A FRAMEWORK FOR COMPARING N95 AND ELASTOMERIC FACEPIECE RESPIRATORS ON COST AND FUNCTION FOR USE DURING A PANDEMIC

by

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Dalhousie University is located in Mi'kma'ki, the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

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ABSTRACT

SARS-CoV-2 has posed implications for personal protective equipment (PPE) supply such as N95 respirators. In this research it was examined if elastomeric facepiece respirators (EFRs) are efficacious substitutes for N95s through comparing their functionality and cost. Dynamic modelling was used to compare respirator stockpiling requirements and costs depending on PPE utilization and disinfection strategies. A case study on Dartmouth General Hospital was examined. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was conducted to assess financial and functional criteria together. N95s are found to be favorable unless cost criteria are given the greatest weight of importance. The research shows that financial and functional findings are predictive, rather than prescriptive, as results vary according to epidemiolocal characteristics of a pandemic. Ultimately, this research provides more sophisticated techniques for forecasting respirator stockpiling demands and offers insights for comparing functional and financial aspects from an operational research perspective.

LIST OF ABBREVIATIONS USED

PPE	Personal Protective Equipment
EFR	Elastomeric Facepiece Respirator
APR	Air-Purifying Respirator
PAPR	Powered Air-Purifying Respirator
UV	Ultraviolet
UVGI	Ultraviolet Germicidal Irradiation
TCID	Texas Center for Infectious Disease
UMMC	University of Maryland Medical Center
VHP	Vaporized Hydrogen Peroxide
STAI	State-Trait Anxiety Inventor
RPP	Respiratory Protection Program
TOPSIS	Technique For Order of Preference by Similarity to Ideal Solution
HCW	Healthcare Workers
MD	Medical Doctor
RN	Registered Nurse
ICU	Intensive Care Unit
WHO	World Health Organization
CDC	Centre for Disease Control
NCIRD	National Center for Immunization and Respiratory Diseases
OSHA	Occupational Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health

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1. INTRODUCTION

1.1 CONTEXT

The 2020 worldwide outbreak of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has posed implications for the supply of personal protective equipment, and in particular, N95 respirators. Studies have shown that the airborne transmission of the virus is the dominant route for spread, ultimately increasing need for personal protective equipment (PPE) (World Health Organization, 2020a). According to the World Health Organization (WHO), 89 million medical masks were required to meet monthly international demands (WHO, 2020b). N95 respirators were among the most highly demanded products, as they filter out 95% of penetrating particles with sizes between 0.1 to 0.3 micron (Qian et al., 1998). This demand led countries like Canada to add the N95 respirator to their medical devise shortage lists as manufacturers struggle to meet the demand (Government of Canada, 2020a).

Several initiatives to manage equipment shortages in Canada were in place during the pandemic. For example, an interim order to accept imported protective equipment even if it did not meet Health Canada's pre- SARS-CoV-2 standards was signed to alleviate or prevent shortages (Government of Canada, 2020b). As well, Ontario Health submitted a recommendations report which aimed to optimize the supply of PPE (Ontario Health, 2020). One recommendation was to stockpile reusable equipment such as elastomeric facepiece respirators (EFR) to help extend the supply of PPE. Many studies have investigated the implementation of an EFR respiratory protection programs to accommodate healthcare system needs, but there are still questions remaining regarding safety, communication, comfort, and cost.

1.2 DESCRIPTION OF EFRs AND N95s

Before further discussion, a brief description of EFRs and N95 respirators is needed. EFRs are tight-fitting respirators with facepieces composed of rubber or synthetic material (Figure 1.1). EFRs can be repeatedly used, contain replaceable filter cartridges, can be disinfected, stored, and reused (Centers for Disease Control and Prevention, 2020). N95 respirators are face masks composed of synthetic plastic fibres that protect against airborne particles but lose their facial seal after several hours of use (Figure 1.2). The main difference between N95 respirators and EFRs is that N95s are not intended for repeated or extended use.

