum value before the ICU population reaches its maximum.

A significant difference between the results of the model and the reality of COVID-19 in England is that patients were declined from intensive care, which did not happen in reality according to National Audit Office (2020b). However, these results are helpful for this research, as it allows testing of the success of supply strategies to organize ventilators in times of crisis.



(a) Population in hospital wards over time

(b) Population in ICUs over time

Figure 5.1: Hospitalized population over time in general wards and ICU. Each line represents one experiment.

5.1.2. Impact of the Decision-Framework

Based on the constructed decision framework in the SD model, the start of different supply strategies is the same across the suggested policies. However, supply strategies differ in how they are applied due to the structure of the decision framework. Next to the decision regarding the application of supply strategies, decision-makers can determine the time horizon for the forecast and the threshold to place orders. The results indicate that both levers affect the order time directly. Since the policy *"Foresight National"* exhibits a lower threshold to order and forecast horizon than the other suggested policies, it is the only policy resulting in earlier order points for different supply strategies. Hence, it is for decision-makers essential to consider not only the applied supply strategies but also other characteristics affecting the order placement.

5.1.3. Differences between Supply Strategies

The following section focuses on the differences between supply strategies over time provided by the results of the open exploration. The results indicate that differences among critical medical supplies exist. As an example, the outcomes regarding the delivery of simple masks are presented. Differences to other PPE and ventilators are mentioned where appropriate.

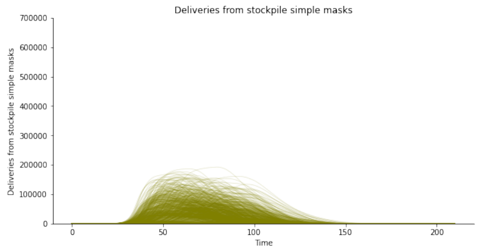
Stockpiling is a supply strategy that allows delivering simple masks as soon as patients are delivered to hospitals, as shown in Figure 5.2a. Figure 5.2 reflects that simple masks are first delivered from the stockpile before simple masks are delivered by other supply strategies, which is also the case for other PPE and ventilators. The volume delivered through stockpiling depends on the PPE/ventilators stored. The differences in deliveries of simple masks per day across different supply strategies are visible in Figure 5.2. Figure 5.2 also shows that the deliveries of simple masks through domestic production and innovation stabilize over time. The maximum deliveries are slightly higher for innovative supply strategies compared to domestic production (Figure 5.2b, Figure 5.2c).

How quickly and how many critical medical supplies are delivered through domestic production or innovative supply strategies depends on the performance of the supply strategy. Innovative supply strategies can have high production capacities in some cases if decision-makers in health systems support them to an extreme extent. Concerning ventilators, loaning ventilators can be an effective supply strategy to reduce the shortage quickly. With regard to its volume of deliveries, purchasing simple masks through direct tender and from the world market have the most significant impact on the number of simple masks delivered (Figure F.1). The deliveries through direct tender and procurement from the world market reach a maximum value and then decrease over time, as shown in Figure 5.3.

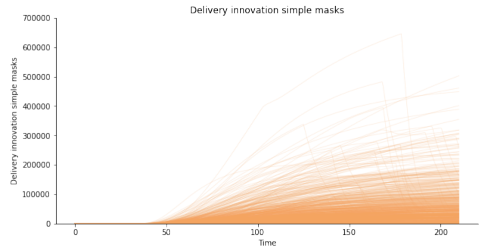
How many products are delivered from suppliers in the world market depends on existing export restrictions and delayed shipment times. Without export restrictions, procuring products from the world market is an effective strategy, as many products can be ordered and delivered. Figure 5.3 shows that export restrictions can reduce possible deliveries tremendously. In comparison, deliveries through direct tender are more stable, as the density of lines in Figure F.1 indicates. The assumption that export restrictions do not apply and lower range in shipment times may impact this difference between direct tender and procurement from the world market.

To provide further insights concerning the combined effect of supply strategies, the Kernel Density Estimation (KDE) for the total demand and the total deliveries of simple masks are shown in Figure 5.4. The KDE provide insight regarding the probability density function of an outcome of interest, in this case, the demand and deliveries of simple masks over time. Areas highlighted in yellow indicate what values in demand or deliveries of simple masks are more likely to be present over time. Concerning the point of time of the deliveries of simple masks, it is evident that simple masks are not provided in time to meet the demand (Figure 5.4). The demand for simple masks reaches its maximum before the delivery approaches its maximum values. Hence, this indicates that not enough simple masks are delivered in time to meet the demand for simple masks. This phenomenon is also visible for other PPE and ventilators.

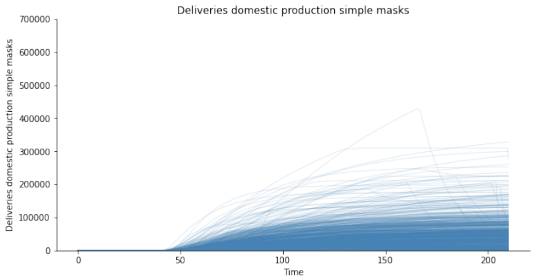
Moreover, it was explored which uncertainties influence the shortage of PPE and ventilators. The feature scoring results showed that the virus's infectivity impacts PPE or ventilator shortages the most.



(a) Deliveries of simple masks over time - Stockpile



(b) Deliveries of simple masks over time - Innovation



(c) Deliveries of simple masks over time - Domestic Production

Figure 5.2: Comparison of deliveries between different supply strategies. Each line represents one experiment.

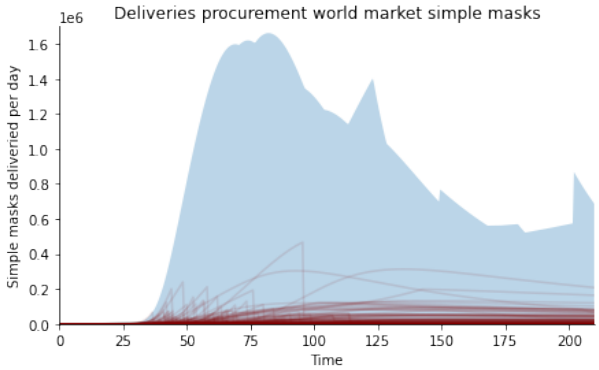


Figure 5.3: Impact of export restrictions. Experiments with extreme export restrictions are highlighted in red. The range of possible deliveries per day for all cases is shaded in light blue.

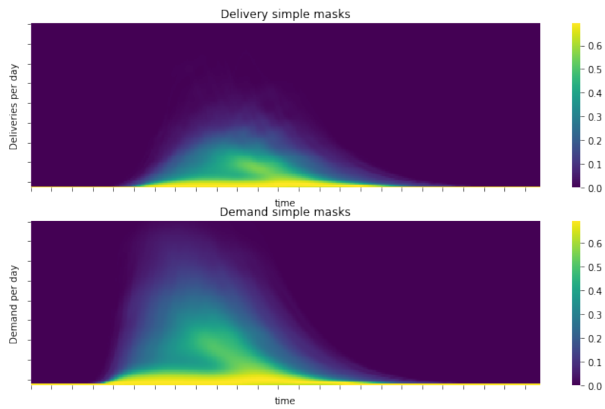
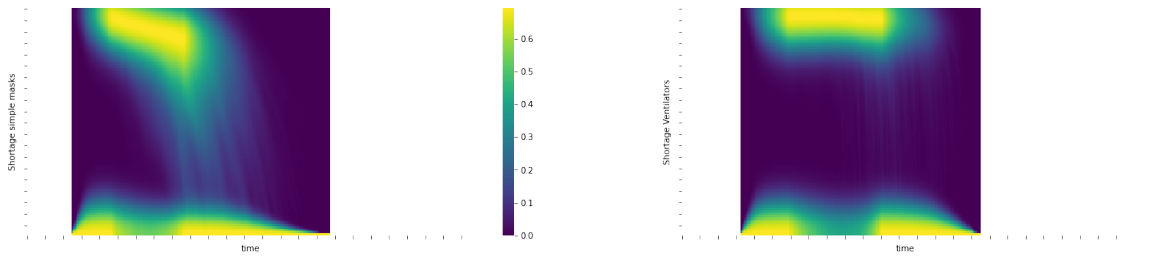


Figure 5.4: Comparison between the eye protection delivered per day to hospitals vs. the demand per day. Areas shaded in yellow indicate what values that are more likely.



(a) KDE plot focusing on the shortage of Simple Masks

(b) KDE plot focusing on the shortage of Ventilators

Figure 5.5: Possible outcomes of the shortage of critical medical supplies presented with KDE plots. Areas shaded in yellow indicate what percentage of shortage is likely to appear.

The influence of other uncertainties is very similar over time and at a significantly lower level. Hence, it was not possible to exclude any uncertainties with confidence for the MORDM process or identify other impactful uncertainties.

5.1.4. Shortages of PPE and ventilators

Decision-makers responsible for the supply of critical medical supplies are interested in the times when shortages of critical medical supplies appear and the extent of such shortages. Hence, the following subsection focuses on the shortage of critical medical supplies and presents the results concerning the impact of the suggested policies introduced in Section 4.3.

The shortage in PPE and ventilators are presented in a normalized measure to provide decision-makers immediate insight. For instance, if the shortage in PPE or ventilators equals 60%, HCWs cannot treat 60% of all patients safely, or 60% of declined patients cannot be served with ventilators. The KDE plots displaying the behaviour of the shortage in simple masks (representing PPE) and ventilators are shown in Figure 5.5 to provide insight regarding their shortages. Areas highlighted in yellow indicate where shortages are more likely to be apparent over time. Hence, shortages in simple masks and ventilators of almost 100% are likely during health-related crises with the implementation of the suggested policies. The shortage of simple masks is expected to decrease at an earlier point of time than the shortage in ventilators, as the comparison between Figure 5.5a and Figure 5.5b reflects. Furthermore, the behaviour across different PPE is very similar, as shown in Figure F.3.

To further investigate the impact of the suggested policies in Section 4.3, an overview of the performance of the four suggested policies is presented in Figure 5.6. The scatter plot contains the total value in coverage for the considered PPE and ventilators, and the legend on the right shows which policy the outcome refers to. Hence, it is the integration of the coverage over time. Ideally, a value of 210 is reached, which would mean no shortage exists. Outcomes located in the top right corner indicate a better outcome. It is visible that the coverage does not approach the maximum value with the suggested policies and that the difference in performance between the policies is limited, as the outcomes are all grouped. The policy *"UK tactic"* performs slightly worse than other policies, but the difference in performance is not significant. The slight difference in performance between policies is also supported by Figure F.2. All policies perform similarly given the uncertainties. Hence, the results of Figure 5.6 support the results provided in Figure 5.5, suggesting that the total coverage seldom reaches the maximum value. The suggested policies do not have the intended impact on the coverage of critical medical supplies.

5.1.5. Conclusion regarding the Model Behaviour

In conclusion, the results of the open exploration indicate that stockpiling helps absorb first demand shocks for PPE. The supply strategies direct tender and procurement from the world market can contribute the most to decreasing the shortage of ventilators and different PPE unless export restrictions are in place. Innovative supply strategies and domestic production can contribute similarly to the availability of medical supplies. Furthermore, loaning ventilators helps to absorb arising needs. The results of the open exploration suggest that the PPE and ventilators' delivery is behind its demand. Hence,

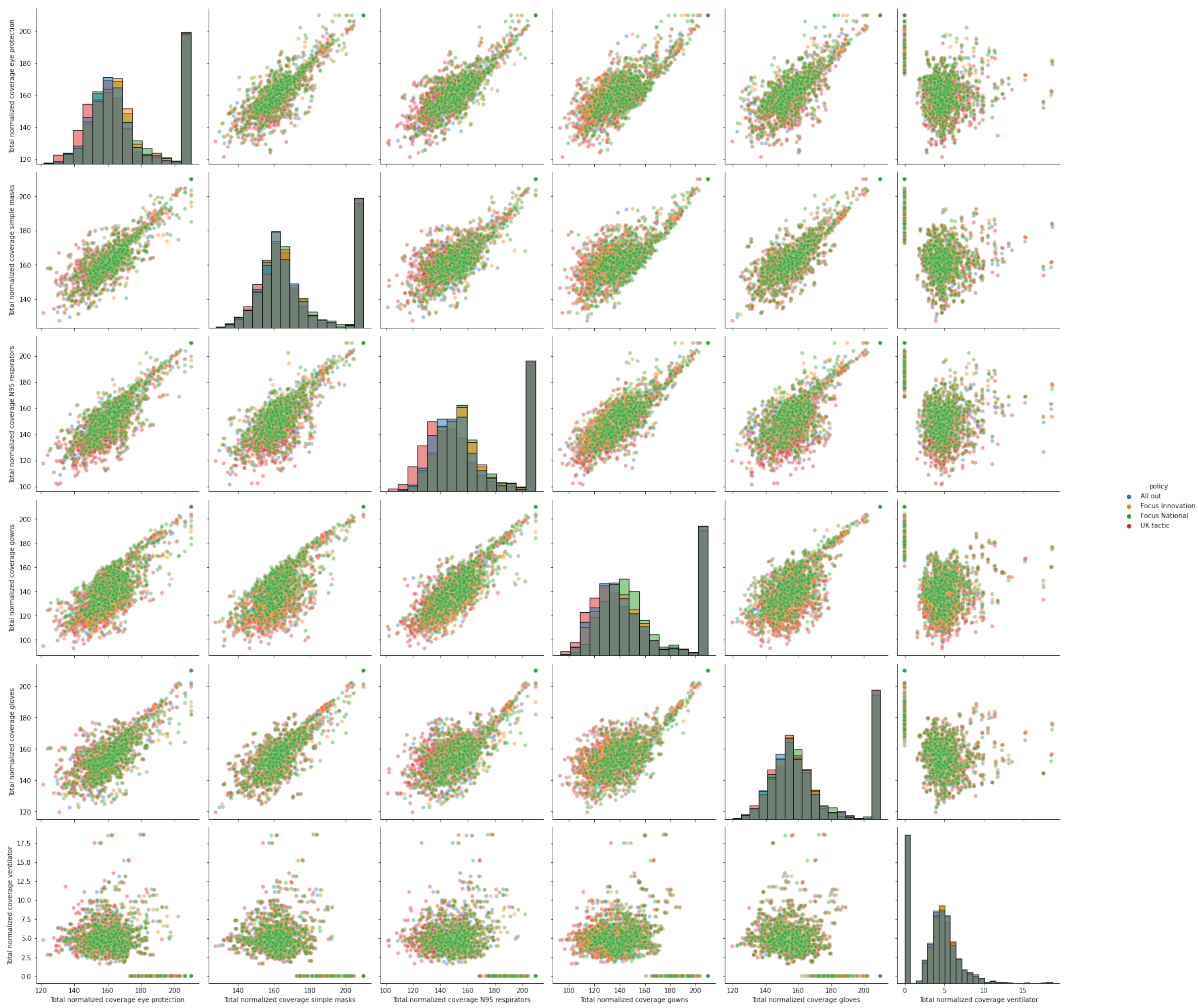


Figure 5.6: Pairs plot to present total coverage over time for PPE and ventilators

a long-lasting shortage in PPE and ventilators is likely to be apparent in various scenarios. Moreover, the comparison between the suggested policies suggests that a significant shortage arises across all policies. Therefore, it is crucial for decision-makers responsible for the availability of critical medical supplies within health systems to identify policies, the combination of supply strategies, that contribute more successfully to the coverage of critical medical supplies.

5.2. Characteristics of Identified Candidate Policies

Since the results presented in Section 5.1 recommend that the performance of the suggested policies is not sufficient, it is appropriate to conduct a directed search as part of a MORDM cycle. The directed search aims to find candidate policies that increase the availability of critical medical supplies at a higher level. The presented candidate policies focus on the supply of PPE, simple masks and gloves, as well as the supply of ventilators. The focus of the presentation of candidate policies aims to identify which supply strategies are applied more often and the characteristics of the suggested policies.

5.2.1. Characteristics of Candidate Policies to Increase the Supply of Simple Masks and Gloves

The directed search considering simple masks and gloves resulted in six candidate policies for simple masks & gloves. The ε-progress indicates that the optimisation process almost converges. The convergence graph is shown in Figure F.4. Hence, it is appropriate to analyse the candidate policies and include them for further analysis.

Figure 5.7 provides an overview of what supply strategies were applied the most across the candidate strategies and the supply strategies' mean order buffer. A mean order buffer indicates a higher order priority given by decision-makers. It is assumed that a stockpile is consistently implemented. From Figure 5.7, it is evident that all six candidate policies procure products from the world market with the highest mean order buffer. Purchasing simple masks and gloves through direct tender is almost inevitable to the candidate strategies but comes with a lower order buffer. In contrast, domestic production and innovation as supply strategies are applied the least. Domestic production appears to have the second-highest mean order buffer. This means that domestic production is prioritised if it is used.

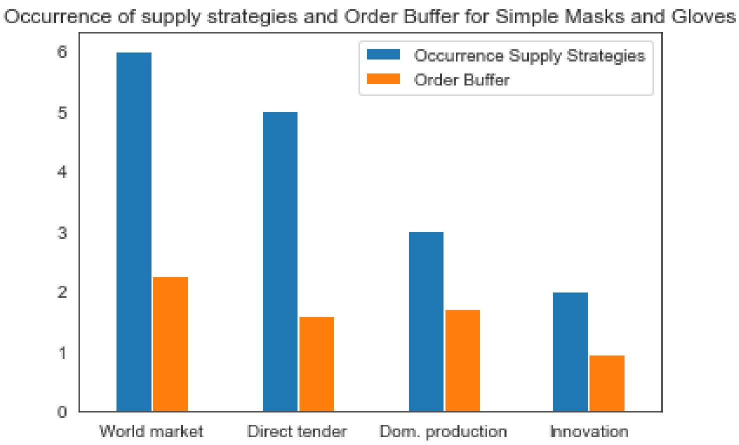


Figure 5.7: Occurrence of supply strategies and average order buffer

To provide insight regarding the combinations of supply strategies applied across candidate strategies and the resulting total coverage, Figure 5.8 is shown. Each line in the trade-off plot represents a policy. The axis in trade-off plots presents the values a policy takes for different decision levers. It stands out that only one candidate policy applies innovation and domestic production (purple line in Figure 5.8). Policies applying domestic production and/or innovation perform lower in the total coverage of simple masks and gloves (purple and orange lines Figure 5.8). The trade-off plot also indicates that candidate policies exhibit a higher time horizon for forecasts than originally assumed (14 days originally). The number of patients combined with the days in stock form the threshold value that determines the order point of PPE. The same threshold value is also used as a reference to display the shortage. The variables number of patients and days in stock are close to the maximum considered values of 500 patients and 30 days in stock. Hence, simple masks and gloves are ordered later, but shortages of simple masks and gloves also appear at a later point in time.

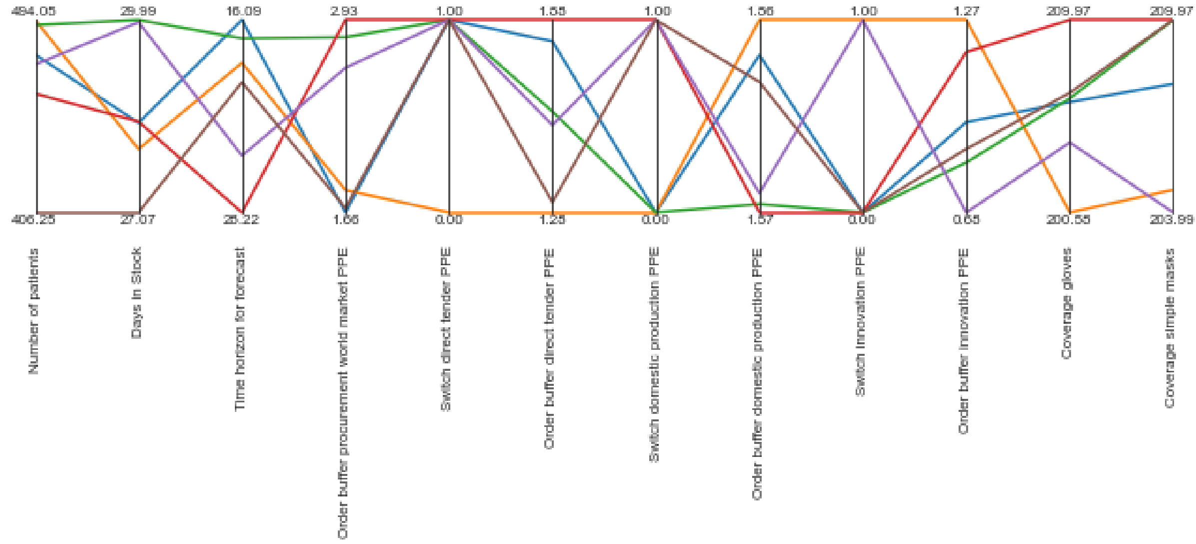


Figure 5.8: Trade-off plot to present combinations of supply strategies applied in policies

Next to the combination of supply strategies, it is relevant to find out how fast decision-makers need to set up the different supply strategies. Figure 5.9 is shown to display the range in set-up times for promising candidate strategies. The range of values chosen for each supply strategy was extreme to depict the importance of set-up times. It stands out that the set-up times to place orders with suppliers through direct tender needs to be lower than ten days to achieve a high coverage of simple masks and gloves, as shown in Figure 5.9. During COVID-19, decision-makers within the English health system were allowed to decrease the procurement process of direct tender to two weeks. Furthermore, the set-up time for PPE procurement through the world market is ambitious, as it ranges between 14 and 21 days. Hence, decision-makers need to be extremely quick in placing orders with suppliers to reach a high coverage. Concerning the supply strategies domestic production and innovation, it stands out that the range in values considered for set-up is higher when a supply strategy is applied. Still, it is challenging to start the PPE production within less than 45 days with innovative supply strategies. Concerning domestic production, it would be very challenging to set up a production line within seven days (red line in Figure 5.9).

As decision-makers are responsible for the operation of the PPE stockpile, it is essential for them to identify how well the stockpile has to be equipped and operated to increase the availability of PPE. To depict the relevant levers influencing the performance of the stockpile of, in this case, simple masks, Figure 5.10 was created. It stands out that the candidate policies suggest stocking a higher amount of simple masks (up to 234 million compared to 156 million recommended by Public Health England, for gloves up to 535 million compared to 360 million recommended by Public Health England (Figure F.5)). Furthermore, most candidate policies suggest delivering more than 90% of the stockpile to hospitals, compared to the 80% in reality. It stands out that almost no delays can be present in the warehouse operations (Preparation time for delivery PPE) and that products have to be delivered on time, as the three suggested policies do not allow for any delay in the delivery (orange, green and blue line in Figure 5.10). A decision lever not highlighted in this graph but of further interest is the time it takes for the PPE to be checked before it can finally be delivered to its destination. The delay here also needs to be almost non-existent (Figure F.6).

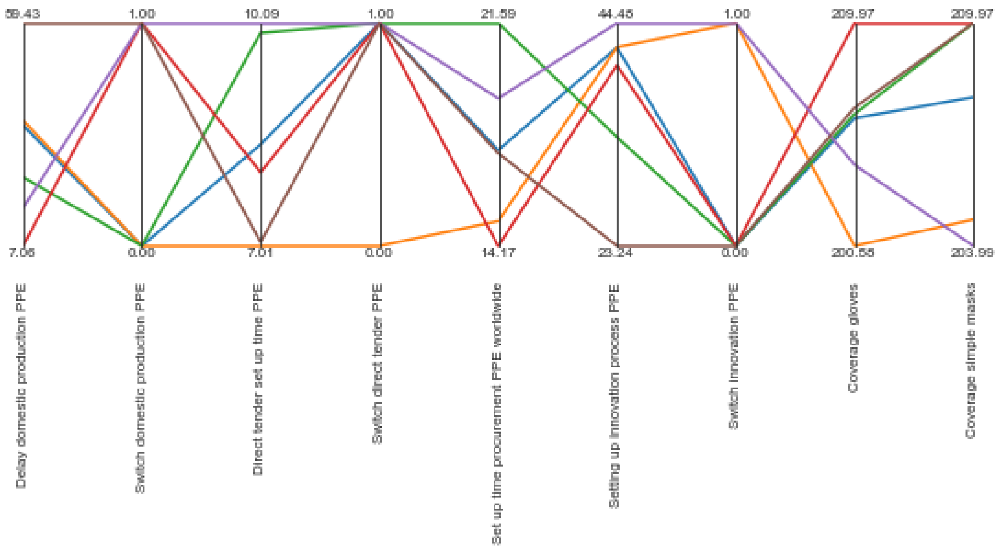


Figure 5.9: Comparisons of set up times for supply strategies applied in candidate policies

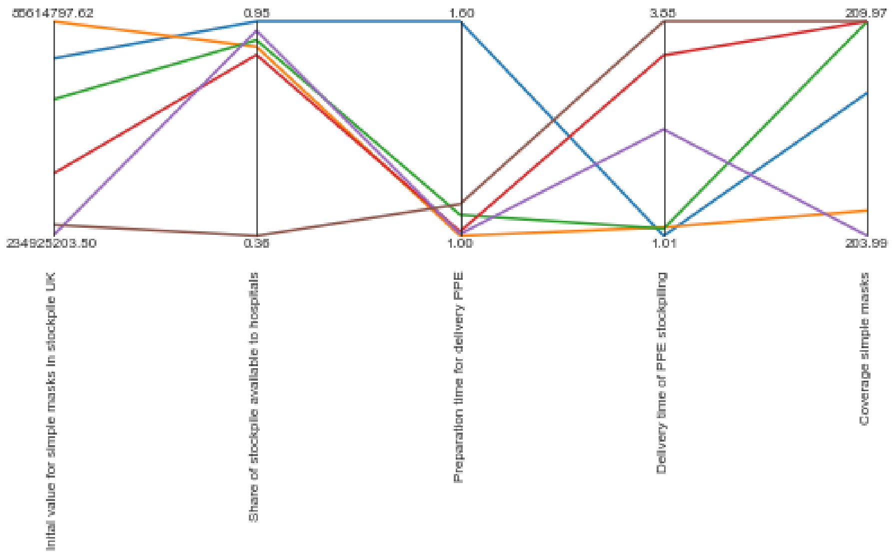


Figure 5.10: Characteristics of Stockpile for simple masks in candidate policies

5.2.2. Characteristics of a Candidate Policy to Increase the Supply of Ventilators

The directed search to identify candidate policies to achieve a high coverage of ventilators based on the identified worst-case scenario for the coverage of ventilators resulted in one candidate policy. The ε-value almost converges, as shown in Figure F.8. Hence, it is unlikely that better-performing are identified. The obtained candidate policy is considered further in this research.

The candidate policy suggests stockpiling 6117 ventilators, loaning ventilators, purchasing ventilators through direct tender, and implementing domestic production. The candidate policy suggests focusing more on buying ventilators through direct tender than through domestic production 5.11.

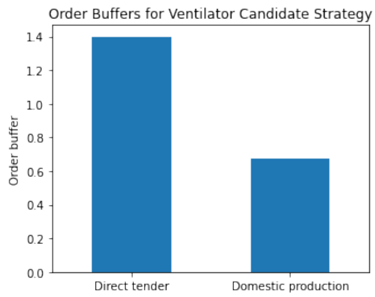


Figure 5.11: Order buffers for supply strategies applied in candidate strategy for ventilators

Similarly to the results of the directed search for gloves and simple masks, set up times for the applied supply strategies have to be extremely low. Domestic production and purchasing ventilators through direct tender would have to start within one week. Furthermore, the stockpile has to be operated with very low delays regarding the operation and delivery of ventilators. The detailed description of the candidate policy for ventilators is shown in Table F.1, Table F.2, and Table F.3. It is also important to highlight that the candidate policy only reaches a total coverage of 13.4, while 210 would be the ideal coverage.

5.3. Performance of Candidate Policies for Gloves, Simple Masks and Ventilators

An uncertainty analysis is performed for the identified candidate policies for ventilators, gloves, and simple masks to explore how the policy performs considering a range of uncertainties. Similarly to the open exploration conducted before, KDE plots over time are created to visualise the shortage of critical medical supplies over time.

As shown in Figure Figure 5.12, the range of outcomes regarding the coverage for ventilators is smaller. Compared to Figure 5.5b, it is visible that the candidate policy can decrease the shortage of ventilators slightly more. But it takes a longer time to reach a state without a shortage of ventilators. It also needs to be considered that Figure 5.5b includes the results of 3200 experiments, whereas Figure 5.12 contains 1000 experiments and uncertainties focusing on the extent of the health-related crisis were excluded. This also contributes to the differences in the KDE plots.

Similarly, Figure 5.13 shows that the shortage of simple masks and gloves is on a significantly lower level compared to the KDE plot in Figure F.3. The shortage does not reach 100% in the evaluated scenarios for gloves and simple masks. Furthermore, the candidate policies allow decreasing the shortage more significantly. It is more likely that the shortage in gloves decreases before the shortage in simple masks. Again, it needs to be considered that the uncertainty analysis considered 2400 experiments compared to the 3200 experiments in the open exploration, and that a significant amount of uncertainties were excluded, which also decreases the range of possible outcomes.

Since several candidate policies were considered for the case of simple masks and gloves, it is interesting to identify how robust the policies performed considering the same scenarios. To compare the robustness of the policies, the box plot shown in Figure 5.14 was created. The only policy apply-

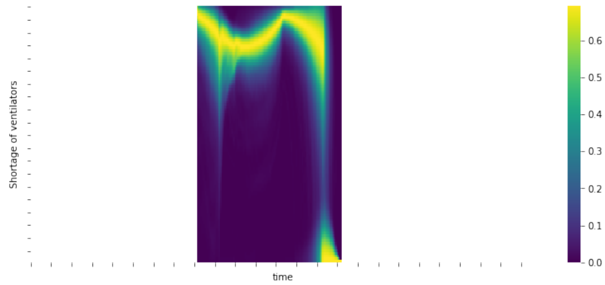
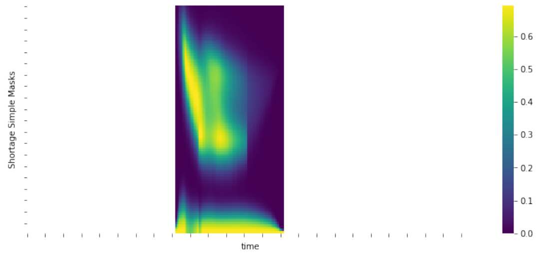
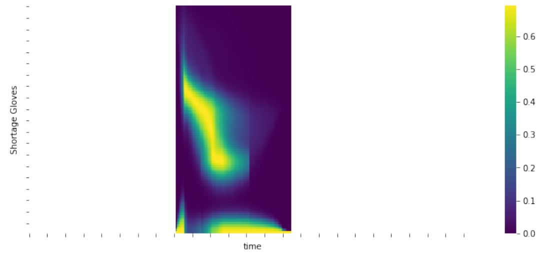


Figure 5.12: KDE plot over time for ventilator shortage



(a) KDE plot focusing on the shortage of simple masks



(b) KDE plot focusing on the shortage of gloves

Figure 5.13: Possible outcomes for the shortage of critical medical supplies presented with KDE plots with Candidate Policies

ing innovation, domestic production, direct tender and procurement from the world market as supply strategies is Policy 4 combined with a stockpile of 234 million masks. This policy is the most robust and performs comparably to the other policies. Policy 0, Policy 1 and Policy 2 store less simple masks in the stockpile than recommended by Public Health England. The robustness of the candidate policies is similar for the case of gloves, as Figure F.7 shows.

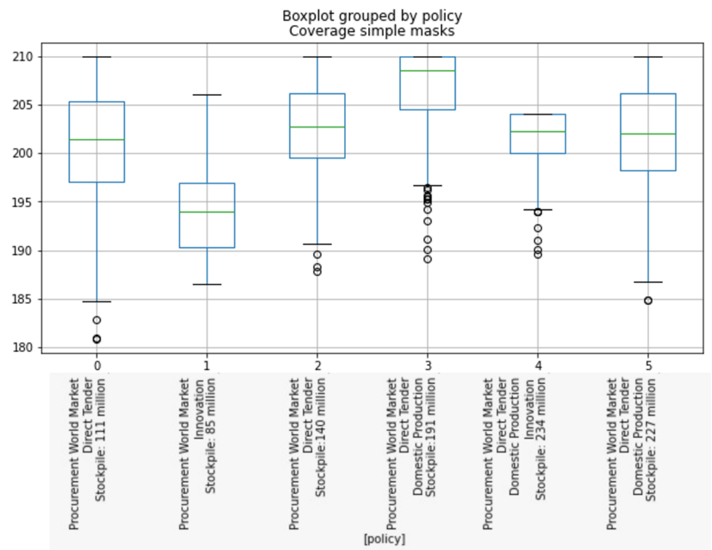


Figure 5.14: Box plot of the candidate policies focusing on simple masks

5.4. Scenario Discovery Results

The following section focuses on the results of the scenario discovery. The scenario discovery focuses on assessing the main vulnerabilities and outcome of the model: Under what conditions do the selected candidate policies result in a low coverage for simple gloves, masks, or ventilators? Answering this question helps decision-makers identify the most impactful uncertainties during crises and how the combination of uncertainties affects the availability of critical medical supplies the most.

5.4.1. Scenario Discovery Results for Candidate Policy to Increase Coverage of Ventilators

The scenario chosen to discover represents more than 75% of cases with low coverage of ventilators, and it can predict more than 70% of the cases with low coverage in ventilators (Figure F.9c). Hence, the scenario is suitable to inform decision-makers about the uncertainties affecting the availability of ventilators during crises.

In Figure 5.15 one can find the uncertainty values that define the scenario of interest the most. 73% of cases fall into the ranges of values for the base production capacity of direct tender ventilator suppliers, the share of unusable ventilators delivered, and the shipment time for direct tender presented in Figure 5.15. If the base production capacity of all suppliers reached through direct tender falls to 260 ventilators per day, a high shortage of ventilators is likely. Whereas the share of unusable ventilators delivered needs to be above 2.6% and the shipment time needs to be above 30 days to result in a low coverage for ventilators. A shipment time above 30 days for ventilators secured through direct tender seems to be likely during a health-related crisis, as the transportation network may not function as wanted. Furthermore, the qp-values indicate that the mentioned uncertainties can be considered significant (<0.2). A scatter plot supporting these results can be found in Figure F.10.

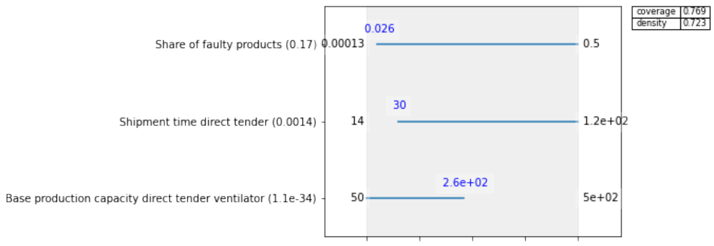


Figure 5.15: Uncertainties used to define the scenario of interest for ventilators

To further investigate the scenario of interest, a dimensional stacking plot is created as shown in Figure 5.16. Dimensional stacking plots identify the combinations of uncertainties affecting the outcome of interest. Next to the combination of uncertainties, it also bins the range of values in uncertainties. The legend in the top left of Figure 5.16 shows that scenarios highlighted in yellow are the most influential. It stands out the combinations of uncertainties, including high shipment times for direct tender result in a low coverage of ventilators. The scenario being the most influential on a low coverage of ventilators is the following combination of

- high shipment times for ventilators delivered through direct tender,
- a large share of unusable ventilators delivered,
- a low base production capacity and a low increase in the production capacity of suppliers reached through direct tender,
- significant delays in the production of suppliers reached through direct tender, and
- delays in the raw material procurement for domestic production.

This means that the performance of the suppliers reached through direct tender has a significant impact on a low coverage of ventilators. The only uncertainty not associated with the supply strategy direct tender is a large delay in the procurement of supplies to produce ventilators domestically (Transportation time ventilator domestic production).

The results regarding the scenario discovery of coverage of ventilators show that depending on the supply strategies, purchasing products through direct tender, domestic production, and stockpile comes with high uncertainty regarding the performance of the supply chains of suppliers reached through direct tender.

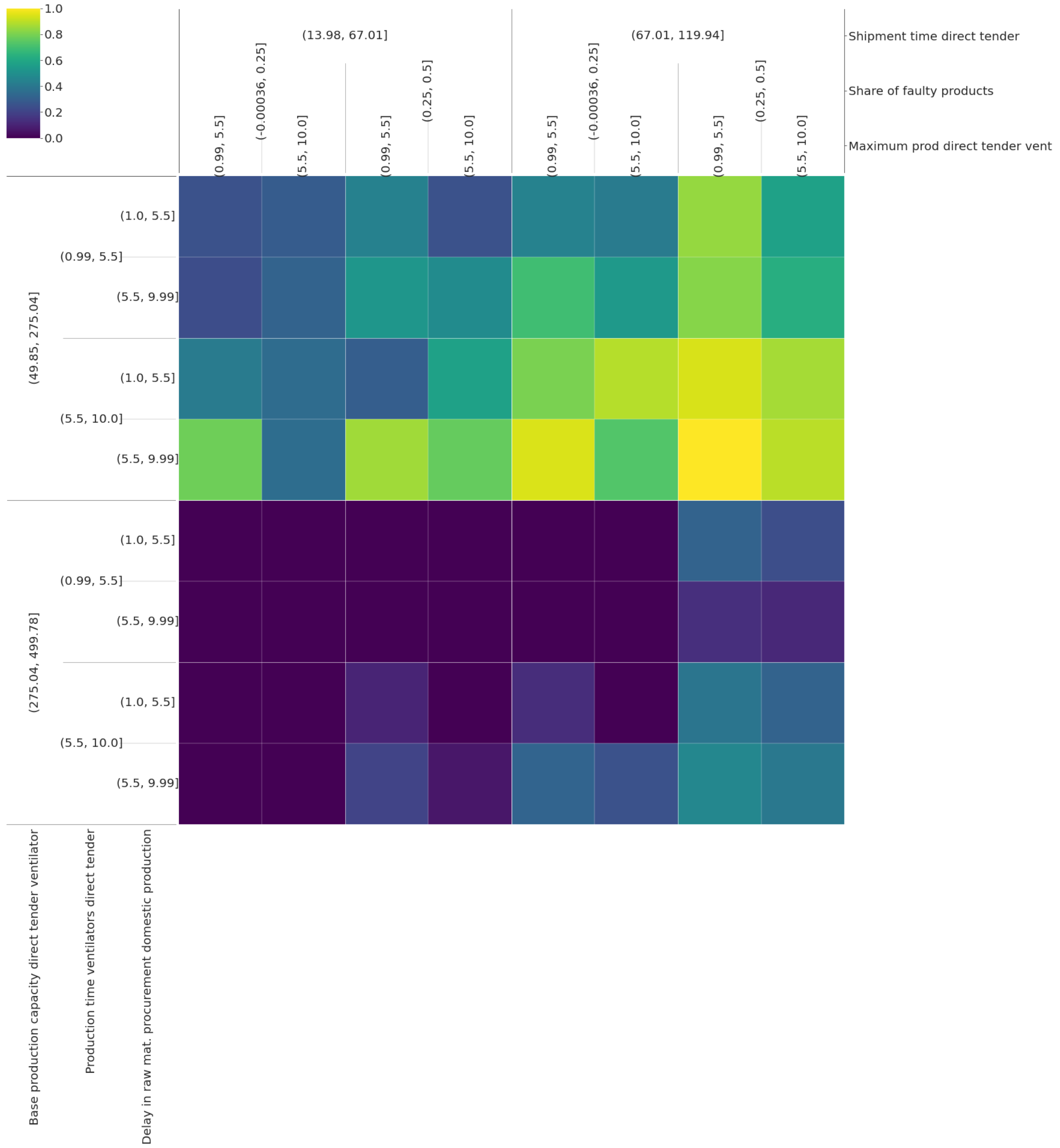


Figure 5.16: Dimensional stacking plot for cases with low coverage in ventilators

5.4.2. Scenario Discovery Results for Candidate Policy to Increase Coverage of Gloves

The outcome of interest to perform a scenario discovery for gloves is low coverage of gloves. The scenario chosen exhibits a coverage of 60% and a density of 58% (Figure F.9b). This means that the chosen scenario represents 60% of the cases with low coverage of gloves and can predict 58% of the cases with low coverage of gloves. It is suitable to explore for decision-makers, but the results need to be interpreted with more caution.

In Figure 5.17 one can find the combinations of uncertainty values that define the scenario of interest. This means with regard to the density that 58% of cases fall into the ranges of values shown in Figure 5.17. More uncertainties are considered as the coverage and density are lower. It is evident that uncertainties surrounding the supply strategies, direct tender and procurement from the world market impact the coverage of gloves. The only uncertainty not referring to the supply strategies direct tender and purchasing products from the world market is the variable "Reach PPE", which refers to the uncertainty of how many businesses can be reached when innovation is applied as a supply strategy. Furthermore, the results suggest that any delay in the supply chains for the suppliers reached through the world market can result in a lower coverage of gloves. Concerning the qp-values, it is evident that the most significant uncertainties are:

- The share of unusable PPE delivered by suppliers reached through direct tender,
- delayed shipments from suppliers reached through the world market,
- delayed shipments from suppliers reached through direct tender, and
- any export restrictions concerning the suppliers reached through the world market.

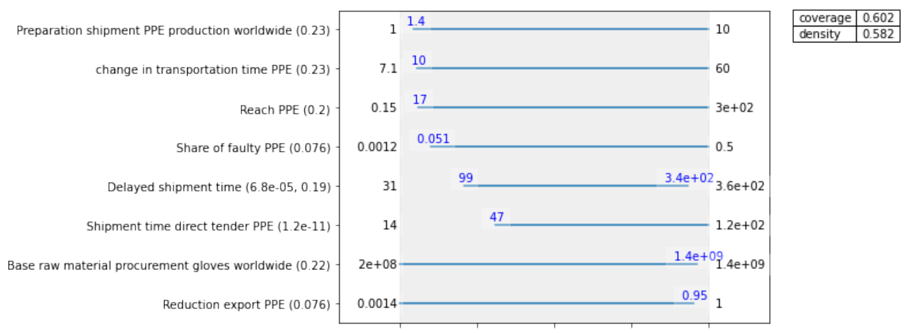


Figure 5.17: Uncertainties used to define the scenario of interest for gloces

To further investigate the scenario of interest, a dimensional stacking plot is created as shown in Figure F.11. It stands out that specifically, the combinations of uncertainties, including a high shipment time for direct tender, result in a low coverage of gloves. The combination of uncertainties that have the most impact on a low coverage of gloves is high shipment time in direct tender and gloves purchased from the world market, combined with a high share of faulty gloves purchased through direct tender, export restrictions and a high amount of gloves changes of HCWs in hospitals.

Uncertainties regarding the performance of the supply strategies direct tender and procurement from the world market have the most impact on a lower coverage of gloves.

5.4.3. Scenario Discovery Results for Candidate Policy to Increase Coverage of Simple Masks

For the scenario discovery, a scenario with a coverage of 60% and a density of 57.9% was chosen (Figure F.9a). Similarly to the scenario discovery of gloves, the values in coverage and density are lower. Hence, the scenario discovery results need to be interpreted with more caution.

In Figure 5.18 you can find the combinations of uncertainty values that define the scenario of interest. Considering the high qp-values of the uncertainties presented in Figure 5.18 (qp-value > 0.2), only the following uncertainties can be regarded as significant in their influence on a low availability of simple masks:

- The share of unusable simple masks delivered by suppliers reached through direct tender,
- delayed shipments from suppliers reached through the world market,
- delayed shipments from suppliers reached through direct tender, and
- any export restrictions concerning the suppliers reached through the world market.

Furthermore, it stands out that for uncertainty affecting the low availability of simple masks, a wide range of values has a significant impact. That indicates that delays in supply chains have a relevant effect on the shortage of simple masks.

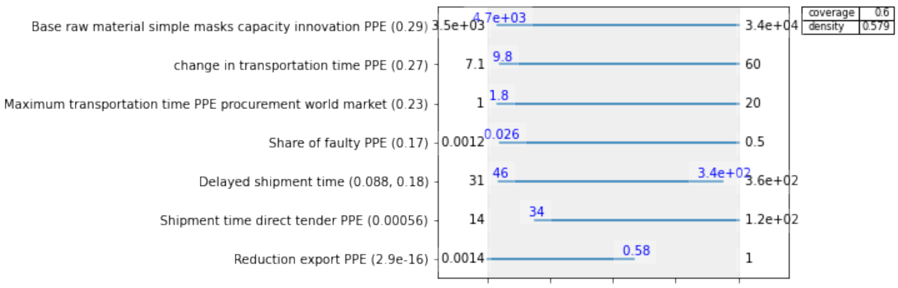


Figure 5.18: Uncertainties used to define the scenario of interest for simple masks

The dimensional stacking plot in is created as shown in Figure 5.19. The dimensional stacking plot contains the same uncertainties as the dimensional stacking plot for gloves, and the combinations of uncertainties affecting the low availability of simple masks are almost the same as for gloves. Figure 5.19 shows that, specifically, the following combination of uncertainties has an impact on the low availability of simple masks:

- delayed shipments from suppliers reached through direct tender,
- delayed shipments from suppliers reached through the world market,
- increased changes of simple masks of HCWs in general hospital wards,
- the share of unusable simple masks delivered by suppliers reached through direct tender,
- any export restrictions concerning the suppliers reached through the world market, combined with
- with low capacities in the raw material procurement of suppliers reached through direct tender.