Both EFRs and N95s are capable of protecting healthcare workers from airborne disease transmission and are essential PPE during SARS-CoV-2. The cost and function of both respirators, however, are quite different making the selection of the best respirator a challenging decision for healthcare organisations.

Figure 1.1: Elastomeric respirator (General Insulation Company, Inc., n.d.)

Figure 1.2: N95 respirator (Honeywell, n.d.)

1.3 PROBLEM STATEMENT

Given preliminary literature research, it is evident that researchers either investigate cost or functionality of respirators, but rarely both. Further, financial models that determine total annual costs of N95s and EFRs omit important considerations such as respiratory protection program implementation costs, disinfection costs and different utilization strategies. These identified research gaps influenced the overarching goal of this thesis which is to compare the functionality, cost, and cost-effectiveness of various approaches to using N95s versus EFRs in healthcare settings. Supporting objectives are to answer the following:

- Are EFRs are more financially advantageous than N95s, and do they meet user functional requirements such as comfort, communication, and safety?
- Is a mixed strategy or phased approach to implementing EFRs less costly than using N95s alone?
- Is there a financial advantage of disinfecting N95s?

- Is there a financial advantage of disinfecting EFRs less frequently than after each patient interaction?
- Is stockpiling N95s always more expensive than stockpiling EFRs?
- Are epidemiological compartmental models suitable for estimating respirator demands?
- How are the respirator demand requirements different across pandemics with varying epidemiological characteristics?
- If both functionality and costs are considered for each respirator alternative, in what circumstances are EFRs chosen over N95s and vice versa?

1.4 OVERVIEW

To determine if EFRs are effective substitutes for N95s, this thesis investigates costs and functions in the following way: Chapter 2 presents the findings of the literature with respect to functional characteristics that need to be considered and summarizes trends in costs studies. Chapter 3 introduces the new methodology used to investigate both costs and functions. Chapter 4 presents the input data used in each model and TOPSIS analysis. Chapter 5 discusses the total costs, financial trends and sensitivity analyses yielded by using the methods introduced in Chapter 3. A TOPSIS analysis is explored and discussed to compare EFRs and N95s with respect to cost and function. Lastly, Chapter 6 summarizes the main findings of the thesis and presents suggestions for future work.

The literature review in Chapter 2 explores previous EFR and N95 studies. We aim to identify and review the state-of-the-art literature on their usability and feasibility in the healthcare industry. More specifically, we overview EFRs and N95s, review recent respirator research, and make recommendations for future research. There are several major findings discussed in the review such as methods for handling PPE shortages amid SARS-CoV-2, functional factors that impact patient care and user experience, and overarching benefits of implementing healthcare EFR programs. The findings underline capabilities and costs for determining whether or not organizations should invest in EFRs. This fundamental knowledge is needed for comprehensive economic analysis and comprehensive behavioural operational research studies.

2. LITERATURE REVIEW

The goal of the literature review was to determine the costs and functional factors that must be investigated in healthcare settings before choosing a respiratory protection program. The review is organized as follows. Section 2.1 further defines EFR and N95 respirators and further motivates the need for this review. Section 2.2 reviews papers discussing the function of each respirator with the purpose of defining the functional factors to consider when choosing between EFRs and N95s. Section 2.3 reviews papers discussing the costs of both respirators with the purpose of identifying the main cost factors to consider when choosing between these two respirators. Section 2.4 provides a summary of the findings, and finally, in Section 2.5 we conclude with an overview of the literature found and identified gaps.

The following search terms were used to locate articles for this literature review: *elastomeric respirators, effectiveness, patient care, filtration, feasibility, N95, simulation, cost, comparison, particulate filters, respiratory protection program.* Variations of these terms were used to ensure exhaustive search results. The search was limited to peer-reviewed articles published between 2005-2020, with some exceptions. The searched databases include Science Direct and PubMed. Inclusion and exclusion criteria can be found in Table 2.1. As overviewed in Figure 2.1, the search results in 339 articles after duplicates were removed. Initial inclusion screening was completed by reviewing the title and abstract resulting in 100 articles. After reading these articles, 51 were deemed relevant for consideration in this review.