It is evident that the most significant uncertainties combined decrease the availability of simple masks. Again, uncertainties regarding the performance of the supply strategies direct tender and procurement from the world market have the most impact on a lower coverage of simple masks.

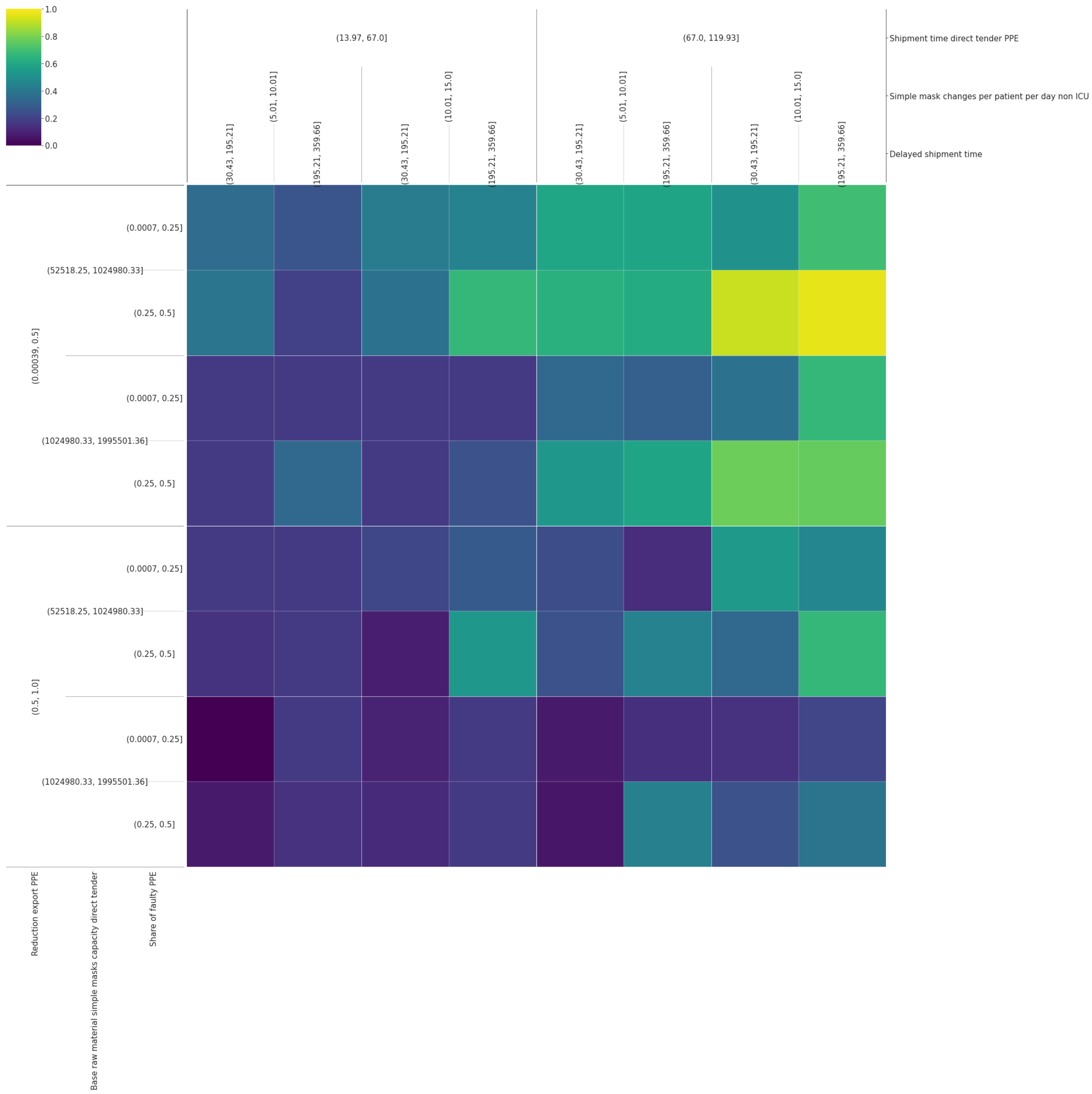


Figure 5.19: Dimensional stacking plot for cases with low coverage for simple masks

5.5. Summary of the Results

The model analysis results in this chapter gave insight into the effect of specific supply strategies, the characteristics of candidate policies that perform better than the suggested policies initially, and the uncertainties impacting the success of candidate policies the most. Hence, the results presented in this chapter help to answer the following sub-research questions:

How can health systems like the English health system improve their supply strategies to organize PPE and ventilators, considering existing uncertainties during health-related crises?

Concerning the application of supply strategies, it can be said that stockpiling helps absorb first demand shocks for PPE. The supply strategies direct tender and procurement from the world market can contribute the most to decreasing the shortage of ventilators and different PPE unless export restrictions are in place. Innovative supply strategies and domestic production can contribute similarly to the availability of medical supplies. Furthermore, loaning ventilators helps to absorb arising needs. The results of the open exploration suggest that the PPE and ventilators' delivery is behind its demand. Hence, a long-lasting shortage in PPE and ventilators is likely to be apparent in various scenarios. Moreover, the comparison between the suggested policies suggests that a significant shortage arises across all of them.

Candidate policies aiming to increase the availability of critical medical supplies exhibit minimum set-up times for the applied supply strategies. It is worth it to purchase simple masks and gloves through direct tender and from the world market. Innovative supply strategies and domestic production are applied fewer times within the candidate policies for simple masks and gloves. For the supply of ventilators, ramping up domestic production is helpful. Concerning the application of supply strategies, short set-up times are needed. Furthermore, stockpiles for PPE and ventilators have higher inventory levels than recommended and need to be operated without any delays with regard to its logistics.

Uncertainties surrounding the supply strategies purchasing products through direct tender or from the world market have the most impact on low availability of simple masks, gloves, and ventilators (only direct tender for ventilators). Especially, high shipment times, delays in production, and export restrictions affect the availability of critical medical supplies.

6 Discussion

The following chapter discusses the impact of preparedness and responsiveness during health-related crises on the availability of critical medical supplies, factors contributing to the success of various supply strategies, as well as potentially successful responsive and prepared supply strategies that need to be considered for future health-related crises. Lastly, it is discussed how the system understanding affects the results and implications of this research.

6.1. Preparedness & Responsiveness

Before one can discuss how national health systems can create responsive and prepared supply strategies, it is important to explore how responsiveness and preparedness contribute to the availability of critical medical supplies during health-related crises and to answer the following question:

How do responsiveness and preparedness of health systems affect the availability of critical medical supplies during a health-related crisis?

According to the WHO (2000), a health system's purpose is to serve its patients at all times. Hence, decision-makers are responsible for maintaining its functions during a health-related crisis like COVID-19, including providing a sufficient quantity of critical medical supplies. To maintain their functions during shocks, health systems need to be resilient. The results of the literature search indicate that a resilient health system can bounce back from shocks promptly by exhibiting the following characteristics: preparedness, responsiveness, recovery, and growth (Hohenstein et al., 2015; Kruk et al., 2017; Nuzzo et al., 2019; Turenne et al., 2019). Since this research focuses on the *immediate actions* taken by decision-makers in health systems to ensure the availability of critical medical supplies in times of crisis, this research focuses on the characteristics of preparedness and responsiveness and their ability to ease the recovery from shocks.

Based on the results of the literature search, *preparedness* refers to any actions aiming to make a system more resilient before a crisis shakes the understanding and normal functioning of a system (Adelman, 2020; Dow et al., 2020; Patel et al., 2017). In general, preparedness sets the frame of how and when health systems are able to act when a crisis appears. Hence, concerning the availability of critical medical supplies, preparedness refers to long-term implementations and is enabled when health-related crises do not threaten health systems. COVID-19 showed that health systems fell back into a false sense of security when it came to preparedness for pandemics. Even now, two years later, countries are not prepared for crises, considering the resources and tools available in health systems (Bell & Nuzzo, 2021; Frutos et al., 2021). Hence, it is still important to remind decision-makers in health systems of the impact of preparedness and responsiveness on the availability of critical medical supplies during crises.

In case of supplying sufficient PPE and ventilators to hospitals, being prepared can include implementing a centralized stockpile with the appropriate types of PPE and ventilators. The results presented in Chapter 5 support that stockpiles exhibiting higher inventory levels than originally recommended are more effective to absorb arising shortages of PPE or ventilators. For instance, candidate policies presented in Chapter 5 suggested storing up to twice the amount of simple masks recommended by Public Health England. Next to high inventory levels, stockpiles must demonstrate extremely low delays concerning their shipment times and the operations within the warehouse (e.g. preparing PPE for delivery, packaging or sorting PPE). It is also crucial to remember that critical medical supplies stored in a stockpile will never be suitable to solve all kinds of health-related crises, as the impact of crises is unforeseen (Alexander, 2005; Robert & Lajtha, 2002).

On the other hand, *responsiveness* focuses on the immediate action to decrease shortages of critical medical supplies once a crisis hits the system. Hence, responsiveness refers to measures that can be applied at the beginning of a crisis in a short-term window. With regard to the definition of supply chain resilience by Hohenstein et al. (2015), the aim of being responsive is to let the dip in performance be as slight as possible. Concerning the availability of critical medical supplies, the literature search results suggest responsiveness entails the prompt organization of supplies using responsive supply strategies. Responsive supply strategies are not limited to creating a domestic production base, supporting innovative supply strategies, and loaning or purchasing critical medical supplies through direct tender processes or from the world market. Their role in diminishing the shortages of PPE and ventilators is significant, as the results of this research show.

As the results of the model and research by Boiko et al. (2020) and Chowdhury et al. (2021) show, time is an influential factor for the success of responsiveness, such as delays in the decision-making of health systems or supply chains jeopardize the successful organization of critical medical supplies. Hence, the impact of responsiveness on the availability of critical medical supplies increases if decision-makers are able to implement responsive supply strategies quickly. To decrease delays impacting the success of responsive supply strategies, researchers provide various recommendations that can be implemented in preparation for health-related crises.

For instance, decision-makers can purchase critical medical supplies using diverse supplier frameworks, meaning that products are purchased from suppliers in various countries and domestic suppliers. A diverse supplier framework allows for more leeway when it comes to responding to a crisis, as more possibilities for purchasing supplies exist (Handfield et al., 2020; Sodhi et al., 2021). This notion is also supported by the results of this model regarding the availability of PPE and ventilators. Moreover, crisis frameworks can be developed to decrease the set-up time of supply strategies. Crisis frameworks can accelerate procurement processes and include a plan of action concerning the implementation of different responsive supply strategies. Accelerating procurement processes is especially relevant for purchasing critical medical through direct tender or from the world market. For example, a plan of action can entail how to best ramp up the domestic production of critical medical supplies, such as frameworks to set up public-private partnerships.

Overall, preparedness and responsiveness are cornerstones for a resilient health system during health-related crises. Preparedness and responsiveness cannot be seen as individual efforts, as the literature search and the model results suggest that health systems can respond faster if they are more prepared. Decision-makers can implement various actions to enable a rapid implementation of responsive supply strategies. Concerning the organization of critical medical supplies during health-related crises, it becomes clear that supply strategies exhibiting preparedness and responsiveness are inevitable.

6.2. Factors Affecting Success of Supply strategies

As preparedness and responsiveness are cornerstones to ensure the availability of critical supplies, it is of interest for this work to discuss how preparedness and responsiveness affected the supply of critical supplies in the English health system during COVID-19. Hence, it is important to reflect on the following question:

Considering the case of England, how did the preparedness and responsive supply strategies affect the availability of PPE and ventilators during COVID-19?

Before discussing the raised question, it is relevant to investigate whether the availability of PPE and ventilators can be guaranteed at all times, considering existing uncertainties. Based on the results of the open exploration, it is evident that substantial PPE and ventilator shortages are likely apparent for a significant amount of days under various scenarios if candidate policies are applied. Still, the policy used by the English health system performed significantly worse than the proposed candidate policies.

To prepare for health-related crises like COVID-19, the English health system implemented a PPE stockpile, and no ventilator stockpile, even though researchers suggest that stockpiling ventilators can be helpful to respond during health-related crises (Greenawald et al., 2021; Huang et al., 2017; Mehrabi et al., 2018; Mehrotra et al., 2020; Yorio et al., 2019). Considering the English stockpile, it was evident that its equipment was not adequate. The PPE stockpile did not include the recommended amount of PPE and not all necessary types of PPE. Even though it was recommended to update the stockpile, as the risk for crises may shift (Greenawald et al., 2021; Public Accounts Committee - House of Commons, 2021a; Wilgis, 2008). Moreover, the operation of the stockpile was not optimal, as delays in deliveries to hospitals and logistics of the PPE stockpile significantly slowed down the response. The slow operation of the stockpile is a relevant difference from the candidate strategies presented in Chapter 5. Additionally, decision-makers did not apply any other measures in preparation for health-related crises. The goal of supply chains within the English health system was lean, aiming to increase supply chains' efficiency and decrease costs. Hence, it did not allow for diverse supplier frameworks.

As decision-makers feared insufficient PPE and ventilator availability, they applied various responsive supply strategies to counteract. The English health system started purchasing PPE and ventilators through direct tender to accelerate processes and from the world market. Based on the investigations by the National Audit Office (2020a), the English health system was late in purchasing PPE and ventilators through direct tender and purchasing products from the world market, which decreased the effect of both supply strategies. The model analysis results support this notion, as identified candidate policies suggest short set-up times, focusing on ordering products promptly. Purchasing critical medical supplies through direct tender was also challenging, as it was challenging to reach suppliers and choose reliable ones. Additionally, export restrictions and delayed shipment times jeopardized the effort of purchasing products from the world market. Both effects were supported by the scenario discovery results, as export restrictions, delayed shipment times, and the production capacities of suppliers were among the most impactful uncertainties affecting a low availability of PPE and ventilators.

Additionally, decision-makers in English health systems reached out to businesses to produce PPE and ventilators domestically. It was evident that domestic production decreased the shortage of PPE and ventilators in the long term, as critical medical supplies were not produced quickly enough. The model results suggest that the maximum value in production was reached once the peak of infections was reached. Compared to other countries and the suggested policies, the UK health system applied fewer initiatives focusing on the innovation of PPE and ventilators. Furthermore, loaning ventilators helped increase the availability of ventilators in the short term.

It is evident that the English health system focused more on applying responsive supply strategies than on actions contributing to the preparedness of health-related crises to maintain the availability of PPE and ventilators during COVID-19. Due to late responses and the apparent structure of the supplier framework, the success of responsive supply strategies was limited. Overall, this discussion highlights the importance of preparedness to organize PPE and ventilators quickly.

6.2.1. Characteristics of Policies Supporting Prepared and Responsive Supply Strategies

This section focuses on the characteristics of policies supporting responsive and prepared supply strategies for critical medical supplies, focusing on the cases for gloves, masks, and ventilators. Other PPE products were not analyzed in the directed search and scenario discovery, as their worst case differed. Hence, no conclusions should be made concerning N95 respirators, gowns and eye protection.

Candidate strategies that help increase the availability of ventilators and PPE apply stockpiling as a supply strategy contributing to the preparedness of health systems. Based on the candidate policies and their characteristics identified in the directed search based on the worst-case scenario, it is evident that the equipment of the stockpiles is higher than recommended for gloves and simple masks. Furthermore, a ventilator stockpile with more than 6000 ventilators can help diminish potential ventilator shortages. Research focusing on the optimal stockpiling level usually concentrates on a balance between costs and inventory level (Chen et al., 2017; Huang et al., 2017). Costs are often used as an argument against implementing a high level of stockpiles, but Dow et al. (2020) points out that it would have been lower for PPE if a stockpile had been in place versus if all products were purchased during an emergency. Hence, it may be applicable to investigate further how to best balance costs and the level of preparedness. However, this topic was out of scope for this research.

Additionally, the composition of products matters, as it may change due to shifts in risks(Greenawald et al., 2021; Wilgis, 2008). Hence, stockpiles need to be adequately maintained - removing expired products and implementing recommendations when necessary (Yorio et al., 2019). Additionally, decision-makers must realize that a stockpile's operation and supplies contribute to its effectiveness during health-related crises. Candidate policies do not allow for delays in the operation of the stockpile. Hence, operations within warehouses (e.g. preparing PPE for delivery, packaging and sorting PPE) must run smoothly, and supplies must be delivered promptly. For instance, candidate policies focusing on PPE supply allow shipment times of up to 1.5 days compared to 5 days by English decision-makers. To improve the operation of stockpiles, Sodhi et al. (2021) suggests researching the management of critical medical supply stockpiles, and Abedrabboh et al. (2021) advises optimizing distribution strategies to manage stockpiles properly.

Concerning the application of responsive supply strategies, which include ramping up domestic production, applying innovative supply strategies, purchasing critical medical supplies through direct tender or from the world market, as well as loaning equipment, short set-up times are apparent. Set-up times refer to the time it takes to place orders with a specific supply strategy or to start production. Decision-makers need to improve set-up times in preparation for health-related crises. The set-up times suggested by the candidate policies are 'possible' but not realistic. Nevertheless, it shows that decision-makers need to decrease the set-up times of different supply strategies. To enable short set-up times, decision-makers can apply crisis frameworks. Crisis frameworks can include accelerating procurement processes and governance processes, as well as a plan of action concerning the implementation of different responsive supply strategies. Such suggestions are also supported by Bhaskar et al. (2020), Frauscher et al. (2020), Okeagu et al. (2021), and Vecchi et al. (2020).

Accelerating procurement processes is especially relevant for purchasing critical medical through direct tender or from the world market. For example, a plan of action can entail how to best ramp up the domestic production of critical medical supplies, such as frameworks to set up public-private partnerships (Dai et al., 2021; OECD, 2020c; Vecchi et al., n.d.). Implementing a diverse supplier framework is another possibility of decreasing the set-up times of the supply strategies purchasing critical medical supplies through direct tender or procurement from the world market. Using a more diverse supplier framework allows decision-makers to reach out to more suppliers during crises. Furthermore, domestic production can be seen as a backup strategy to enable the domestic production of critical medical supplies. in that case, raw materials are stocked to start domestic production quickly.

Regarding the combination of supply strategies applied for the provision of PPE, it stands out that purchasing PPE through direct tender or from the world market are the most prominent supply strategies. Hence, it will be crucial for decision-makers to decrease uncertainties surrounding these supply strategies. Domestic production and innovation were not chosen as often as other supply strategies for PPE. However, the comparison between the candidate policies suggests that applying all available supply strategies can make policies more robust towards uncertainties. Hence, using a wide range of supply strategies can increase the availability of PE and ventilators.

Next to supply strategies itself, factors such as the forecast quality can contribute to the success of a supply strategy, as it helps to organize the correct order size. In the developed SD model, the forecast capturing the PPE and ventilator demand is based on the slope of the demand on the day of the forecast. Using this method can lead to inaccurate order sizes if projections are made for the far future or if sharp increases in demand appear. Hence, it is suggested to collect usage data from hospitals to increase the accuracy of forecasts (Manuel et al., 2021). Furthermore, Friday et al. (2021) points out that knowledge gaps exist in creating better forecasts about extreme situations such as pandemics. Hence, decision-makers need to consider the methods used to forecast the future demand for critical medical supplies.

Overall, it can be said that policies supporting prepared and responsive supply strategies are designed and implemented before a crisis shocks health systems. Concerning stockpiling, this research highlights its importance and reinforces the work of others, suggesting further research on stockpiles' operation. Based on the characteristics of candidate policies, it is also evident that decision-makers must find ways to accelerate the set-up times for responsive supply strategies in preparation for health-related crises. Furthermore, the research result supports the call by researchers to improve the forecast quality during pandemics further.

6.2.2. Mitigating the Impact of Uncertainties on the Success of Supply Strategies

This section focuses on the uncertainties affecting the success of specific supply strategies, so decision-makers in health systems can consider the impact of uncertainties when deciding what supply strategies to apply during a crisis. Furthermore, it considers the scenarios when the candidate policies result in low coverage of ventilators or PPE. Hence, it is also essential to discuss how their impact could be mitigated. The discussion summarizes the uncertainties affecting the availability of ventilators, simple masks, and gloves, as similarities exist.

The scenario discovery results suggest that especially uncertainties associated with the supply strategies purchasing critical medical supplies through direct tender and from the world market have the most impact on the availability of simple masks, gloves, and ventilators. The most prone to uncertainties are supply strategies with the highest production capacities. Especially, delayed shipment times and varying production performances negatively influence both supply strategies' success. To mitigate the effect of these uncertainties, decision-makers can implement diverse supplier frameworks, which means that critical medical supplies are purchased from more suppliers from various countries combined with the development of a domestic production base. Bhaskar et al. (2020), Handfield et al. (2020), and Sodhi et al. (2021) suggest implementing diverse supplier frameworks to decrease the dependency on specific suppliers. Having a diverse supplier framework can help spread orders among many suppliers; hence, a lower performance of one supplier is not as impactful. However, Jiang et al. (2022) raises the valid question of how much a diverse supplier framework can help if the entire network is affected by transport restrictions causing delayed shipment times.

Another possibility to counteract the impact of a drop in suppliers' performance is implementing an information system. Currently, decision-makers place orders with different supply strategies without considering information about the supply strategies' performance. Implementing an information system could allow decision-makers to be more flexible with placing orders with adequate supply strategies/suppliers. Furthermore, Hohenstein et al. (2015) points out that information systems contribute to the resilience of health systems.

The success of the supply strategy purchasing critical medical supplies is also affected significantly by the share of unusable supplies delivered. It is also evident that any percentage above 2.5% can significantly impact a low availability of critical medical supplies. To minimize the percentage of unusable supplies, decision-makers responsible for placing orders must choose reliable suppliers. To have more reliable suppliers available, it is advisable for health systems to diversify their supplier framework. Furthermore, a diverse supplier framework can help to mitigate the effect of export restrictions in case critical medical supplies are purchased from the world market.

The scenario discovery results also show that the combination of the mentioned uncertainties strengthens a low availability of ventilators or PPE. Observing the uncertainties, it is evident that COVID-19 as a health-related crisis was a scenario where this combination of uncertainties appeared. Hence, it is even more critical for decision-makers to mitigate the effect of the uncertainties highlighted in this discussion section.

Overall, it is apparent that especially the supply strategies purchasing products through direct tender and from the world market are affected by uncertainties. Decision-makers within health systems cannot mitigate the uncertainties directly, but they can apply measures to reduce their effect. Furthermore, they can support various supply strategies simultaneously and look into using additional, not yet considered supply strategies.

6.3. Potential Responsive and Prepared Supply Strategies in the Future

The results of this research indicate that the considered supplied strategies are not effective enough to increase the availability of critical medical supplies to a sufficient level. Hence, it is suitable to explore what additional supply strategies health systems could deploy to ensure the availability of critical medical supplies during health-related crises. The presented supply strategies focus on the critical medical supplies ventilators and PPE. The focus of this section is to identify either new supply strategies or ways to enhance the performance of already identified supply strategies. The suggested supply strategies here are either motivated by results of the model and/or supported by literature.