Table 2.1: Summary of literature review inclusion and exclusion criteria

Inclusion Criteria	**Example**
Functional measures	Functional metrics must be included such as comfort scores, fit test pass rates, etc.
Financial measures	Annual costs, cost savings, etc.
Pandemic setting	Studies investigating stockpiling respirators for pandemics
Exclusion Criteria	**Example**
Availability	Studies whose full text could not be found
Data	Studies that did not provide data as a raw number

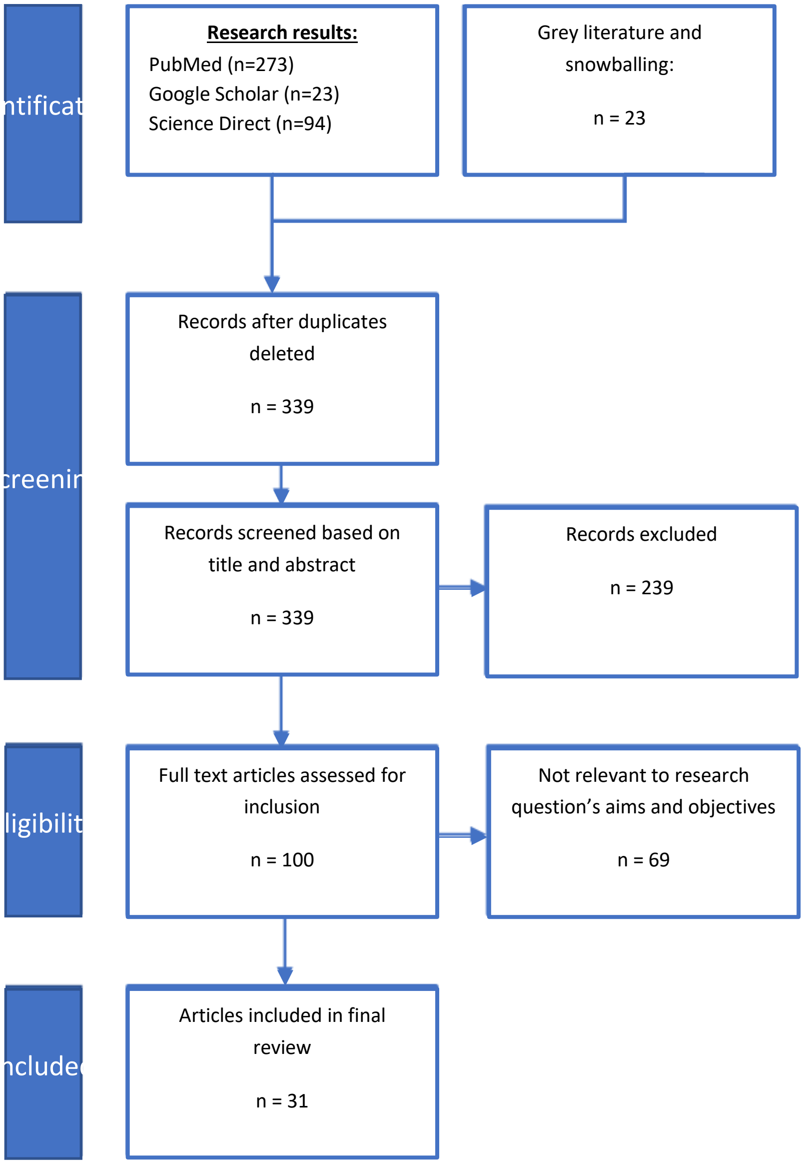


Figure 2.1: PRISMA diagram

2.1 BACKGROUND

The following section provides a brief overview of respirator classes and subclasses. There are two classes of respirators that can be used depending on the environment and level of protection required against contaminants. They are air-purifying (APR) and supplied-air respirators. The focus of this review is on air-purifying respirators which absorb air contaminants via a sorbent in a canister or cartridge. Respirators can have full-face, half-piece, quarter piece or mouthpiece forms. The mouthpiece form is uncommon and therefore is not included in this review. There are additional subclasses of APRs including: particulate respirators designed to withstand dust or mist; chemical cartridge respirators for different varieties of contaminants; gas masks which have greater protection than chemical cartridge respirators; and powered APRs. It is important to note that cartridges protect against gases and vapours, while filters protect against particulate hazards (i.e., aerosols such as mist, bacteria, or dust). The focus of the research is on particulate filters, as they are used in N95 respirators and EFRs.