Based on the results of this research, potentially successful responsive and prepared supply strategies need to exhibit short set-up times and short shipment times. First refers to the times it takes for a supply strategy to either place the first order or start production.

A supply strategy that has not been considered in this research is sharing PPE and ventilators across countries. Sharing medical equipment can be a way to use any available overcapacity. Best and Williams (2021) suggests sharing of medical equipment among communities. Hence, it would be interesting to investigate the impact of sharing PPE and ventilators across countries. Similarly, Dey et al. (2020) suggest developing a global stockpile of medical equipment, including a global organization responsible for the management, which could be an attractive solution to consider.

Furthermore, the questions arise whether there is a possibility to loan PPE from other sectors, such as veterinarians. Further research would be needed to identify whether PPE used in other sectors, such as the manufacturing or restaurant sector, could apply to health systems.

Innovative supply strategies considered in the developed system so far focus on financing different innovations. Hence, it is important to realize that the health system can act as an accelerator of innovation by creating platforms where people and nations can collaborate. Kieslinger et al. (2021) suggests open collaboration on a local level. Hence, health systems could create collaborations on a national level. Furthermore, health systems can focus on the support of innovations that are not new inventions but rather improvements in, for instance, manufacturing technologies (Kelley et al., 2021), or innovations focusing on the circularity of critical medical supplies (Klemeš et al., 2020). Gandrup-Marino et al. (2021) points out that little investments are made in research regarding new PPE. Hence, governments have the responsibility to act to enable the responsible reuse of PPE and decrease the amount of waste generated by PPE.

To improve the loaning process of ventilators, it would be possible to create a database with all available ventilators within health systems and other sectors. Relevant information to include in such a database is the location of ventilators, their suitability for different contexts, and information about their user-friendliness.

The ideas presented in this section show that health systems could employ additional supply strategies and improve innovative supply strategies as well as the loaning process of ventilators. Such improvements could increase the success of these supply strategies and increase the availability of critical medical supplies during crises.

6.4. Discussion of System Understanding

This research looked at the understanding of the problem from a rational point of view, considering the impact of a health-related crisis on the demand for critical medical supplies, its resulting shortages, and on the other hand, how health systems can organize equipment. It was assumed that decision-makers responsible for the availability of critical medical supplies during crises could solely focus on the task of organizing equipment. During my research, I came across the following quote to describe political crisis response:

"Action is always ahead of understanding" (Pain & Goodhand, 2002)

During crises, often politics, rather than evidence and lessons learnt from the past or similar contexts, shape the decisions made. For instance, decision-makers responsible for the availability of critical medical supplies are not solely responsible for the organization of supplies but also need to communicate their actions to the public. Hence, this phenomenon is also applicable to health systems, and it highlights the importance of preparedness for health-related crises. Apart from the fact that preparedness enables the responsiveness of health systems, preparedness allows health systems to act in a meaningful manner without fully understanding the problem. Preparedness can prevent the application of response solutions that may not be applicable to the problem at hand. For instance, decision-makers could decide to purchase products from the world market, even though export restrictions may arise shortly, or suppliers may face difficulties in procuring products. Applying this phenomenon to this research means that actions contributing to the preparedness of health systems aiming to maintain the availability of critical medical supplies during health-related crises can prevent the application of ineffective responsive supply strategies.

Before concluding the main research question, I want to present my thoughts regarding the system understanding of this model and its interpretation. It needs to be accounted for that based on the system boundaries, the English health system acts as an independent actor in the world market, aiming to maintain the availability of critical medical supplies during crises. Hence, the impact of the English purchasing behaviour on other health systems was out of scope for this research. Based on the system understanding, a health system's purchasing power determines its position in the world market. In that case, health systems with more financial resources can purchase large quantities of critical medical supplies from the world market once the fear of future shortages appears, also referred to as panic buying. In the developed SD model, the English health system can purchase medical equipment through direct tender and from the world market with high order buffers. Hence, it participates in panic buying. Panic buying appeared during COVID-19 (Bradsher & Alderman, 2020) and aggregated the inequalities concerning the availability of critical medical supplies between countries in the Global North and Global South (Besson Koum, 2020). As the system boundaries did not allow to model the effects of panic buying, the advice to extensively purchase critical medical supplies from the world market is not complete, as the wellbeing of countries with less financial resources is not considered. If the English health system understands itself as independent of other health systems, it is advisable for them to focus on purchasing critical medical supplies from the world market with high order buffers.

7 Conclusion

COVID-19 showed how unprepared health systems worldwide were for a health-related crisis, as shortages of PPE and ventilators appeared. Health systems in the Global North applied a range of supply strategies to organize PPE and ventilators. Still, it was visible that their efforts were not sufficient, as critical medical supplies were scarce. Researchers argued that lean supply chains of medical equipment suppliers and health systems were not prepared and unable to act in times of crisis, which slowed down the response. Given this background and a knowledge gap regarding modelling the supply & demand interaction of critical medical supplies, the question emerged about how health systems could create resilient and responsive supply strategies to meet the demand for ventilators and PPE during a health-related crisis like COVID-19. Hence, this chapter focuses on answering the main research question as well as the four sub-research questions, which helped to develop a coherent answer.

SQ1: How do responsiveness and preparedness of health systems affect the availability of critical medical supplies during a health-related crisis?

According to the WHO (2000), a health system's purpose is to serve its patients at all times. Decision-makers are responsible for serving all patients during a health-related crisis like COVID-19 with sufficient critical medical supplies, such as PPE and ventilators. To maintain its functions during shocks, health systems need to exhibit resilience in all functions. At the beginning of a health-related crisis, preparedness and responsiveness are inevitable, as both enable quick response to ensure the availability of critical medical supplies.

Preparedness refers to any actions taken aiming to make a system more robust before a crisis shakes the understanding and normal functioning of a system. Hence, this characteristic sets the frame of how quickly health systems can act when a crisis hits. This means such actions are also enabled when a health-related crisis like COVID-19 does not threaten health systems. Concerning supply strategies, stockpiling is a prominent supply strategy counting toward preparedness. Furthermore, being prepared for health systems entails actions and policies that enable responsiveness, such as diverse supplier frameworks for critical medical supplies or developing crisis frameworks. These policies take place in preparation for a health-related crisis to ensure the functioning of responsive supply strategies.

On the other hand, *responsiveness* focuses on the immediate actions taken once a crisis hits a health system. Hence, responsive supply strategies are supply strategies that decision-makers can apply to act in a short-term window. Being responsive aims to decrease the decline in the availability of critical medical supplies at the beginning of a crisis. Supply strategies contributing to the responsiveness of a health system and its aim to diminish shortages of critical medical supplies can include creating a domestic production base or supporting the production of innovations. How quickly such responsive supply strategies can be implemented depends on the actions taken by decision-makers in preparation for health-related crises.

Overall, preparedness and responsiveness jointly affect the availability of critical medical supplies during health-related crises. Furthermore, it is essential to realize that the success of responsive actions depends on the preparedness of health systems. Hence, decision-makers responsible for the supply of critical medical supplies during health-related crises need to realize that preparedness is a prerequisite for responsiveness concerning the supply of critical medical supplies during health-related crises.

SQ2: Considering the case of England, how did the preparedness and responsive supply strategies affect the availability of PPE and ventilators during COVID-19?

During the first wave of COVID-19, the availability of critical medical supplies was not always ensured. The results of this research also suggest that shortages of PPE and ventilators are present with a high probability for a significant amount of days, given the uncertainties surrounding health-related crises and critical medical supply chains. It is also evident that the applied supply strategies in England were not ideal, as supply strategies were not implemented effectively. In terms of preparedness strategies, the English system implemented a PPE stockpile to prepare for a health-related crisis. However, delays in deliveries of PPE and delays in warehouse operations slowed down the deliveries of PPE. Furthermore, the availability of PPE within the stockpile was limited, as not enough PPE and not the right PPE were stored. One explanation for this may be that supply chains were designed to be lean, which means they focussed on a few suppliers and a limited domestic production base to increase their efficiency. Preparedness measures that could enable quicker responsiveness were not applied.

In terms of responsive strategies, England applied several responsive supply strategies. On the one hand, the English health system focused on purchasing products through direct tender and from the world market. Both supply strategies can be powerful but were influenced by uncertainties such as delayed shipment times. Additionally, purchasing critical medical supplies from the world market was specifically prone to export restrictions. On the other side, purchasing products through direct tender is influenced by the delivery of unusable PPE or ventilators. England also focused on creating a domestic production base for PPE and ventilators, which helped decrease shortages of PPE and ventilators in the long-term, as the delivery of critical medical supplies reached significant levels after the peak in demand. Lastly, the English health system decided to loan ventilators from the private health sector, which helped to decrease shortages quickly.

In conclusion, the prepared supply strategies stockpiling contributed positively to the availability of PPE; however, not in its full potential due to low quality in operation, maintenance, and volume of the stockpile. The English health system applied a range of responsive supply strategies that contributed to the availability of PPE and ventilators not quickly enough. A deciding factor diminishing the effect of responsive supply strategies was their proneness to uncertainties. Additionally, the English health system's response was slowed down as no policies were implemented to enhance the preparedness for health-related crises. The missing preparedness contributed to a slower success of responsive supply strategies.

SQ3: How can health systems like the English health system improve their supply strategies to organize PPE and ventilators, considering existing uncertainties during health-related crises?

The effect of uncertainties surrounding the responsive supply strategies purchasing critical medical equipment through direct tender and procurement from the world market were significant for the availability of critical medical supplies. The most significant uncertainties are high shipment times, delays in production, export restrictions and the share of unusable critical medical supplies delivered. The uncertainties separately and in combination with each other can significantly impact a low availability of PPE and ventilators during crises. Furthermore, delays in the procurement of raw materials for domestic production are influential.

To mitigate the uncertainties surrounding the responsive supply strategies purchasing products through direct tender or procurement from the world market, decision-makers can apply the following recommendations: (i) developing diverse supplier networks to purchase critical medical supplies from various suppliers from different countries combined with a higher domestic production base, (ii) developing crisis frameworks that allow to accelerate procurement processes and include a plan of action concerning the implementation of responsive supply strategies, (iii) implementing information systems that enable the exchange of information about suppliers and health systems can help decision-makers to place orders with suppliers that are not affected by uncertainties.

To improve the supply strategy stockpiling, decision-makers can apply the following recommendations: (i) implementing a stockpile with raw materials to decrease the set-up time of domestic production, (ii) improving the operations of the stockpile to ensure no delays, (iii) increasing the equipment stored in the stockpiles (up to twice the recommended amount in the case of the English health system). Hence, the optimal inventory level needs to be determined with the knowledge gained through COVID-19.

The recommendations presented in this sub-research question need to be implemented in preparedness for health-related crises, as decision-makers need to decrease potential uncertainties surrounding responsive supply strategies proactively. More, decision-makers can move away from responsive supply strategies prone to uncertainties. To do so, health systems can apply diverse supply strategies simultaneously to reduce the dependency on a specific supply strategy. Such supply strategies can include loaning critical medical supplies, focusing on innovative supply strategies, or investigating additional supply strategies.

SQ 4: What additional strategies can health systems deploy to meet the demand of PPE and ventilators during crises?

The research results suggest that it is necessary for decision-makers in health systems to deploy additional supply strategies to increase the availability of critical medical supplies. To improve current supply strategies by decreasing set-up times or increasing the production capacity, and apply additional responsive supply strategies, decision-makers can implement the following changes: (i) loan ventilators from other sectors and create a database with available ventilators in a country, (ii) loan PPE from other sectors, such as veterinarians, (iii) implement open collaboration to innovate PPE products, (iv) invest in research regarding new PPE products, focusing on increasing reusability of PPE, and (v) share PPE across national health systems.

How can health systems create prepared and responsive critical medical equipment supply strategies during health-related crises?

Before answering the main research question, it is important to highlight that this research suggests that shortages of critical medical supplies are likely to present during health-related crises. Decision-makers can use this information in their communication with HCWs and citizens. Furthermore, it is essential to acknowledge that responsiveness is dependent on preparedness. Preparedness ensures the availability of capacities during crises. It allows decision-makers responsible for the organization of critical medical equipment within health systems to be less reliable on impulsive actions – as during crises *”action comes before understanding”* Pain and Goodhand (2002).

Concerning prepared supply strategies, decision-makers should implement stockpiles for critical medical supplies. Based on this research, stockpiles need to be characterized by higher inventory levels than recommended previously and exhibit no delays concerning the operation within the warehouse or the shipment times.

To increase the success of responsive supply strategies, decision-makers can implement the following recommendations in preparation for health-related crises:

(i) Develop crisis frameworks to decrease the time until orders can be placed with a supply strategy. Crisis frameworks accelerate procurement processes and include a plan of action concerning the implementation of all considered responsive supply strategies.

(ii) Implement a diverse supplier framework with various suppliers from different countries combined with a domestic production base at all times to decrease uncertainties surrounding purchases through direct tender or from the world market.

(iii) Implement an information system that enables exchanging information between suppliers and health systems, so decision-makers can place orders with suppliers that are not affected by uncertainties.

(iv) Store raw materials for the domestic production of critical medical supplies to decrease the set-up time of domestic production processes.
(v) Set up frameworks for public-private partnerships in preparation to decrease the set-up time of domestic production processes.

Additionally, it is recommended that health systems further investigate additional supply strategies and research how currently applied strategies can be improved. Hence, decision-makers can:

(i) Investigate what kind of critical medical supplies can be loaned and create databases with all available critical medical supplies in preparation for future health-related crises.
(ii) Invest in innovative critical medical supply strategies to increase the reusability of specifically PPE and improve manufacturing technologies.
(iii) Create platforms for innovators to collaborate during crises to act as an accelerator for innovative supply strategies.

Concerning the implementation of responsive supply strategies, the research results suggest that decision-makers need to apply several supply strategies simultaneously to decrease the impact of uncertainties. Information systems and more accurate forecasts regarding the future demand can improve the accuracy of order sizes and the decision-making concerning order placements with specific supply strategies.

Lastly, it is essential to understand that if health systems understand themselves as independent actors within the world, purchasing medical equipment from the world market and through direct tender with a high order priority can be successful supply strategies to apply. However, it can come with the cost of increasing inequality between health systems worldwide. Hence, it is suggested to further research the potential of sharing products between health systems.

7.1. Strengths of this Research

One of the strengths of this research is its application of different supply strategies applicable to health systems in the Global North, under the assumptions that the organization of critical medical supplies is centralized during health-related crises. The research applies to health systems with high financial resources, as the applied supply strategies require significant financial capacities and a high level of health system organization. Furthermore, costs are not considered in this research. Additionally, the importance of stockpiling results applies to different kinds of critical medical supplies.

Another strength of this research is that it contributes to the understanding of preparedness and responsiveness within health systems. This research explains how preparedness and responsiveness can affect the availability of critical medical supplies during health-related crises and contributes to the further understanding of resilience in health systems. Furthermore, it explains how preparedness contributes to the responsiveness of health systems.

This research can be considered novel as it combines transmission models with the resulting demand and supply interaction of PPE and ventilators in hospitals. It provides a whole system perspective of a problem, which is relevant to decision-makers of health systems. Furthermore, the developed system dynamics model can give insights into the performance of supply strategies and relevant characteristics of supply strategies. Additionally, using exploratory modelling and analysis contributed to the strength of this work, as it helped identify relevant uncertainties and attributes of successful candidate policies.

Lastly, this research can be adapted for different health-related crises, in this case, prepared for virus infections, different health systems, by changing the initial population or changing the critical medical supplies of interest.

7.2. Limitations

The presented research opportunities focus on the system understanding, the developed System Dynamics model, and the conducted Exploratory Modelling and Analysis.

In the developed system, the English health system is seen as an independent actor in competition with other countries. Even though sharing critical medical supplies may be a suitable solution to increase the availability of medical supplies, it is not yet considered in the system understanding. Furthermore, more research and data are needed to define the uncertainties regarding different supply strategies further. To make this research applicable to health systems globally, the influence of costs needs to be considered. It would be interesting to consider a trade-off analysis between the different supply strategies and their costs for future research. To further validate the system understanding, interactions with experts in the application of the varying supply strategies would be needed.

Concerning the developed SD model, several improvements can be made. An important part of the system that can be improved is the applied decision framework and forecasting method. The decision framework currently does not consider already planned deliveries of products, which is relevant to create more precise order sizes. The forecast is currently solely based on the derivative of the demand for critical medical supplies. Hence, additional factors could be considered in the future. Furthermore, in the model, it is assumed that export restrictions are not applied under the supply strategy direct tender. This leads to a higher use of direct tender combined with a shorter delivery, which may not be the case in reality. Lastly, the procurement world market for PPE is not implemented with delay fixed, but 3rd order delay to make it work. This causes an immediate delivery of products at a lower level, which would not be the case with delay fixed. This feature makes the procurement world market more attractive than it might be in reality.

Additionally, limitations with regard to the applied Exploratory Modelling and Analysis exist. To further investigate the impact of uncertainties on suggested policies, it would be applicable to rerun the open exploration without uncertainties with regard to the spread of a virus to identify relevant uncertainties of different supply strategies. Furthermore, the MORDM cycle could be applied to other PPE products to identify differences between them. Currently, the robustness of policies was evaluated based on box plots. To further analyze the robustness of policies, it would be applicable to select policies based on robustness measures such as the signal-to-noise ratio or maximum regret. In the scenario discovery, the PRIM algorithm could not handle all relevant uncertainties. Hence, I had to reduce the number of uncertainties based on the insufficient values provided by the open exploration. Ideally, I could conduct a scenario discovery including all relevant uncertainties.

7.3. Further Research Opportunities

Based upon the results of this research, I suggest further research on the implementation of crisis frameworks, the operations within stockpiles, and the effect and design of a diverse supplier framework that contributes to the availability of critical medical supplies during health-related crises.

As the results of this thesis highlight the importance of short set-up times for responsive supply strategies, it would be interesting to investigate what actors within the health systems are needed to implement recommendations to achieve short set-up times. Additionally, it would be necessary to explore how the recommended crisis frameworks would have to be designed in detail.

One of the recommendations to shorten set-up times of supply strategies is to implement a diverse supplier framework, as it decreases the dependency on single suppliers. Future research would be relevant to identify what characteristics suppliers would have to exhibit for the supplier framework to be successful and what combination of suppliers would work best to prepare for health-related crises.

Furthermore, this research highlights the importance of operations of critical medical supply stockpiles. Hence, it will be of future interest to research how such a stockpile can be designed and implemented in detail. This would include the equipment stored as well as operational characteristics, for instance, how PPE could best be stored.

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A

National Audit Office as a Source

Reports by the National Audit Office (NAO) have been a resourceful origin of information for this master thesis. Hence, it is useful to explain the NAO's role in the UK and their way of working. The NAO is a "public spending watchdog" independent of the government (National Audit Office, n.d.). The NAO aims to hold the government accountable and to improve public services by conducting audits, that to provide accessible independent insight about issues at hand.

The reports by the NAO included in this master thesis include details regarding their scope, method, and evidence base. The scope of the reports is clearly explained, including pointing out what topics are excluded from the reports. Methods used to gather the information covered in the reports include (National Audit Office, 2020a, 2020b, 2021):

- Reviewing documents, such as policy notes, guidance documents or contract and tendering information.
- Analysing data regarding the topic of interest of a report.
- Interviewing and collecting comments from government officials and relevant stakeholders and sector organizations.
- Engaging with relevant organizations.
- Reviewing frameworks used by government bodies.

The evidence presented in the reports is based on the information collected with the used methods. Limitations of the evidence as well as sources are presented in the reports. This makes the NAO a reliable source to use for this master thesis.

B
Model Overview

This Appendix presents the created Vensim model and its subsystems. In Figure B.1, you can find how different parts of the model presented in the following pages are connected to each other.

How many people are infected in the SEIR model, presented in Figure B.2, depends on the public behaviour regarding contact restrictions (B.3, B.4, B.5), and the susceptible population. How many people can be treated in hospitals in the SEIR model, depends the hospital capacities (B.6). On the other hand, the SEIR model determines the demand for PPE and ventilators (B.7, B.8). The resulting shortages of PPE and ventilators depends on the demand and supply of PPE (B.9,B.11). Which supply strategies are applied and how many products are ordered, depends on the decision framework (B.13), which is based on the shortages of PPE and ventilators. Supply strategies are shown in Figures B.14, B.15, B.16, B.17, B.18, and B.19 The deliveries of PPE and ventilators feed back to the hospital capacities, as well as the shortage of PPE and ventilators.

Since the decision framework and supply strategies follow the same structure for PPE and ventilators, this appendix focuses on the case for ventilators.