There are a variety of particulate filters used in respirators which have a minimum filtration efficiency for different contaminants. There are N, R and P-series cartridges where N means not resistant to oil, R is somewhat resistant to oil, and P means strongly resistant to oil. Table 2.2 summarizes NIOSH's nine filter classifications based on minimum filtration efficiency and type of aerosol. EFRs can use any of the particulate filters in Table 2.2. Further, they can utilize chemical cartridges (for vapors and gas only) or a combination of cartridge and filter depending on application safety requirements. Particulate filters and cartridges can be used until it becomes too difficult to breathe. Depending on the model and application, filters can last from eight hours of use (intermittent or prolonged) to several months once opened (Centers for Disease Control and Prevention, 2020). Filter and cartridge replacement is completed once breathing is strained.

Table 2.2: Particulate filter classifications (NIOSH, 2014)

Oil Resistance Categories			
Minimum Efficiency	**N Non-Oil Aerosols**	**R Includes Oil Aerosols**	**P Includes Oil Aerosols**
95%	N95	R95	P95
99%	N99	R99	P99
99.97%	N100	R100	P100

In this review the choice being considered by hospitals is categorized to be broadly between EFRs using the P100 filter and N95 filter facepiece respirators. They are not strictly equivalent in providing protection, for example, N95s can filter particles, but do not protect against vapors and gases (Centers for Disease Control and Prevention, 2020), but they both provide the minimum requirement in our context. As such, for the purpose of this review, EFRs are assumed to be efficacious substitutes for N95s when preventing airborne transmission of SARS-CoV-2 since N95s are the minimum requirement (CDC, 2018). For further discussion on the relative particulate filtering performance of these respirators see Zhuang et al. (2015) who compared P100 filtered EFRs with N95s in a simulated workplace.

2.2 FUNCTIONALITY

In this section the functionality of N95 and EFRs is considered. The manner in which these respirators are designed and used impacts user experience, user function and patient experience. User function and experience are investigated to understand the performance of a potential respirator program. Patient experience is also investigated because PPE policy changes impact how healthcare workers provide care.

2.2.1 FUNCTIONALITY SUBFACTORS

Hines et al. (2017) conducted two case studies on EFR programs in healthcare to outline functional factors of EFR usage. One case study was at the University of Maryland Medical Center (UMMC) and the other at the Texas Center for Infectious Disease (TCID). The case studies focussed on efficacy and effectiveness of half-facepiece EFRs, cleaning and disinfection, physiological and psychological considerations, and recorded experiences with EFRs. Several factors impacted the adoption of an EFR program such as N95 shortages during emergencies, presence of trained healthcare workers with experience and knowledge using EFRs, storage, risk perceptions and safety culture.

The case studies also identify key functional considerations of EFR use in healthcare. UMMC first adopted the EFR program due to perceptions of greater protection. However, the university stepped away from the program, as many EFR disinfection protocols were not followed due to the presence of problems with accessibility for mobile staff (i.e., physicians, respiratory therapists). Conversely, TCID adopted and maintained the EFR program by training staff, ensuring correct usage, maintenance, testing, and documentation of respirator usage. Several EFR weaknesses that the facilities highlighted were the fit of the respirators on oily skin, temperature discomfort, reduced communication abilities which negatively impacted patient care and the time required to clean the equipment. These findings show that there are components of EFR programs that influence program success because they impact safety, communication, and comfort.

Hines et al. (2019) investigated the user acceptance of reusable respirators in healthcare in a more recent study. Healthcare staff enrolled in an EFR half-facepiece respirator program, a powered air-purifying respirator (PAPR) program or a N95 respirator program. After a period of use they answered questionnaires on beliefs, attitudes, and respirator preferences under different situations. It was found that N95 users highly favoured N95 respirators due to better communication and comfort in comparison to EFRs. However, EFRs were ranked higher by users when asked about sense of protection. Lastly, for all users, EFRs were preferred in higher-risk situations. These findings provide evidence that EFR usage during SARS-CoV-2 may have higher user acceptance than expected. However, the study did not consider the impact of different healthcare training programs in place for respirator use which may have varying impacts on efficacy of EFR protection.

Hines et al. (2020) also conducted a study that investigated the impact of EFR use on patient care by surveying 1152 participants from US hospitals and ambulatory services. The survey covered questions pertaining to respirator interferences in patient care, care activities and presence of patient fear. Results showed that only 16% of EFR users found their respirator interfered with patient care. In comparison, 17% of N95 users found their respirator negatively impacted patient care. Users rated EFRs "significantly more favorably with respect to sense of protection afforded" (p. 653). Given these findings, care providers may prefer more cumbersome PPE during SARS-CoV-2. In addition, this study provides indication that there is opportunity for improvements to reduce mask size and improve voice transmission for better patient care activities.

The research in Hines et al. (2017), Hines et al. (2019) and Hines et al. (2020) indicate that there are possible circumstances in which the use of EFRs may be preferred over N95s. In contrast, it is also apparent that there are several prominent drawbacks of using reusable respirators that may have various impacts on choosing a PPE program strategy. To investigate further, several studies are reviewed with respect to comfort, communication, and safety. This framework is derived from Clever et al. (2019). Comfort concerns the experience of the user wearing the respirator and includes physiological and psychological strains. Communication factors include influences on speech transmission such as noise or enhanced features to improve user experience. Lastly, safety consists of several subcategories such as sterilization, training, and fit testing since they impact PPE efficacy and protection. The durability of the PPE is also listed, as it can be impacted by user adherence, length of use and reprocessing.

The remaining papers in this section are categorized by safety, comfort, and communication. This is used throughout this review as a framework for discussion and analysis. An overview of this framework is provided in Table 2.3.

Table 2.3: . Summary of comfort, disinfection, and communication subfactors derived from Clever et al., (2019), Hines et al. (2017), Hines et al. (2019) and Hines et al. (2020).

Comfort	**Communication**	**Safety**
Temperature discomfort	Muffling	Manual and automated reprocessing
Skin irritation	Environment factors	Fomite transmission
Respirator weight, harness, and size	Modified rhyme test: 70 % pass rate requirement	User adherence, dedicated space, and lack of procedures
Breathing difficulty	Speech transmission index	Centralized reprocessing
Carbon dioxide buildup	Hearing-impaired considerations	Time burden
Anxiety and stress	Speech enhancing features and respirator design	Durability

2.2.2 SAFETY

Subcategories of safety include Protection and fit and Cleaning/Disinfection. Protection factors consider emergency utilization strategies which can reduce the effectiveness of respirators. Respirator fit directly impacts protection and whether the PPE is sealed i.e., if there is any leakage. Several factors affect fit such as respirator design, fit testing, and facial hair. Cleaning/Disinfection allows the respirator to be reused safely. Section 2.2.2.2 presents common methods for disinfecting N95s and EFRs.

2.2.2.1 PROTECTION AND FIT

What are the elements that impact respirator fit and do N95s provide better protection against hazardous particulates than EFRs? To answer this, consider research by Duling et al. (2007) who investigated 5th percentile and random effects model methods for measuring performance of EFRs, N95s and surgical masks in a simulated workplace. They conducted six simulated work tasks with removal and redonning of the masks between each test and measured face seal leakage and filter penetration. The simulated tasks included breathing exercises, moving the head in several directions, repeating a message, and bending at the waist. It was found the EFRs had the highest protection, while surgical masks had the lowest protection. However, results were not consistent for each mask indicating the significance of standardized respirator fit tests. Further studies have shown that almost half of all healthcare professionals fail their second N95 fit test which occurs three months after their first test (Lee et al., 2008). In addition, N95 masks have been found to lose aerosol protection within ten minutes due to loss of seal during routine body movements (Suen et al., 2017).