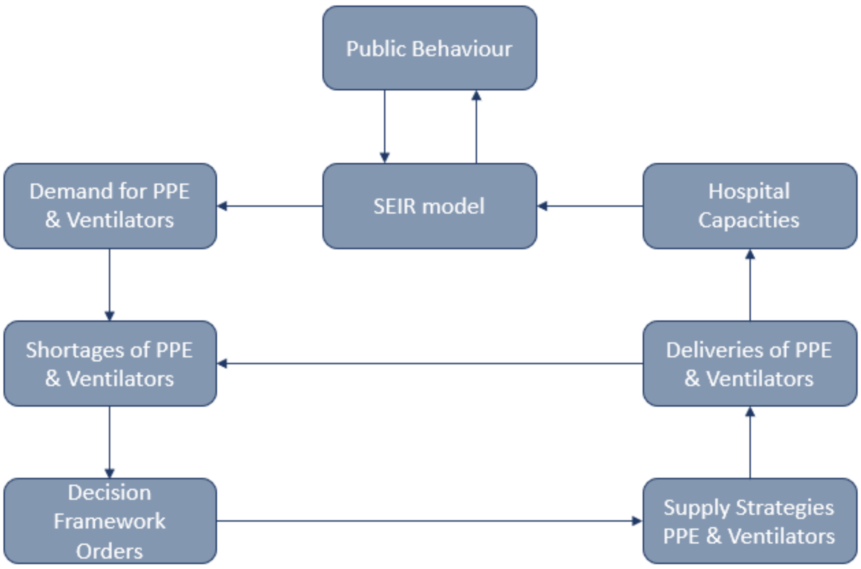


Figure B.1: Connections between subsystems modelled in Vensim

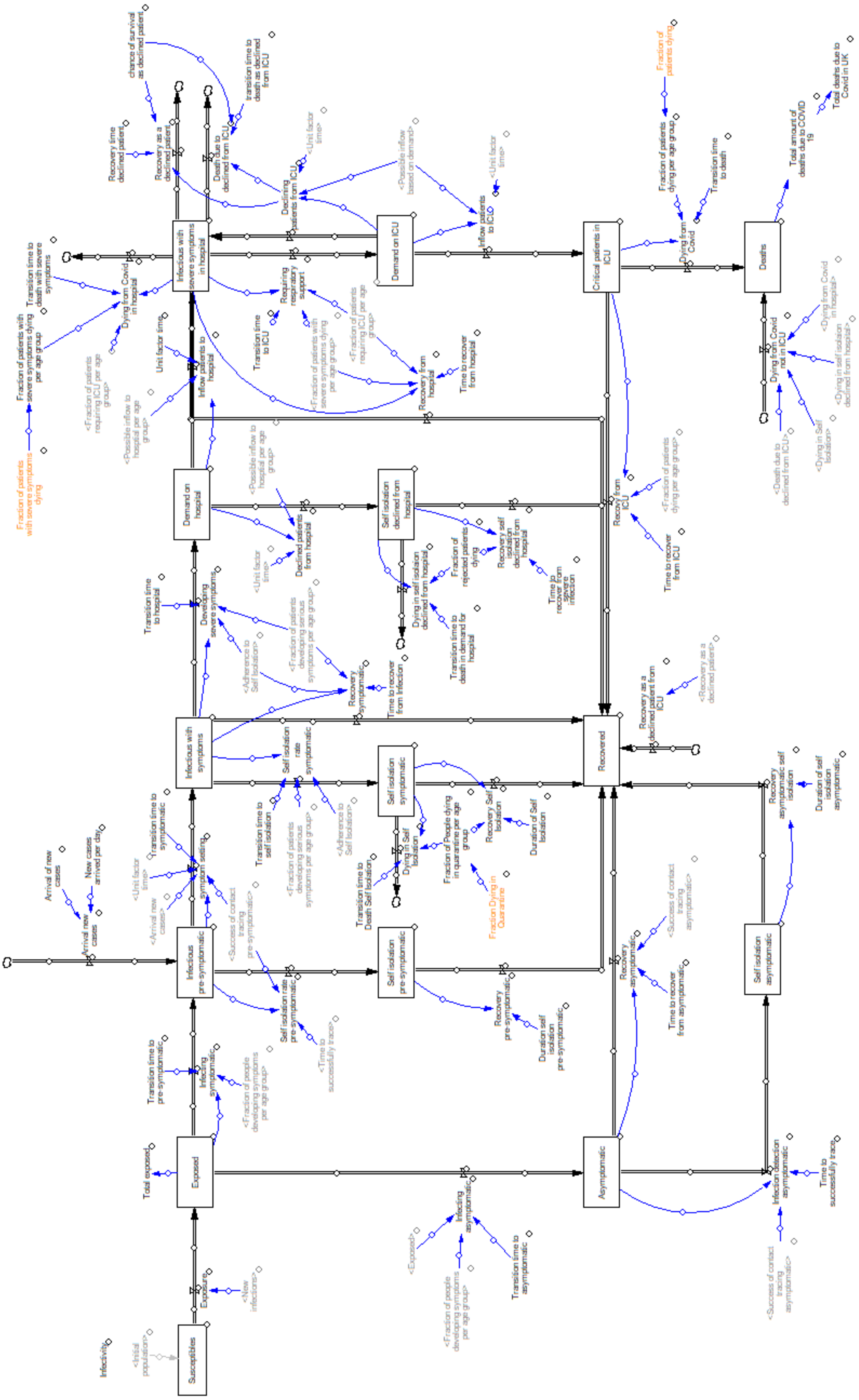


Figure B.2: SEIR model implemented in Vensim

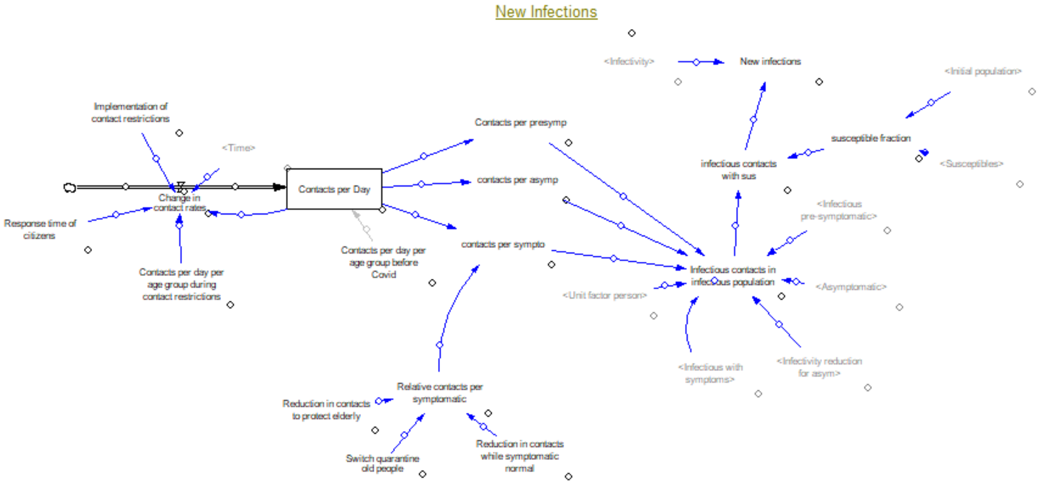


Figure B.3: Development of New Infections based on Contact Restrictions

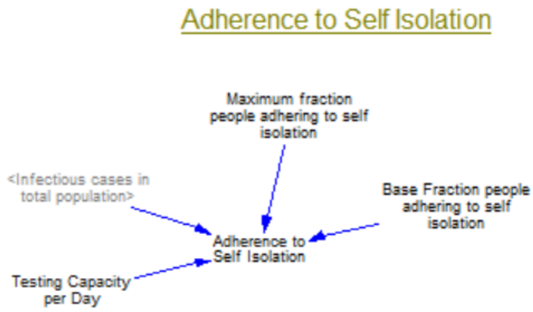


Figure B.4: Changes in Adherence to Self-Isolation

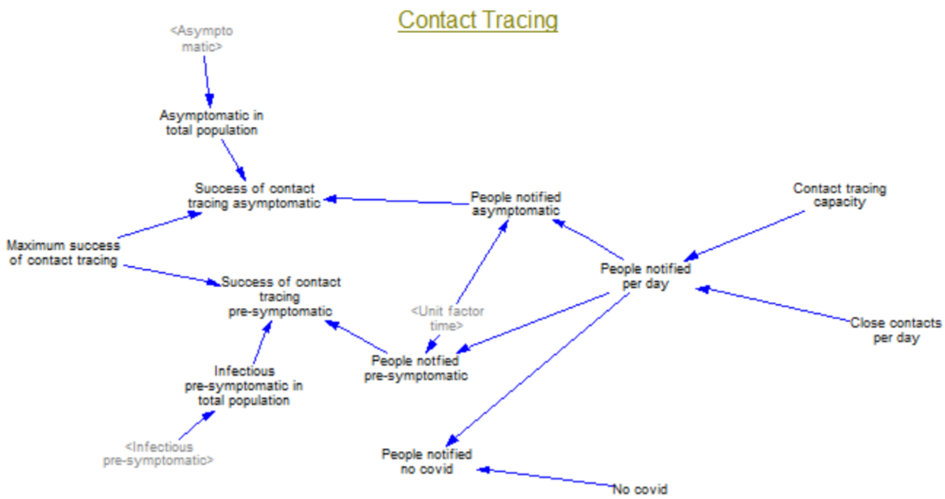


Figure B.5: Impact of Contact Tracing

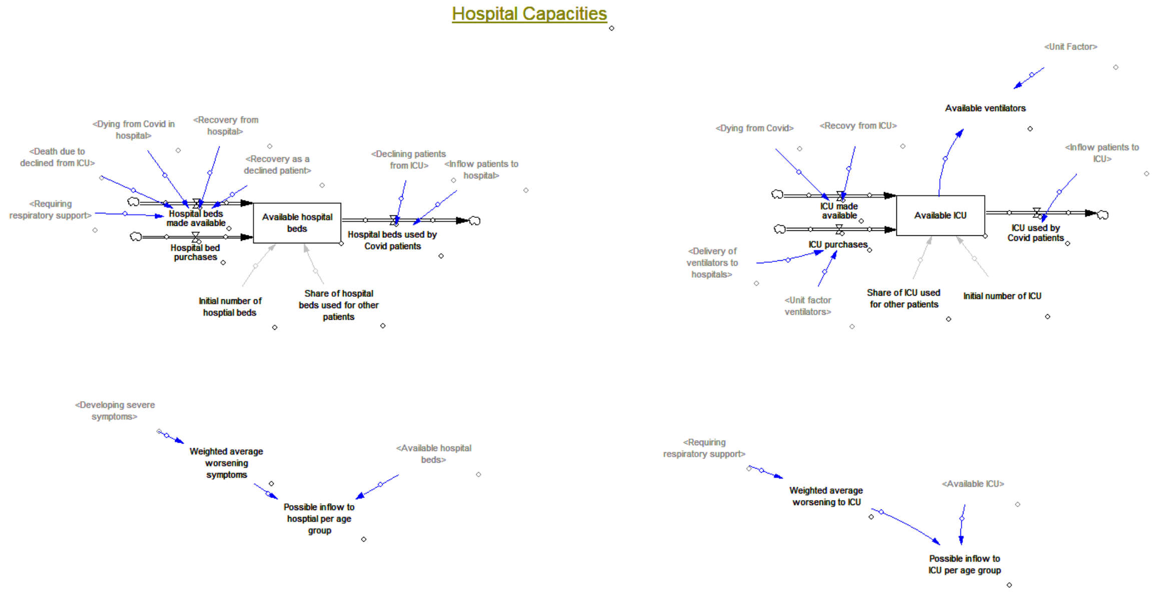


Figure B.6: Hospital Capacities

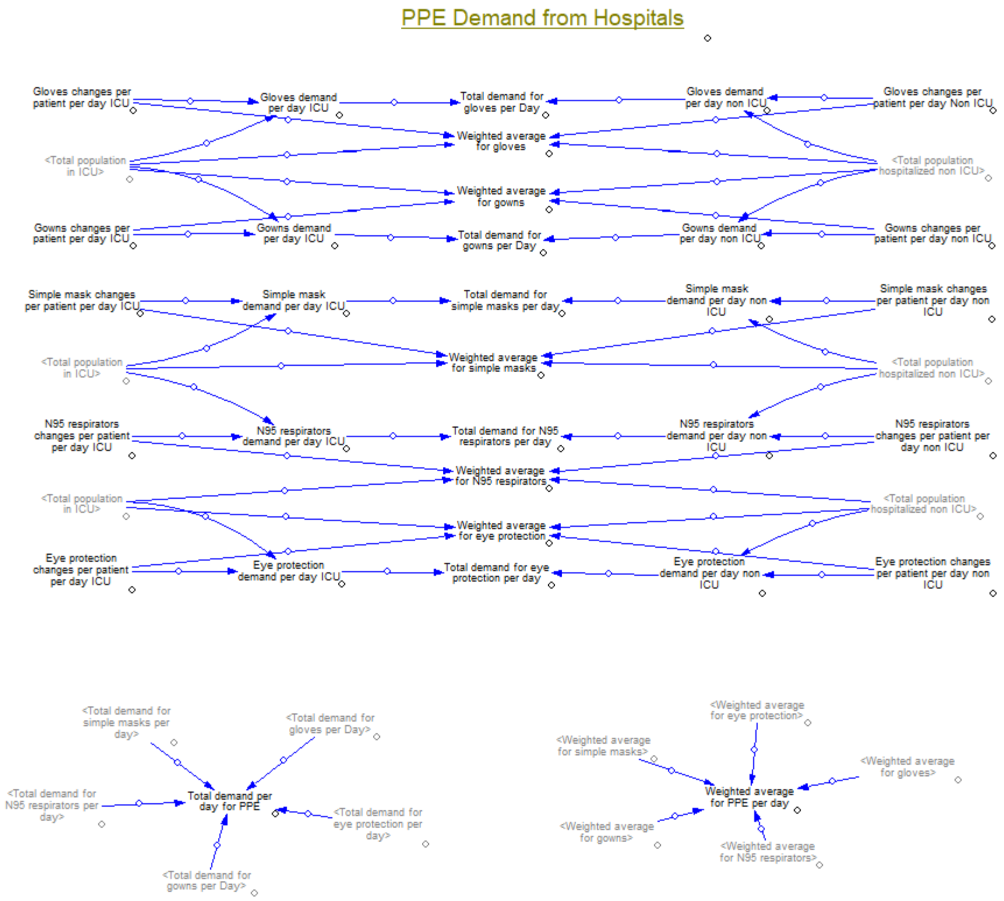


Figure B.7: Demand for PPE per Day

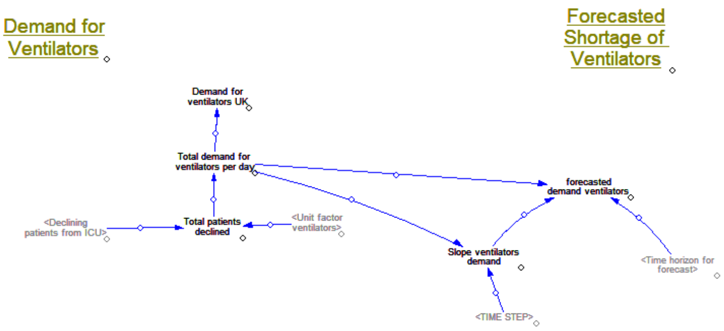


Figure B.8: Demand for Ventilators per day

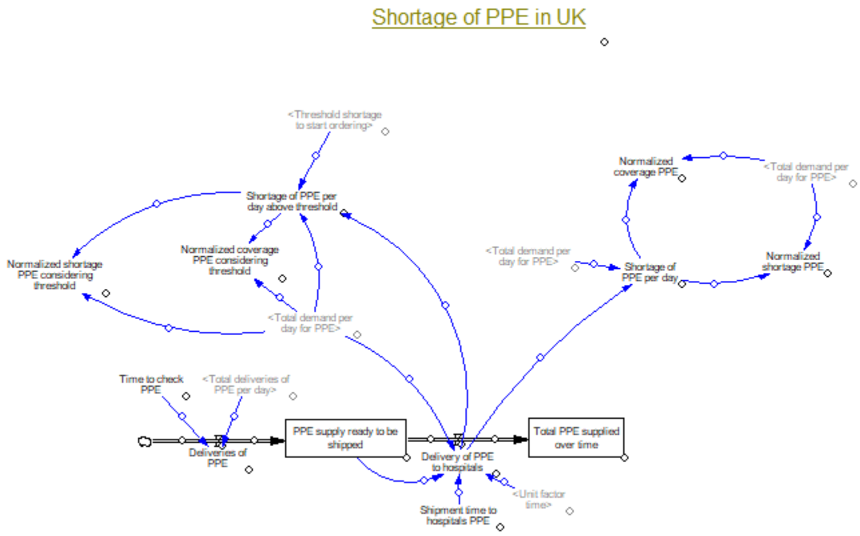


Figure B.9: Shortage of PPE per day based on the deliveries per day

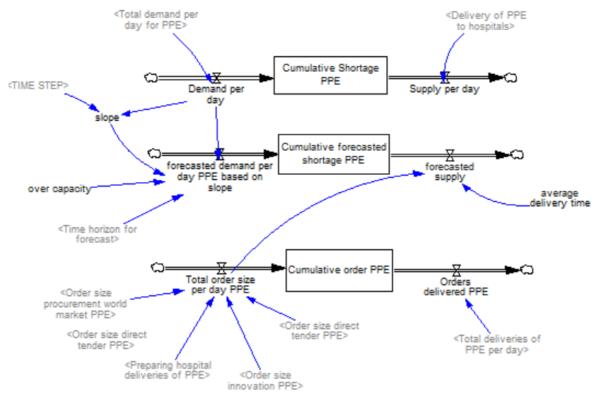


Figure B.10: Focus on forecasted demand of PPE.The entire figure gives an overview of cumulative orders.

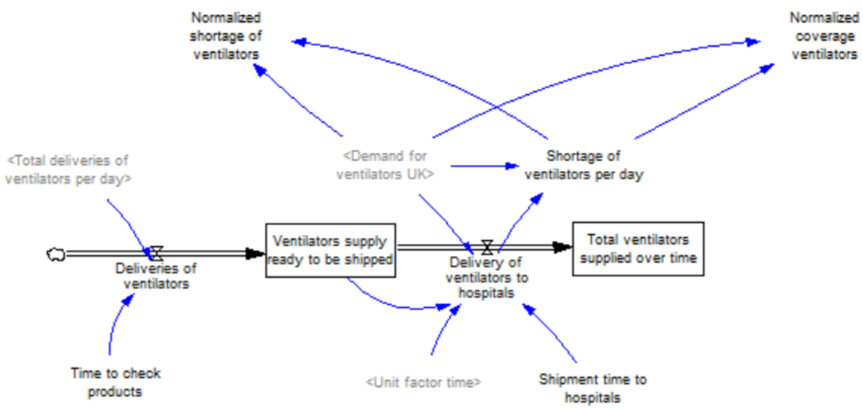


Figure B.11: Shortage of ventilators per day based on the deliveries per day

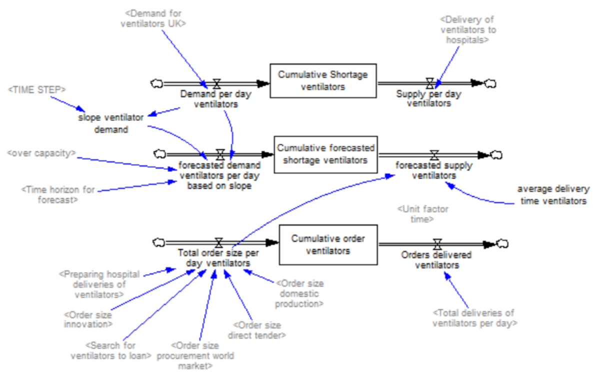


Figure B.12: Focus on forecasted demand for ventilators. The entire figure gives an overview of cumulative orders..

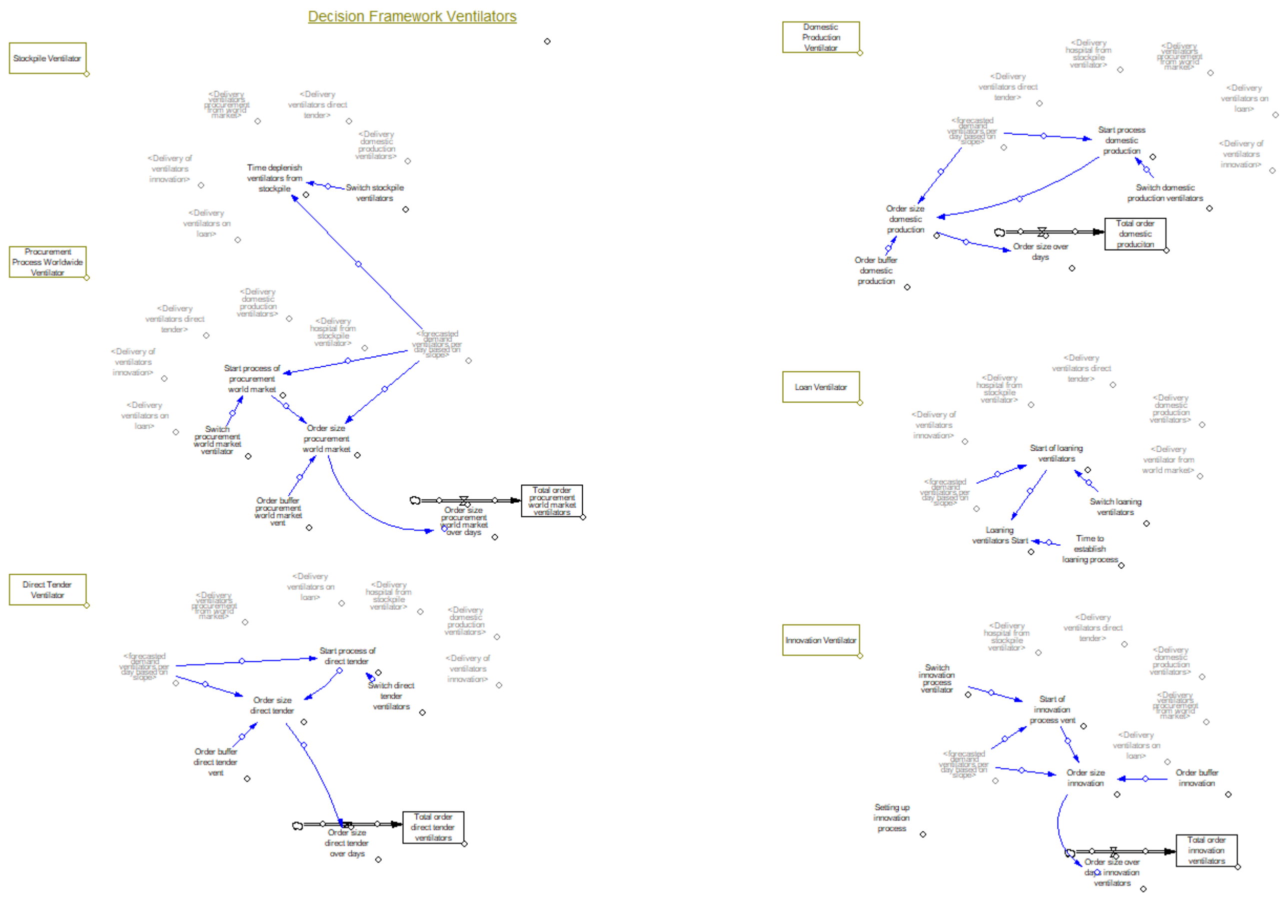


Figure B.13: Overview of decision framework for ventilators

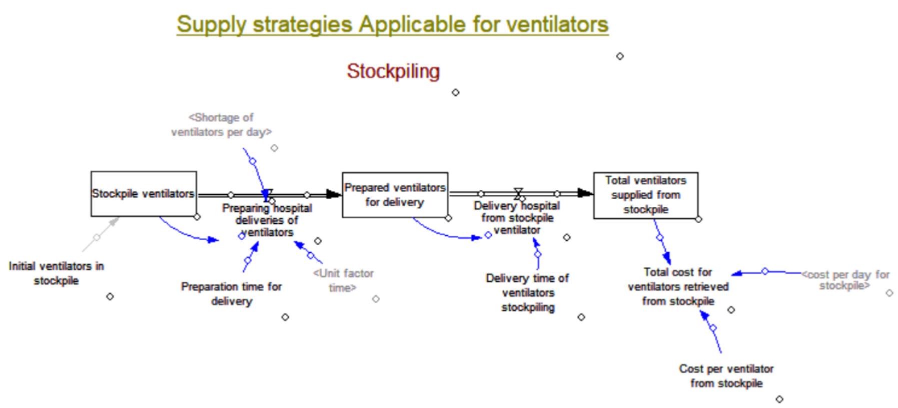


Figure B.14: Stockpiling as a supply strategy

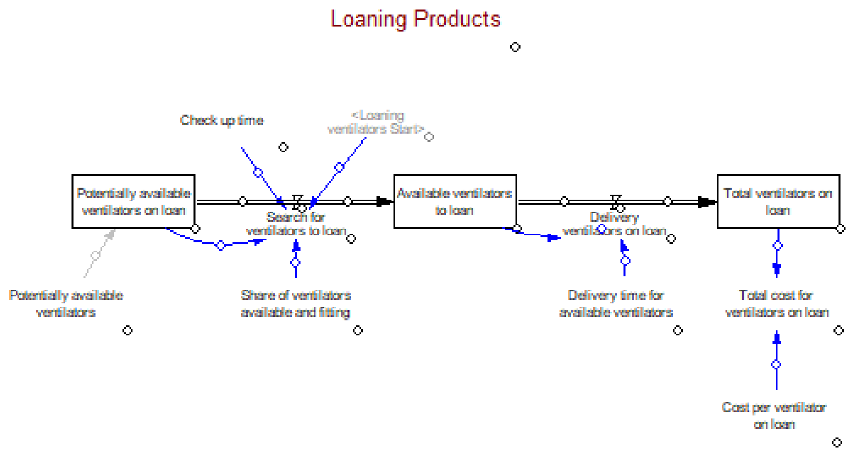


Figure B.15: Loaning ventilators as a supply strategy

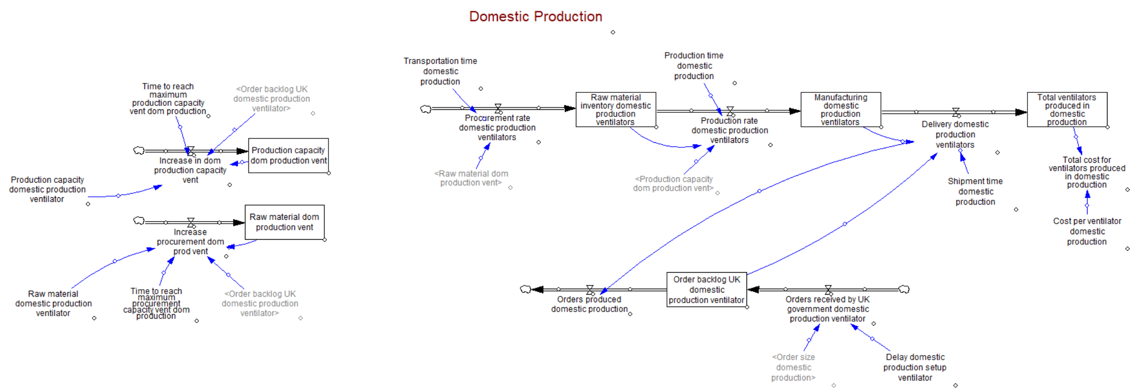


Figure B.16: Domestic production as a supply strategy

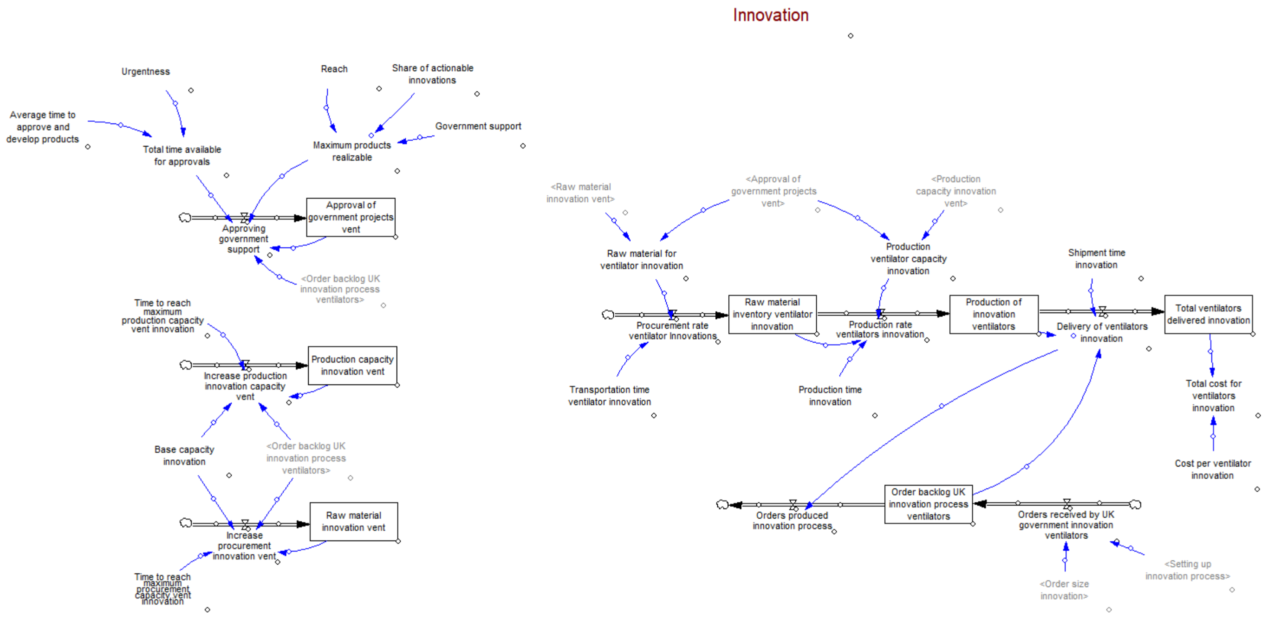


Figure B.17: Innovation as a supply strategy

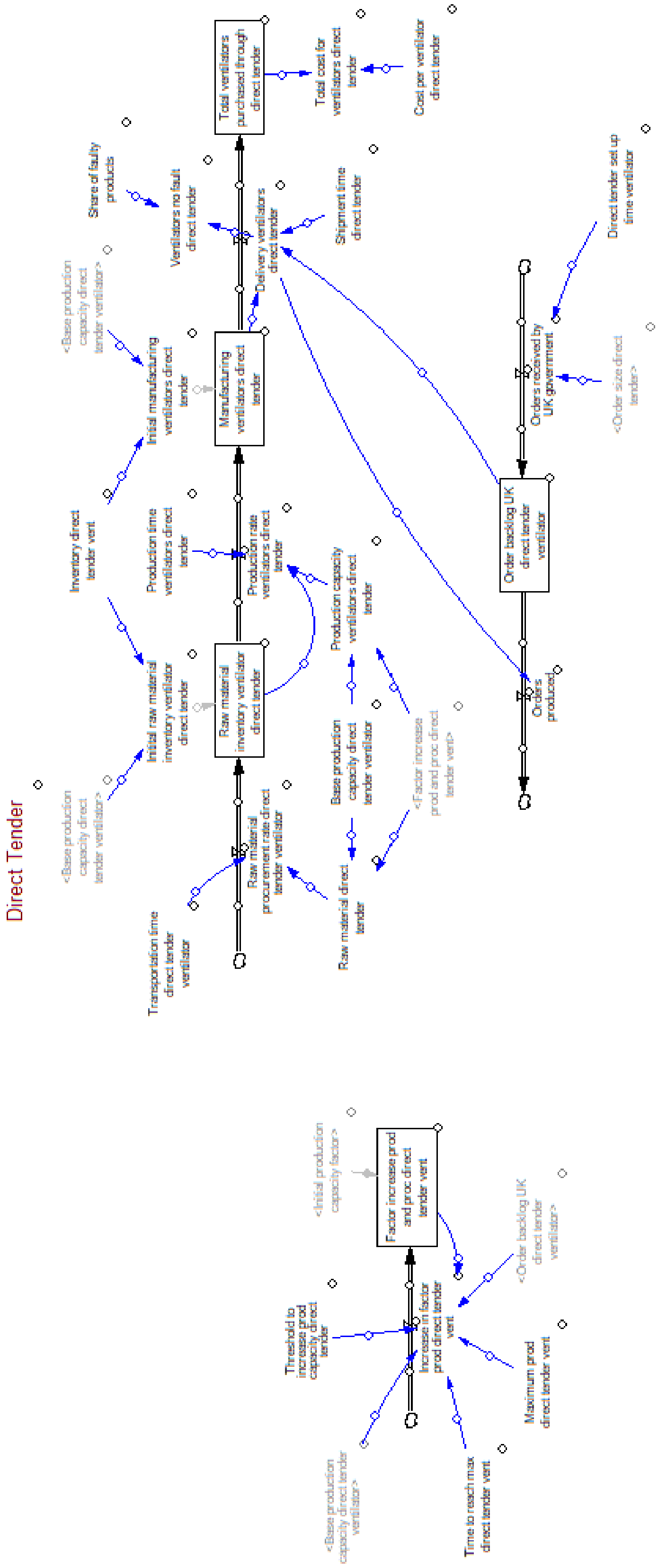


Figure B.18: Direct tender as a supply strategy

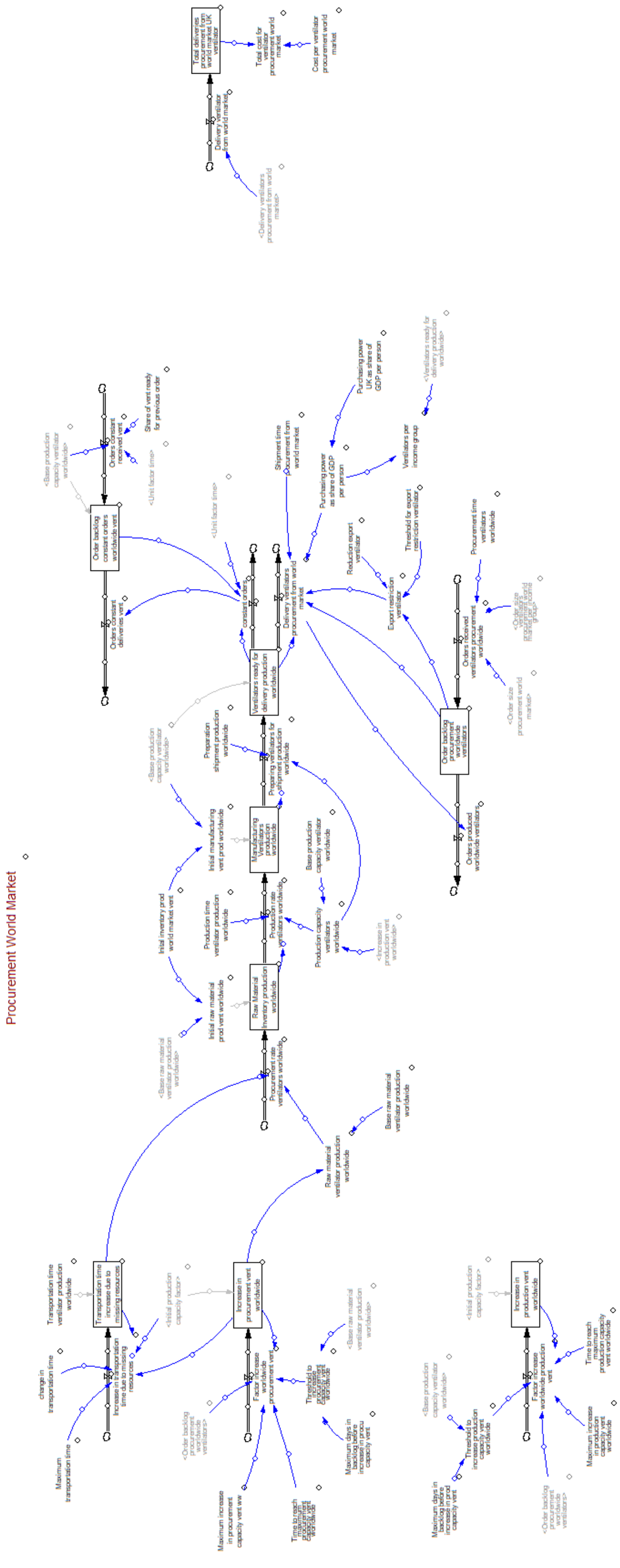


Figure B.19: Procurement from the world market as a supply strategy

C

System Parameters

The input data and assumptions used for the SD model described in chapter 4 can be found in the following tables. Each table focuses on a different subsystem. In the following part, the UK is used as an acronym for England. This table also shows why it is useful to look at a health-related crisis like Covid-19, as many data inputs are assumed. The input data used for the *supply strategies for PPE and ventilators* can be found in Appendix E. This allows the reader to compare the uncertainty range immediately with values used in the base case.

Table C.1: Input for parameters in SEIR model

Parameter	**Value**	**Unit**	**Source/ Basis for Assumption**
Infectivity	0.08	dmnl	Assumed based on report by Public Health England (2021) and journal article by Thompson et al. (2021).
Fraction developing symptoms [Subscripted over 21 age groups]	[(0,0)-(21,1)], (0,0.53), (4,0.53), (5,0.68), (12,0.68), (13,0.8), (21,0.8)	dmnl	Sah et al. (2021)
Fraction of patients developing serious symptoms [Subscripted over 21 age groups]	[(0,0)-(21,1)], (0,0), (1,0.02), (2,0.02), (3,0.05), (4,0.05), (5,0.05), (6,0.05), (7,0.07), (8,0.07), (9,0.11), (10,0.11), (11,0.17), (12,0.17), (13,0.3), (14,0.3), (15,0.31), (16,0.31), (17,0.42), (21,0.42)	dmnl	Keegan and Lyons (2021)
Fraction of patients requiring ICU [Subscripted over 21 age groups]	[(0,0)-(21,1)], (0,0.125), (1,0.125), (2,0.14), (3,0.17), (4,0.19), (5,0.23), (6,0.25), (7,0.26), (8,0.31), (9,0.35), (10,0.4), (11,0.45), (12,0.49), (13,0.47), (14,0.42), (15,0.31), (16,0.77), (17,0.05), (21,0.05)	dmnl	Knock et al. (2021)
Fraction of patients requiring ICU [Subscripted over 21 age groups]	[(0,0)-(21,1)], (0,0.125), (1,0.125), (2,0.14), (3,0.17), (4,0.19), (5,0.23), (6,0.25), (7,0.26), (8,0.31), (9,0.35), (10,0.4), (11,0.45), (12,0.49), (13,0.47), (14,0.42), (15,0.31), (16,0.77), (17,0.05), (21,0.05)	dmnl	Knock et al. (2021)

Fraction of patients with severe symptoms dying [Subscripted over 21 age groups]	[(0,0)-(21,1)], (0,0), (1,0), (2,0), (3,0), (4,0), (5,0), (6,0), (7,0), (8,0.01), (9,0.04), (10,0.05), (11,0.08), (12,0.125), (13,0.15), (14,0.22), (15,0.3), (16,0.375), (17,0.45), (18,0.45), (21,0.45)	dmnl	Knock et al. (2021)
Fraction of patients dying [Subscripted over 21 age groups]	[(0,0)-(21,1)], (0,0), (1,0), (2,0), (3,0), (4,0.05), (5,0.12), (6,0.25), (7,0.25), (8,0.25), (9,0.3), (10,0.35), (11,0.4), (12,0.45), (13,0.52), (14,0.6), (15,0.63), (16,0.65), (17,0.625), (21,0.625)	dmnl	Knock et al. (2021)
Chance of survival as declined patient	0.3	dmnl	Assumption
Fraction of rejected patients dying (from hospital)	0.7	dmnl	Assumption
Fraction dying in Quarantine	[(0,0)-(21,1)],(0,0),(15,0),(16,0.1),(21,0.1)	dmnl	Assumption: Older patients are more likely to pass away while in quarantine
Transition time to pre-symptomatic	3.5	Day	WHO (2020a)
Transition time to symptomatic	1.5	Day	WHO (2020a), Tan et al. (2021)
Arrival of new cases	PULSE(0,40)	dmnl	Assumption: Presents Covid-19 cases arriving through international travel.
New cases arrival per day	UK: 3 High-income countries: 35 Middle-income countries: 160 Low-income countries: 21	Person/Day	Assumption: Based on arrival of cases in the UK in the beginning of Covid-19. Extrapolated to other income groups.
Transition time to hospital	5	Day	Assumption
Transition time to death with severe symptoms	10	Day	Knock et al. (2021)
Recovery time declined patient	21	Day	Assumption: No data was found on this case.
Transition time to death as declined from ICU	7	Day	Assumption: No data was found on this case. Assumed to be faster than recovery.
Transition time to asymptomatic	3.5	Day	WHO (2020a)
Time to successfully trace	2	Day	Kretzschmar et al. (2020)

Duration self-isolation pre-symptomatic	10	Day	Assumption: Transition time to symptomatic + transition time to self-isolation + duration of self-isolation
Transition time to self-isolation	1	Day	Assumption: People go into self-isolation within the day symptoms appear.
Time to recover from Infection	14	Day	It can take up to two weeks to recover (John Hopkins Medicine, 2022).
Duration of self-isolation	7	Day	Advised length of self-isolation if symptomatic during first wave of Covid-19 (Eraso & Hills, 2021).
Transition time to Death Self Isolation	10	Day	Assumption.
Transition time to death in demand for hospital	5	Day	Assumption.
Fraction of rejected patients dying	0.7	dmnl	Assumption: High fraction as insufficient care leads to higher risk of death. No data was found for this case.
Time to recover from severe infection	16	Day	Assumption: No data was found for this case. Based on time to recover from ICU (Knock et al., 2021)
Time to recover from hospital	11	Day	Knock et al. (2021)
Transition time to ICU	2.5	Day	Knock et al. (2021)
Time to recover from asymptomatic	11	Day	Assumption based on research by Sah et al. (2021).
Duration of self-isolation asymptomatic	14	Day	Assumption based on research by Eraso and Hills (2021).
Time to recover from ICU	16	Day	(Knock et al., 2021)
Transition time to death	12	Day	(Knock et al., 2021)

Table C.2: Data Sources for initial population

Parameter	Value	Unit	Source/ Basis for Assumption
Initial Population UK	Values can be found in Vensim model.	Person	Office for National Statistics (UK) (2021)
Initial Population high-income countries	Values can be found in Vensim model.	Person	United Nation - Department of Economic and Social Affarid (2019). When data were not available for specific age groups, data were extrapolated based on the available data. The population in high-income countries excludes England.
Initial Population middle-income countries	Values can be found in Vensim model.	Person	United Nation - Department of Economic and Social Affarid (2019). When data were not available for specific age groups, data were extrapolated based on the available data.
Initial Population low-income countries	Values can be found in Vensim model.	Person	United Nation - Department of Economic and Social Affarid (2019). When data were not available for specific age groups, data were extrapolated based on the available data.

Table C.3: Input data to capture hospital capacities

Parameter	Value	Unit	Source/ Basis for Assumption
Initial number of hospital beds	UK: 139113, High-income countries: 6.69439e+06 Middle-income countries: 1.38073e+07 Low-income countries: 542998	Person	Based on total population and data retrieved from World Bank (2017, 2019)
Share of hospital beds used for other patients	0.5	dmnl	Assumption
Share of ICU used for other patients	0	dmnl	Assumed to be 0 due to high amount of cases of Covid-19
Initial number of ICU	UK: 5938, High-income countries: 221041 Middle-income countries: 86295.8 Low-income countries: 3878.55	Person	Based on total population and assumptions/data retrieved from OECD (2020b), Pasquale et al. (2021), Schultz et al. (2017), and H. C. Turner et al. (2019).

Table C.4: Assumptions used for PPE demand per day

Parameter	Value	Unit	Source/ Basis for Assumption
Glove changes per patient per day ICU	170	PPE/Person/Day	Assumption: Gloves are counted per piece. Changes with patient encounter as per normal practice by all healthcare workers. (Johns Hopkins Center for Health Security, 2020)
Glove changes per patient per day non-ICU	80	PPE/Person/Day	Johns Hopkins Center for Health Security (2020)
Gown changes per patient per day ICU	20	PPE/Person/Day	Johns Hopkins Center for Health Security (2020)
Gown changes per patient per day non-ICU	20	PPE/Person/Day	Johns Hopkins Center for Health Security (2020)
Simple mask changes per patient per day ICU	10	PPE/Person/Day	Johns Hopkins Center for Health Security (2020)
Simple mask changes per patient per day non-ICU	10	PPE/Person/Day	Johns Hopkins Center for Health Security (2020)
N95 respirators changes per patient per day ICU	4	PPE/Person/Day	Assumed to be 4 due to mistake. Johns Hopkins Center for Health Security (2020)
N95 respirators changes per patient per day non-ICU	2.6	PPE/Person/Day	Johns Hopkins Center for Health Security (2020)
Eye protection changes per patient per day ICU	4	PPE/Person/Day	Assumed to be the same amount of changes as for N95 respirators.
Eye protection changes per patient per day non-ICU	2.6	PPE/Person/Day	Assumed to be the same amount of changes as for N95 respirators.

Table C.5: Input data to calculate new infections and adherence to self-isolation

Parameter	Value	Unit	Source/ Basis for Assumption
Response time of citizens	14	Day	It is assumed it takes citizens two weeks to reduce their contacts
Implementation of contact restrictions	70	day	Assumed to be in an early phase of the pandemic. The value can be adjusted.
Contacts per day per age group during contact restrictions	[(0,0)-(21,10)], (0,2.8), (1,2.8), (2,2.8), (3,2.8), (4,2.8), (5,3), (6,3), (7,3.1), (8,3.1), (9,3.1), (10,3.1), (11,3), (12,3), (13,2.5), (14,2.5), (15,2), (21,2)	Person/Day	Jarvis et al. (2020)
Contacts per day per age group during contact restrictions	[(0,6)-(21,20)],(0,6.31579), (1,7.4), (2,7.4), (3,8), (4,10.8), (5,12), (6,12.1), (10,12), (12,9), (14,8.5), (16,8.5), (17,7.6), (20,7.6), (21,7.6)	Person/Day	Jarvis et al. (2020)
Reduction in contacts to protect elderly	0.3	dmnl	Assumption that public behaviour changes if people are encouraged to protect elderly. Depends on Switch.

Reduction in contacts to protect elderly	0.6	dmnl	Assumption that symptomatic people reduce contacts further
Maximum fraction people adhering to self-isolation	0.86	dmnl	Eraso and Hills (2021)
Base fraction people adhering to self-isolation	0.666	dmnl	Eraso and Hills (2021)
Testing capacity per day	0	Person	In the beginning people were not able to get tested frequently in the UK. Hence, the assumption that the testing capacity is 0.
Maximum success of contact tracing	0.3	dmnl	Between 20% - 40% (Gardner & Kilpatrick, 2021).
Contact tracing capacity	50000	dmnl	Assumption
Close contacts per day	4	Person/Day	Assumption
No covid	0.1	dmnl	Share of people contacted without Covid-19. Assumption.

Table C.6: Assumptions for PPE and ventilator demand by other income groups

Parameter	**Value**	**Unit**	**Source/ Basis for Assumption**
Share of forecasted PPE demand covered by procurement world markets	0.5	dmnl	Assumption. This variable determines what fraction of the demand for PPE is purchased by procurement from the world market.
Share of forecasted shortage covered by procurement world market (for ventilators)	0.5	dmnl	Assumption. This variable determines what fraction of the demand for ventilators is purchased by procurement from the world market.

D

Overview of suggested policies

Table D.1: Detailed description of policy suggestions for ventilators

	UK Tactic	**All Out**	**Focus Innovation**	**Foresight National**
Order buffer innovation	–	1	2	2
Switch innovation process ventilator	0	1	1	1
Start of innovation process vent	–	From beginning	From beginning	From beginning
Switch loaning ventilators	1	1	1	1
Start of innovation of loaning ventilators	Forecasted demand – delivery stockpile – delivery procurement world market – delivery direct tender	From beginning	Forecasted demand – delivery stockpile – delivery innovation	Forecasted demand-delivery stockpile – delivery innovation – delivery domestic production
Order buffer domestic production	2	1	2	2
Switch domestic production ventilator	1	1	1	1
Start process domestic production	Forecasted demand – delivery stockpile-delivery procurement world market – delivery direct tender	–	Forecasted demand -delivery stockpile – delivery innovation	From beginning
Order buffer direct tender vent	2	1	1	1
Switch direct tender ventilators	1	1	1	1

Start of direct tender	Forecasted demand – stockpile	From beginning	Forecasted demand – delivery stockpile – delivery innovation – delivery domestic stockpile – loan	Forecasted demand – delivery stockpile – delivery innovation - delivery domestic production
Order buffer procurement world market vent	2	1	1	1
Switch procurement world market ventilator	1	1	1	1
Start process of procurement world market	Forecasted demand – stockpile	From beginning	Forecasted demand – delivery stockpile – delivery innovation – delivery domestic stockpile – loan	Forecasted demand – delivery stockpile – delivery innovation - delivery domestic production
Switch stockpile ventilators	0	0	0	1
Time deplenish ventilators from stockpile	–	–	–	From beginning
Initial ventilators in stockpile	0	0	0	1000
Government support	0.05	0.05	0.1	0.07
Reach	5000	5000	5000	5000
Urgency	1	1	5	2.5
Preparation time for delivery	2	2	2	1
Delivery time of ventilators stockpiling	5	5	5	2.5

Table D.2: Detailed description of policy suggestions for PPE

	UK Tactic	**All Out**	**Focus Innovation**	**Foresight National**
Order buffer innovation PPE	–	1	2	2
Switch innovation PPE	0	1	1	1
Start of innovation process PPE	–	From beginning	From beginning	From beginning
Order buffer domestic production PPE	1	1	2	2
Switch domestic production PPE	1	1	1	1
Start process domestic production PPE	Forecasted demand – delivery stockpile – delivery procurement world market – delivery direct tender	From beginning	Forecasted demand - delivery stockpile – delivery innovation	From beginning

Order buffer direct tender PPE	1.25	1	1	1
Switch direct tender PPE	1	1	1	1
Start process of direct tender PPE	Forecasted demand -stockpile	From beginning	Forecasted demand – delivery stockpile – delivery innovation – delivery domestic production – loan	Forecasted demand – delivery stockpile – delivery innovation – delivery domestic production
Order buffer procurement world market PPE	1.25	1	1	1
Switch procurement world market PPE	1	1	1	1
Start process of procurement world market PPE	Forecasted demand – stockpile	From beginning	Forecasted demand – delivery stockpile – delivery innovation – delivery domestic production – loan	Forecasted demand – delivery stockpile – delivery innovation – delivery domestic production
Switch stockpile PPE	1	1	1	1
Time deplenish PPE from stockpile	From beginning	From beginning	From beginning	From beginning
Government budget for PPE	0.5	0.75	1	1
Reach PPE	100	100	200	100
Urgency	0.8	2.5	5	2.5
Preparation time for delivery PPE	10	10	10	5
Delivery time of PPE stockpiling	5	5	5	2.5
Initial value PPE	Initial values	Initial values value	Initial values	1.5 * initial values
Time horizon for forecast	14	14	14	21
Number of patients	100	100	100	100
Days in stock	14	14	14	7
overcapacity	1	1.5	1.5	1.5
Delays in innovation supply chain for PPE and ventilators			no delays in innovation supply chain	no delays in innovation supply chain

E

Outcomes, Uncertainties & Decision Levers in the System

The following appendix focuses on the outcomes of interest, decision levers and uncertainties within the system. The outcomes of interest are summarized as it is applicable. Decision levers and uncertainties for PPE and ventilators are presented separately.

The outcomes of interest are the same for ventilators and PPE. Hence, the outcomes of interest are summarized. In the directed search, only the total normalized coverage was considered. For the uncertainty analysis, all the listed outcomes were implemented to be able to provide a more thorough analysis if needed.

Table E.1: Outcomes of interest for PPE and ventilators

Outcome	**Maximize/ Minimize**	**Definition**
Total normalized coverage	Maximize	This variable tracks the total normalized coverage over time. This means the cumulative value is report. Ideally, the coverage equals 210, which would mean that at all days all patients can be served with ventilators, or all HCWs have sufficient PPE available to serve patients. During the analysis, only the value at the end of the simulation is of interest.
Shortage of PPE/ventilators per day		This variable reports the absolute shortage of medical equipment reported per day. This variable is of less interest, as it provides less insight to decision-makers, given they do not know the absolute demand for PPE or ventilators.
Normalized shortage of PPE/ventilators		This variable provides insight about how high the shortage per day is relative to the total demand. The normalized shortage can be insightful to decision-makers as it shows what percentage of patients or HCWs receive sufficient equipment per day. This variable highlights at what point of time the most shortages exist and when improvements start to be visible.

Normalized coverage PPE/ventilators		The normalized coverage of PPE and ventilators reports the coverage of PPE and ventilators in the same manner as the shortage of ventilators. This outcome is used as an input for the total normalized coverage.
Total cost for PPE/ventilators		This variable reports the costs of PPE or ventilators purchased and delivered considering all supply strategies. Furthermore, the maintenance costs for stockpiling medical equipment are considered.
Supply ready to be shipped		This outcome report the amount of supply that is ready to be distributed to hospitals in England per day. It shows decision-makers at what point of times buffers start existing.

The levers decision-makers have available are described in detail below. This means the decision lever the range of values for the decision lever is defined and the reasoning for the choice is presented. Where possible, sources are implemented. It is differentiated between the decision levers considered for PPE and ventilators. For PPE, only the decision levers relevant for simple masks and gloves are presented, as these two PPE products were used for the MORDM cycle.

Table E.2: Decision levers to affect the provision of PPE

Decision lever	**Range**	**Assumption Description**
Switch procurement world market PPE	(0, 1)	The switch determines whether a supply strategy is applied or not.It can be applied, if it takes the value 1. The value 0 indicates it is not applied.
Switch direct tender PPE	(0, 1)	
Switch domestic production PPE	(0, 1)	
Switch innovation PPE	(0, 1)	
Order buffer procurement world market PPE	(0.5, 3)	The order buffer indicates the overcapacity in ordering. It is assumed that decision-makers can order more products than needed. The UK for instance ordered as much as possible. A higher value presents a higher prioritization.
Order buffer direct tender PPE	(0.5, 3)	
Order buffer domestic production PPE	(0.5, 3)	
Order buffer innovation PPE	(0.5, 3)	
Delay domestic production PPE	(7, 60)	The delays regarding the set-up times for each process indicate when the first order is placed. The lowest times possible are 7 days as an equivalent to one week. Set-up times that take a shorter time initally, consider a lower minimum and a lower maximum value.
Direct tender set up time PPE	(7, 45)	
Set up time procurement PPE worldwide	(14, 50)	
Setting up innovation process PPE	(10, 45)	
Days in Stock	(7, 30)	The days in stock determine the threshold to start ordering PPE. The values considered are between a week and a month. No data could be found online regarding this value.
Number of patients	(10, 500)	The number of patients determine the threshold to start ordering PPE. The values considered are between a week and a month. No data could be found online regarding this value.
Time horizon for forecast	(5, 30)	Decision-makers can decide what time horizon is considered for shortages. A maximum range of one month is chosen. One week is considered a short-forecast horizon, 3 to 4 weeks can be considered a long horizon (Coroneo et al., 2022). Also, given the simplicity in calculating the forecast value no higher time horizon is considered.

Government budget for PPE	(0, 1)	The government can choose to a share of PPE innovation supply strategies. It is considered that the government support all proposed innovative projects to increase the attractiveness of innovative supply strategies.
Urgency	(0, 5)	Similarly, it is assumed that the government can influence how urgent action is taken to develop ideas regarding innovative PPE supply strategies. It is assumed that this value can range between 0 and 5. 5 is the maximum value considered on the scale.
Share of products expiring per day	(0, 0.0016667)	It was evident that expired products were stored in the stockpile for PPE (National Audit Office, 2020b). This value determines how high the share of PPE expiring each day is. A maximum value of 5% per month of the the entire inventory is assumed to be the maximum. No data was found about what share of the PPE stockpile expired in reality per month.
Share of stockpile available to hospitals	(0, 1)	This variable determines what share of PPE in the stockpile is delivered to hospital compared to other settings. In reality, 80% of the English stockpile went to hospitals (National Audit Office, 2020b).
Initial value for simple masks in stockpile UK	(0, 468000000)	3 times the advised value mentioned in reports by National Audit Office (2020b) were considered to be the maximum PPE to be stored. This value may be difficult to reach in reality due to costs.
Initial value for gloves in stockpile UK	(0, 1079700000)	
Preparation time for delivery PPE	(1, 10)	The values refer to the delay in days in the operation of the stockpile, as it was the case (National Audit Office, 2020b).
Delivery time of PPE stockpiling	(1, 21)	
Time to check PPE	(1, 5)	The values refer to delay in days in checking products and their distribution.
Shipment time to hospitals PPE	(1, 10)	

Table E.3: Decision levers for the provision of ventilators

Decision lever	**Range**	**Assumption Description**
Switch procurement world market ventilator	(0, 1)	The switch determines whether a supply strategy is applied or not. It can be applied, if it takes the value 1. The value 0 indicates it is not applied. Stockpiling is assumed to be applied.
Switch direct tender ventilators	(0, 1)	
Switch innovation process ventilator	(0, 1)	
Switch loaning ventilators	(0, 1)	
Switch domestic production ventilators	(0, 1)	
Direct tender set up time ventilator	(7, 45)	The delays regarding the set-up times for each process indicate when the first order is placed. The lowest times possible are 7 days as an equivalent to one week. Set-up times that take a shorter time initally, consider a lower minimum and a lower maximum value. More complicated procurement processes come with a higher maximum value.
Check up time	(5, 21)	
Delay domestic production setup ventilator	(7, 60)	
Procurement time ventilators worldwide	(15, 60)	
Time to establish loaning process	(3.5 , 21)	

Order buffer procurement world market vent	(0.5, 3)	The order buffer indicates the overcapacity in ordering. It is assumed that decision-makers can order more products than needed. The UK for instance ordered as much as possible. A higher value presents a higher prioritization.
Order buffer direct tender vent	(0.5, 3)	
Order buffer domestic production	(0.5, 3)	
Order buffer innovation	(0.5, 3)	
Initial ventilators in stockpile	(0, 10000)	No data was available regarding the number of ventilators stored. The range is based on the maximum demand plus an assumed bugger.
Delivery time of ventilators stockpiling	(1, 14)	The values refer to the delay in days in the operation of the stockpile (National Audit Office, 2020b). A delay is also possible for the delivery.
Preparation time for delivery	(1, 10)	
Time horizon for forecast	(5, 30)	One week is considered a short-forecast horizon, 3 to 4 weeks can be considered a long horizon (Coroneo et al., 2022).Given the simplicity in calculating the forecast value no higher time horizon is considered.
Urgency	(0, 5)	It is assumed that the government can influence how urgent action is taken to develop ideas regarding innovative ventilator supply strategies. It is assumed that this value can range between 0 and 5. 5 is the maximum value considered on the scale.
Government support	(0, 0.1)	The government can choose to a share of ventilator innovation supply strategies. It is considered that the government support cannot support all proposed projects, as the development of ventilators is often more expensive. The number refers to the amount of ventilator designs approved during the ventilator challenge versus its reach (National Audit Office, 2020a).
Time to check products	(1, 5)	The values refer to delay in days in checking products and their distribution.
Shipment time to hospitals	(1, 10)	

The uncertainties considered for the directed search of PPE (simple masks and gloves) and ventilators are presented in Table E.4 and E.5. Next to the range considered for MORDM, this table also includes the assumed value in the original Vensim model, as well as the source or assumption that is supporting the assumed value and the range of values considered.

Table E.4: Uncertainties considered for PPE

Uncertainty	Assumed Value	Range	Source/Reason
Gloves changes per patient per day ICU	170	(85,250)	The assumed value is based on the assumptions provided by Johns Hopkins Center for Health Security (2020). For the uncertainty analysis, a value of from 50% to 150% of the orignal assumptions to consider for changes.
Gloves changes per patient per day Non ICU	80	(40,120)	
Gowns changes per patient per day ICU	20	(10, 30)	
Gowns changes per patient per day non ICU	20	(10, 30)	
Simple mask changes per patient per day ICU	10	(5, 15)	
Simple mask changes per patient per day non ICU	10	(5, 15)	

N95 respirators changes per patient per day ICU	3	(2, 6)	
N95 respirators changes per patient per day non ICU	2.6	(1.3 , 3.9)	
Eye protection changes per patient per day ICU	6	(3, 9)	
Eye protection changes per patient per day non ICU	6	(1.3 , 3.9)	
Infectivity	0.08	(0.02, 0.2)	Based on the assumption, that the infectivity of a coronavirus varies, as it did among different wave of COVID-19.
Transportation time domestic production PPE	7	(1, 14)	Refers to the delay in material procurement. It is assumed that the delivery of products can be up to 14 days late due to raw material shortages.
Base raw material procurement eye protection domestic production	12000	(20000, 240000)	No information was provided regarding production values. Hence high varieties were chosen. Products that are easier to produce have higher ranges (gloves, simple masks). Furthermore, orders by the English health system were considered as corner points (National Audit Office, 2020b), as well as production capacities of other countries.
Base raw material procurement simple masks domestic production	598800	(20000, 900000)	
Base raw material procurement N95 respirators domestic production	17400	(5000, 50000)	
Base raw material procurement gowns domestic production	120000	(20000, 240000)	
Base raw material procurement gloves domestic production	698630	(144000, 1440000)	
Shipment time domestic production PPE	5	(1,21)	Department of Health and Social Care (2020) assures deliveries within 5 days for PPE from stockpile. The assumption is made that the same delivery time is considered for domestic supply strategies. Additional delays are considered as an uncertainty.
Production time domestic production PPE	1.5	(1,10)	Refers to appearing delays in the production, likely to happen due to learning process in production.
Time to reach maximum production capacity PPE dom production	45	(5, 90)	Refers to the time it takes to reach the maximum production or procurement capacity. Assumption, that it can take up to three months to reach maximum. (Based on shipment times)
Time to reach maximum procurement capacity PPE dom production	30	(5, 90)	
Transportation time direct tender PPE	5	(1,21)	Delays in purchasing raw material for production of PPE. Such delays can increase due to raw material shortages (OECD, 2020a).
Threshold to start direct tender PPE	7	(1,21)	This value determines when suppliers reached through direct tender start to increase their production. It refers to the existing order backlog.
Time to reach max direct tender	21	(1,90)	Time it takes to reaches maximum increase in production & procurement capacity

Maximum prod direct tender PPE	4	(1,12)	Based on the increase possible for Chinese producers (OECD, 2020a).
Base raw material eye protection capacity direct tender	199600	(20000, 400000)	Assumed to be 5% of production & procurement capacity worldwide. Assumption that Enlgish health system can reach up to 10% of capacity purchasing products from world market.
Base raw material simple masks capacity direct tender	998000	(50000, 2000000)	
Base raw material N95 respirators capacity direct tender	29000	(10000, 100000)	
Base raw material gowns capacity direct tender	199600	(20000, 400000)	
Base raw material gloves capacity direct tender	3.49315 e+07	(800000, 50000000)	
Shipment time direct tender PPE	45	(14, 120)	It is assumed products are flown into the country, as the delivery is guaranteed and the price per piece is higher. This takes between 1 and 3 months (Gandrup-Marino et al., 2021).
Share of faulty PPE	0.15	(0, 0.5)	7& of ordered PPE was unusable in the first year of Covid-19 (Public Accounts Committee - House of Commons, 2021b). Assumed to reach up to 50%.
Reach PPE	100	(0, 300)	Maximum businesses that can be reached. No information was available. Hence, the values is assumed to be uncertain. Values above 300 return unrealistic production capacities.
Production time Innovation PPE	2	(1, 7)	Delays in production of suppliers using innovative supply strategies. Uncertainty range assumed, as no data was found.
Transportation time PPE innovation	7	(3.5, 21)	Delays in prcorument of raw material. Likely to occur as suppliers often procure smaller amounts of raw material, and suppliers are new to production. Hence, higher uncertainty compared to other delays in procurement.
Shipment time innovation PPE	5	(3.5, 14)	Department of Health and Social Care (2020) assures deliveries within 5 days for PPE from stockpile. The assumption is made that the same delivery time is considered for domestic supply strategies. Fewer than domestic production because of smaller the design of innovative supply strategies.
Base raw material eye protection capacity innovation PPE	1000	(500, 30000)	Refers to the production capacity per idea. Uncertainty ranges based on information found in articles, plus additional range where applicable (Cates, 2020; Dixon, 2020; Pagliacolo & Pavka, 2020).
Base raw material simple masks capacity innovation PPE	7200	(3400, 34000)	
Base raw material N95 respirators capacity innovation PPE	1000	(3400, 25200)	
Base raw material gowns capacity innovation PPE	2000	(500, 30000)	
Base raw material gloves capacity innovation PPE	20000	(5000, 160000)	

Average time to approve and develop PPE	60	(15, 120)	Assumption, based on time it took to develop ventilators (National Audit Office, 2020a). Range can be smaller or higher depending on PPE and innovation.
Time to reach maximum production capacity PPE innovation	30	(5, 90)	Time it takes to reach their maximum capacity. The uncertainty range considers the length of the pandemic.
Time to reach maximum procurement capacity PPE innovation	30	(5, 90)	
Base raw material procurement eye protection worldwide	3.992e+06	(1000000, 8000000)	Assumed values consider the available data where possible (Bhutta & Santhakumar, 2016; OECD, 2020a; Statista, 2022). Uncertainty ranges assume up to 3 times the current output.
Base raw material procurement simple masks worldwide	1.996e+07	(10000000, 60000000)	
Base raw material procurement N95 respirators worldwide	580000	(120000, 1200000)	
Base raw material procurement gowns worldwide	3.992e +06	(1000000, 8000000)	
Base raw material procurement gloves worldwide	6.9863e +08	(200000000, 1400000000)	
Preparation shipment PPE production worldwide	1	(1, 10)	Delay in preparing shipments for delivery. Interruptions of production are more likely due to health-related crisis.
Threshold for export restriction PPE		(1000000, 100000000)	Value determines at what order backlog of orders due to Covid-19, the export is restricted. As no information was available, a wide range was considered.
Delayed shipment time	90	(30, 360)	Lead times of up to 9 months were possible (Gandrup-Marino et al., 2021).
Normal shipment time	21	(7, 45)	Delivery times from PPE producers in China ranges between 15 to 30 days (HisoMedical, 2020). A wider range was considered to account for suppliers located in other countries as well.
Reduction export PPE	1	(0, 1)	Value determines to what percentage the export is reduced. It can take on any value between 0 and 1.
Maximum increase in procurement capacity PPE	10	(1, 20)	Assumption based on production icnrease by Chinese suppliers (OECD, 2020a). Considered uncertainty range based on length of simulation run.
Time to reach maximum procurement capacity PPE worldwide	120	(14, 210)	
Maximum days in backlog before increase in procurement capacity	10	(1, 45)	
Maximum increase in production capacity PPE	10	(1, 20)	Assumption based on production icnrease by Chinese suppliers (OECD, 2020a). Considered uncertainty range based on length of simulation run.
Time to reach maximum production capacity PPE worldwide	120	(14, 210)	
Maximum days in backlog before increase in prod capacity	14	(1, 20)	Determines when suppliers increase their production. No knowledge available.
Share of PPE ready for previous order	0.6	(0.2, 1)	Assumption, that share of products goes to orders that were placed before Covid-19 hit the system.

Maximum transportation time PPE procurement world market	8	(1, 20)	Assumption based on production icnrease by Chinese suppliers (OECD, 2020a). Considered uncertainty range based on length of simulation run.
change in transportation time PPE	21	(7, 60)	

Table E.5: Uncertainties considered for ventilators

Uncertainty	Assumed Value	Range	Source/Reason
Production time domestic production	1	(1,5)	Delay in domestic production.
Transportation time domestic production	1.5	(1,10)	Delay in procurement of materials for domestic production. Higher than the delay in domestic production, as it may be more difficult to reach raw suppliers ad hoc.
Shipment time domestic production	3	(1,21)	Department of Health and Social Care (2020) assures deliveries within 5 days for PPE from stockpile. The assumption is made that the same delivery time is considered for domestic supply strategies. Additional delays are considered as an uncertainty. Higher for ventilators, since transportation may be more difficult.
Time to reach maximum production capacity vent dom production	14	(5,30)	Assumption based on information about ventilator challenge provided by Leggett (2020). Assumption is that it also includes raw materials.
Time to reach maximum procurement capacity vent dom production	10	(5,30)	
Production capacity domestic production ventilator	214	(50,430)	
Raw material domestic production ventilator	214	(50,430)	
Delivery time for available ventilators	5	(1,21)	Department of Health and Social Care (2020) assures deliveries within 5 days for PPE from stockpile. The assumption is made that the same delivery time is considered for domestic supply strategies. Additional delays are considered as an uncertainty. Higher for ventilators, since transportation may be more difficult.
Share of ventilators available and fitting	0.7	(0,1)	Refers to share of ventilators suitable to be loaned, it can take any value between 0 and 1
Potentially available ventilators	1700	(0,2400)	Refers to the ventilators that may be suitable to loan. Assumption based on National Audit Office (2020a)
Transportation time direct tender ventilator	1.5	(1,10)	Delays may occur in the procurement of raw material for production of ventilators.
Production time ventilators direct tender	1	(1,10)	Delays may occur due Covid-19 in the production.

Base production capacity direct tender ventilator	250	(50,500)	Assumed to be similar to the values of domestic production, as it is difficult to order products.
Maximum prod direct tender vent	5	(1,10)	Assumption
Shipment time direct tender	30	(14,120)	Range based on available information about shipment times of PPE.
Share of faulty products	0.05	(0, 0.5)	Assumption that up to half of purchased ventilators can be useless, based on reports about unusable ventilators (Campbell, 2020).
Reach	2000	(0,2000)	Based on the number of participating businesses (National Audit Office, 2020a).
Production time innovation	1	(1,7)	Assumption that production may be delayed.
Share of actionable innovations	0.1	(0.01, 0.2)	Share of actionable innovations is assumed to lower for ventilators, as they are more complicated to produce.
Transportation time ventilator innovation	1.5	(1,10)	Assumption that delays may exist in the delivery of raw material for innovative suppliers.
Shipment time innovation	5	(1,21)	Department of Health and Social Care (2020) assures deliveries within 5 days for PPE from stockpile. The assumption is made that the same delivery time is considered for domestic supply strategies. Additional delays are considered as an uncertainty. Higher for ventilators, since transportation may be more difficult.
Average time to approve and develop products	45	(15,120)	Higher range of values compared to PPE chosen because it is more complicated to produce. Range is based on information from ventilator challenge (National Audit Office, 2020a).
Time to reach maximum production capacity vent innovation	30	(10,90)	No information available regarding both variables. Range of uncertainty is choasen based on length of pandemic
Time to reach maximum procurement capacity vent innovation	21	(10,90)	
Base capacity innovation	10	(1,30)	Assumed to be very low, as single project may only produce a few ventilators per week.
Production time ventilator production worldwide	1	(1,10)	Delays may occur due to health-related crisis.
Base raw material ventilator production worldwide	850	(430,1720)	Assumption, that US produces 1/3 of ventilator supply, and based on the information about ventilator production in US (Statista, 2020).
Preparation shipment production worldwide	1	(1,10)	Delays may occur due to health-related crisis.
Purchasing power UK as share of GDP per person	0.0881	(0.05, 0.33)	Refers to the purchasing power of England. Based on the GDP of the UK, compared to other countries.

Shipment time procurement from world market	30	(14,90)	Shipment times may be delayed (similar assumption as with PPE)
Maximum increase in procurement capacity vent ww	10	(1,15)	Based on information about ventilator production in US (Statista, 2020).
Time to reach maximum procurement capacity vent worldwide	210	(60,480)	Based on information about ventilator production in US (Statista, 2020).
Maximum increase in production capacity vent worldwide	10	(1,15)	Based on the data derived from (Statista, 2020).
Reduction export ventilator	1	(0,1)	Export restrictions may apply to ventilators.
Time to reach maximum production capacity vent worldwide	240	(60,480)	Due to the complexity of the ventilator production, it takes more time to reach full production capacity.
Maximum days in backlog before increase in prod capacity vent	30	(14,60)	No information available regarding both variables.
Maximum days in backlog before increase in procu capacity vent	21	(14,60)	
Share of vent ready for previous order	0.7	(0.2,1)	Assumption that share of ventilators is delivered to customers whose demand did not result from COVID-19.
Maximum transportation time	3	(1,3)	No information available regarding both variables.
change in transportation time	21	(7,60)	

F

Exploratory Modelling and Analysis

The appendix presents additional material concerning the results in Chapter 5.

F.1. Open Exploration

Figure F.1 presents the results of the open exploration concerning the deliveries of simple masks per day of the supply strategies direct tender and procurement from the world market.

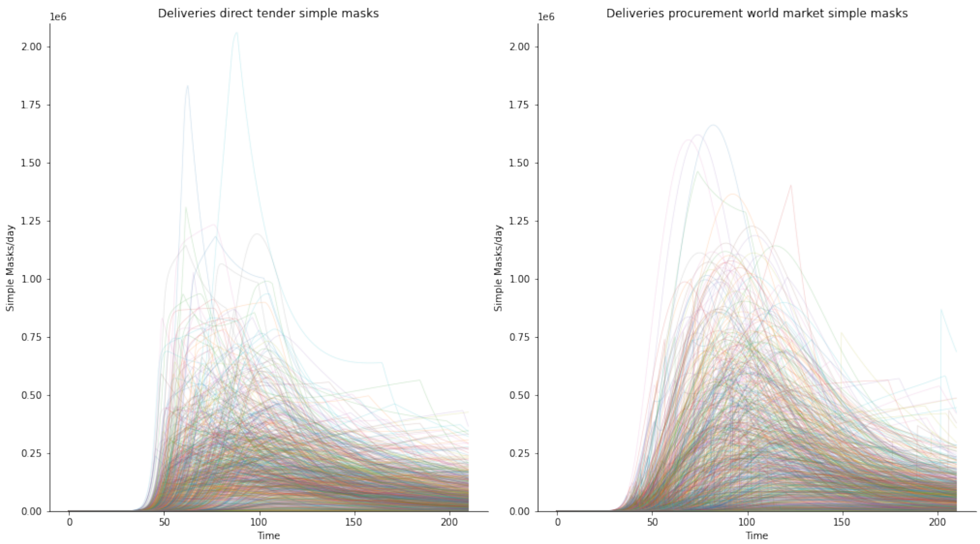


Figure F.1: Deliveries of Simple Masks through Direct Tender and Procurement from the World Market

In Figure F.2, you can find the range of possible outcomes regarding the total normalized coverage of PPE. Ideally, this value equals 210 as the simulation runs for 210 days. The first thing that stands out is that all policies perform in a similar manner given the uncertainties. The envelopes of results are almost identical, similarly, the density in results is almost identical. The range in coverage over time is almost the same, as the form of the envelopes (shaded areas) and density in results show.

Figure F.3 presents the KDE plots concerning all PPE products in this research. It is visible that the shortage across different PPE behave similarly. A high shortage for a significant amount of time is apparent under the considered experiments

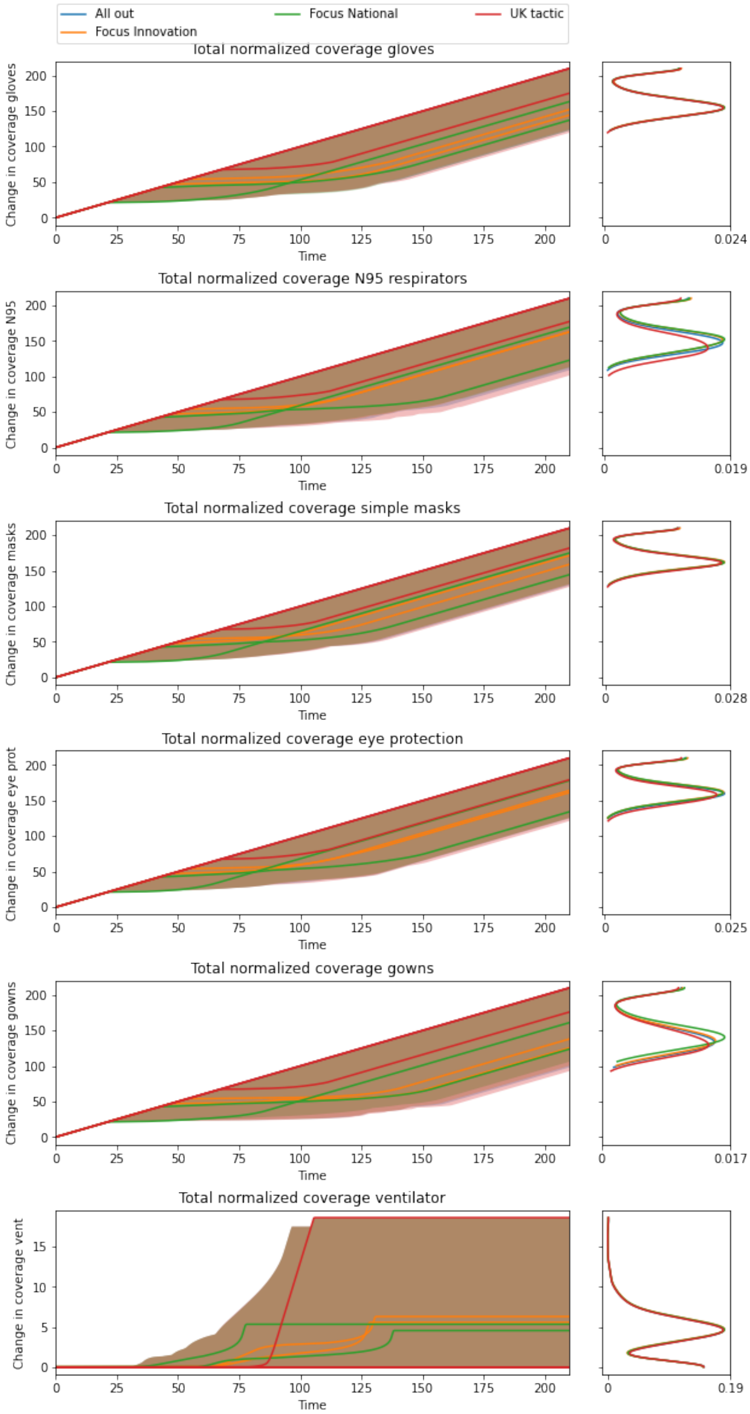


Figure F.2: Change in coverage of demand for eye protection over time

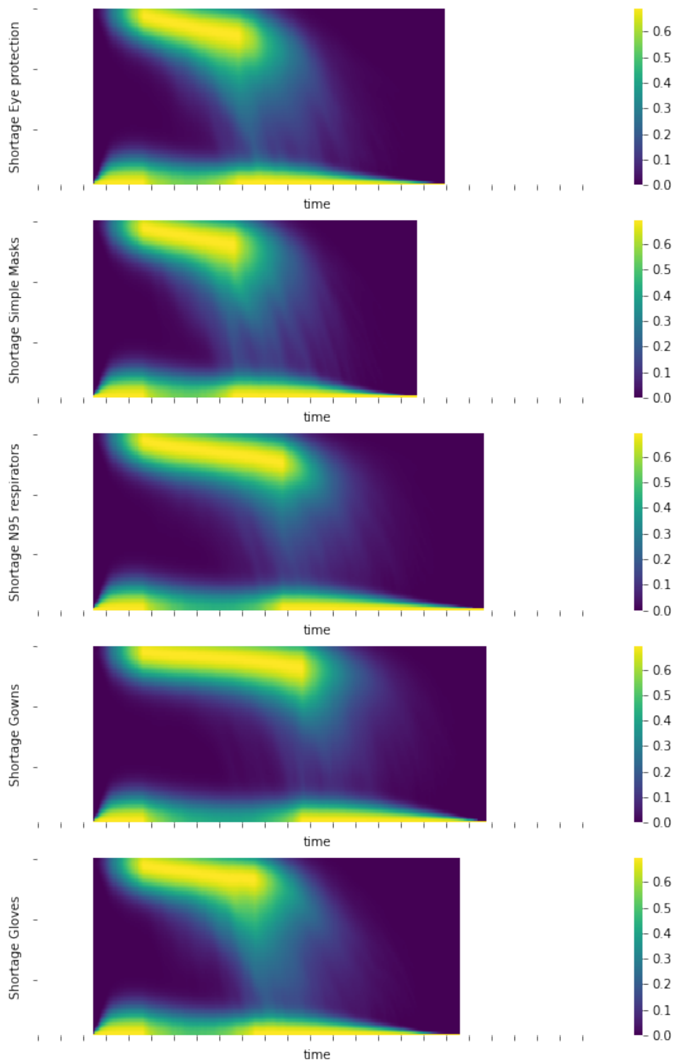


Figure F.3: KDE plots for each PPE over time

F.2. Characteristics of candidate policies simple masks and gloves

To track the convergence of the optimization process to find candidate policies, the ε-progress is considered. The ε-value almost converges, as Figure F.4 shows. Hence, it is likely that the six discovered candidate strategies that perform best given the worst case scenario. Furthermore, it is possible to consider six candidate policies for the uncertainty analysis.

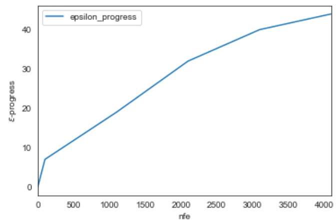


Figure F.4: ε-progress over nfe for gloves and simple masks

Figure F.5 provides insights regarding the characteristics of the gloves stockpile suggested by the identified candidate policies. Figure F.6 provides insight about the effect of operational variables on the coverage of gloves and simple masks.

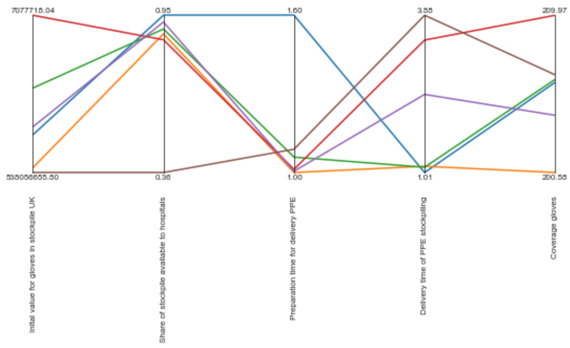


Figure F.5: Characteristics of Stockpile for Simple Masks in Candidate Policies

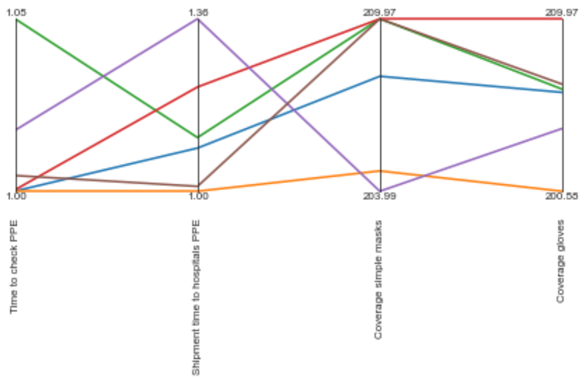


Figure F.6: Trade-off plot concerning checking PPE

Figure F.7 shows the box plot of the candidate policies. It is visible that the robustness of the candidate policies is similar for the case of gloves and simple masks.

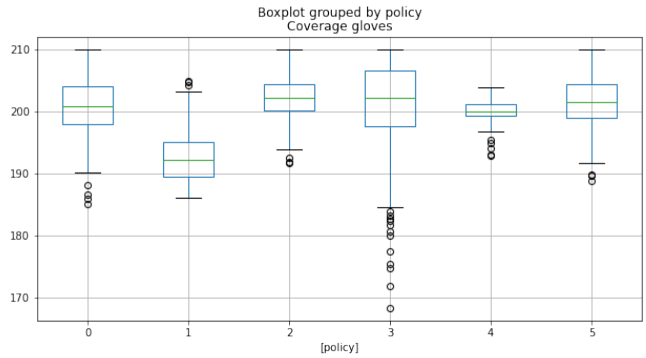


Figure F.7: Box Plot of the Candidate Policies focusing on Gloves

F.3. Characteristics of candidate policies ventilators

The ε-value almost converges, as Figure F.8 shows. Hence, it was applicable to consider the candidate policy for the further analysis.

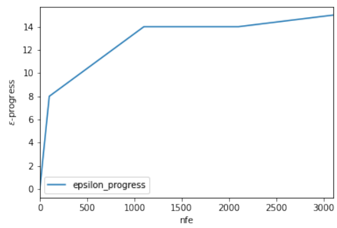


Figure F.8: ε-progress over nfe for ventilators

Table F.1, Table F.2, and Table F.3 describe the decision levers of the candidate strategy of interest for ventilators.

Table F.1: Set-up times for Supply Strategies used for Candidate policy for ventilators

Delay direct tender setup	**Time to establish loaning process**	**Delay domestic production setup**
7.97	15.27	7.26

Table F.2: Characteristics of Ventilator Stockpile

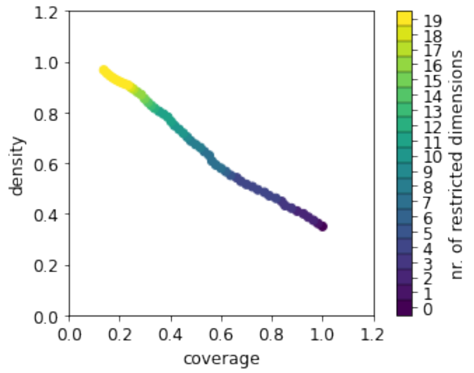
Initial ventilators in stockpile	**Preparation time for delivery**	**Delivery time of ventilators stockpiling**
6117	2.02	1.08

Table F.3: Operational Characteristics of Candidate Policy for Ventialtors

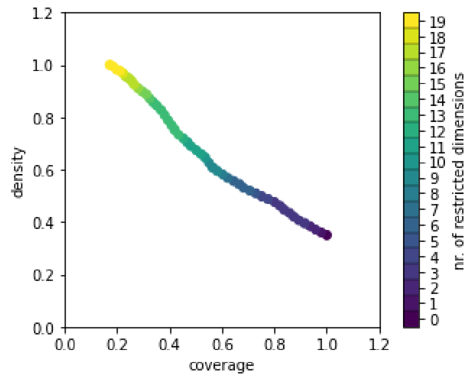
Time to check products	**Shipment time to hospitals**	**Time horizon for forecast**	**Check up time**
1.05	1.00	21.8	7.3

F.4. Scenario Discovery

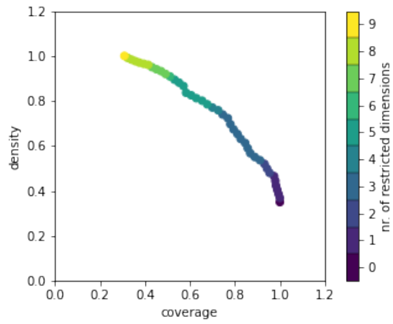
To run PRIM, the outcomes of interest need to be defined. The outcome of interest is a low coverage of ventilators, gloves or simple masks. The coverages of are considered low if it falls below the 35th percentile of coverage. This threshold value was chosen because it returns policies that perform poorly and the resulting coverage-density tradeoff curves yield satisfactory results. A scenario is selected based on the combination of density and coverage. Ideally, a scenario achieves a high value in both. The coverage-density tradeoff curves for ventilators, gloves, and simple masks are in **??**.



(a) Coverage-density trade-off plot for simple masks



(b) Coverage-density trade-off plot for gloves



(c) Coverage-density trade-off plot for ventilators

Figure F.9: Coverage-denisty Trade-Off plots for simple masks, gloves, and ventilators

Figure F.10 presents the relationships between the most significant uncertainties in form of a scatter plot.
The dimensional stacking plot for the case of gloves is shown in Figure F.11.

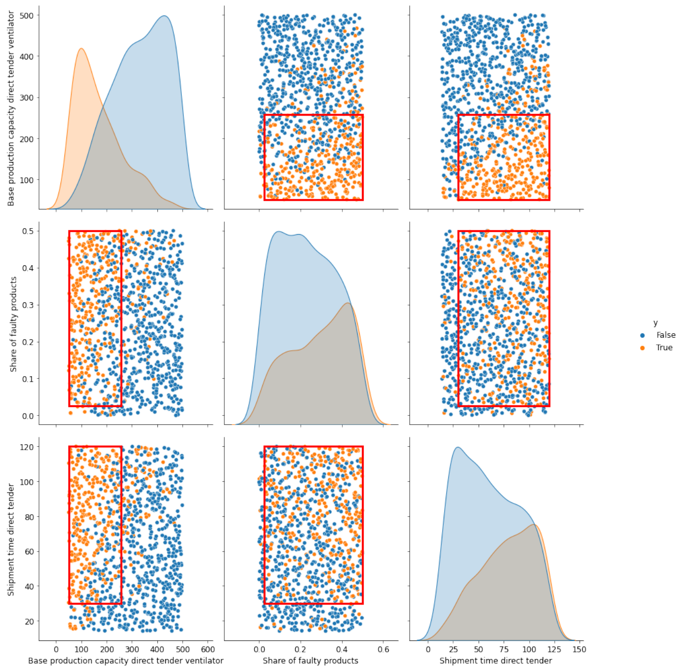


Figure F.10: Influential Uncertainties - Scatter Plot Ventilators

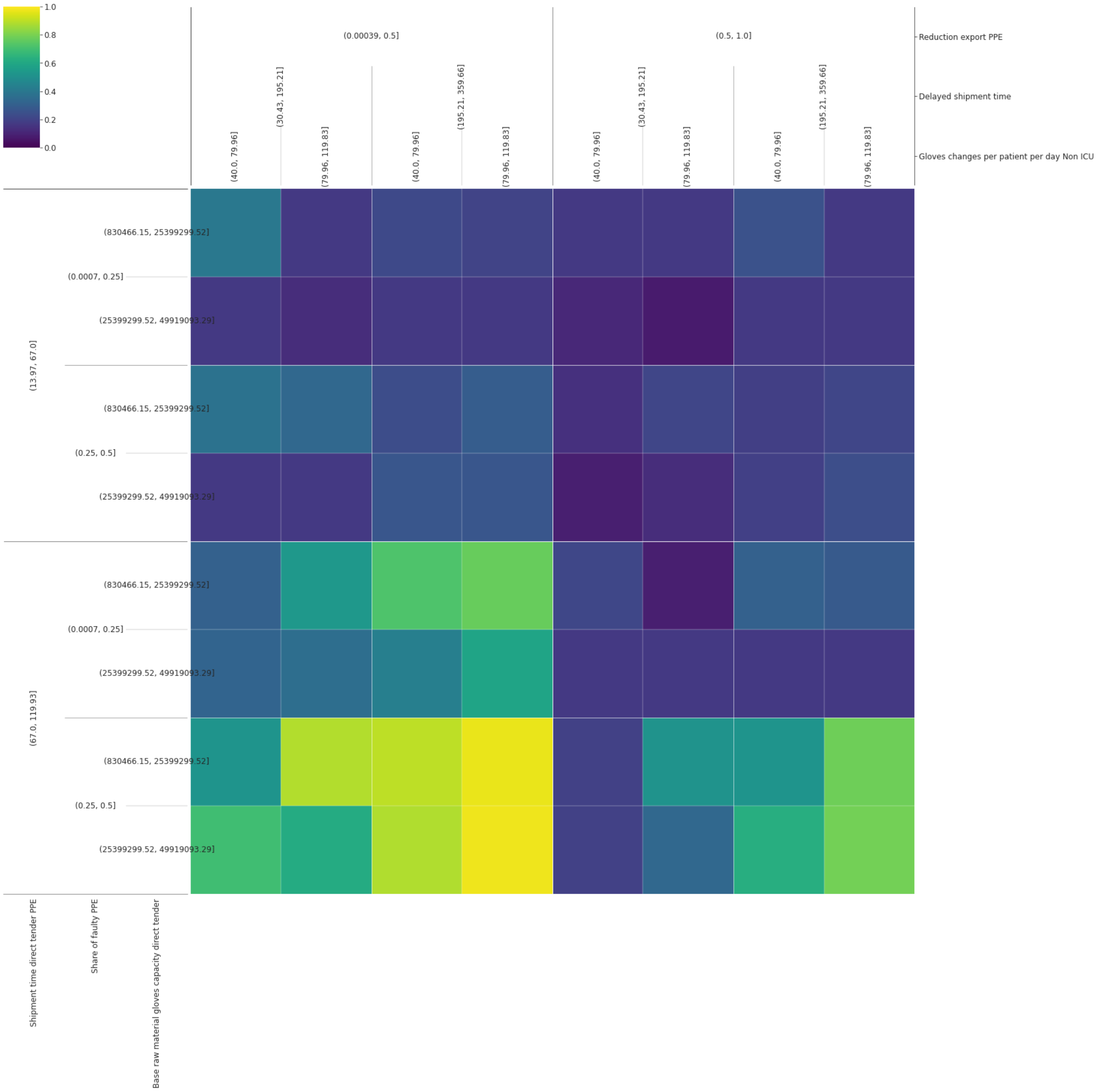


Figure F.11: Dimensional stacking plot for the worst case coverage gloves