An ASTM study investigating fit capability of full facepiece air-purifying respirators was conducted and found that the methods were appropriate if the fit factors were increased or the rigor of the test requirement was increased (Bergman, 2019). In addition, they concluded that not all users are similar, stressing the need for routine fit testing and variable respirator sizes and designs. A study conducted in 2005 found that face length and lip length were not sufficient measures for N95 respirator fit testing (Zhuang, Coffey & Ann, 2005). Instead, face length and face width were recommended to be used for the half-face respirator fit test panel. OSHA has released a review of literature, citing that minimal facial hair is also required to achieve a sealed fit (Cichowicz, Shaffer & Shamblin, 2017). A more recent study indicates that facial hair must be removed to achieve a proper seal (Regli, Sommerfield and vonUngern-Sternberg, 2021, p. 94).

Another study investigated safety and protection of respirators during the SARS-Cov-2 pandemic by exploring possible N95 utilization strategies. De Perio et al. (2020) focused on optimizing the supply of N95 respirators by reviewing engineer controls, administrative controls, and personal protective equipment controls. They recommended that research be completed to investigate utilization strategies such as using respirators that are past their shelf-life, decontaminated and reused, and worn for an extended period. As De Perio explains, respirator effectiveness relies on evaluation of fit testing and filtration, as well as determining the best PPE to avoid different modes of viral transmission. They recommended that further analysis be conducted on the length of time that SARS-CoV-2 remains infective in the air, and on respirator surfaces to understand modes of viral transmission. Chiang (2020) suggests that viral particulates may remain the air for up to three days.

2.2.2.2 Cleaning and Disinfection

A significant difference between N95s and EFRs is that N95s are intended for single use, while EFRs are intended to be used repeatedly and for extended use, as they can be sterilized. Due to N95 shortages during SARS-CoV-2, cleaning, and disinfection of N95s was undertaken by many health providers and investigated by researchers to determine the number of times they could be reused. Fischer et al. (2020) investigated ultraviolet (UV) radiation, dry heat, 70% ethanol and vaporized hydrogen peroxide (VHP) methods for decontaminating N95 facemasks over three contamination cycles. Findings indicated that VHP was most effective after all three cycles at deactivating SARS-CoV-2 while also maintaining the integrity of the facemask. This is consistent with Bergman's et al (2010) evaluation of multiple VHP decontamination processing for facepiece respirators. UV was slower acting but can be used for two cycles. Dry heat was found to be effective for two cycles, while 70% ethanol was reaffirmed to be least effective due to the degradation of the N95 material, as previous studies have shown (Heimbuch, 2011). A more recent study indicates that N95s can be reprocessed up to 50 cycles with heat treatment (<85 °C) at various humidity levels without changing the filtration efficiency (Liao, 2020, p. 6348).

A study completed by Ontiveros, et al. (2020) also investigated sterilization methods for N95 layer material. They employed a commercially available UV surface device for use in hospital room settings. The materials used were a hydrophobic outer layer, middle electrostatically charged layers, and an inner biocompatible layer. The layers were preliminarily investigated to determine if combinations of the layers would impact results. The research concluded that it was not possible to penetrate all layers of N95 material without flipping throughout the sterilization process. In summary, researchers have found that the number of times an N95 can be reused is between 2 and 50 cycles depending on, among other things, the cleaning and sterilization method.

While there are manufacturer protocols for disinfecting EFRs, there is a lack of research on disinfection protocols for routine use of EFRs in healthcare settings (Clever et al., 2019). As well, there are no universal standards for disinfection of different types of reusable respirators (Bessesen et al., 2015). Furthermore, higher concentrations of viral particles have been found in rooms where healthcare professionals remove PPE. In the case of SARS-CoV-2, viral particles can be detected in the air three hours after aerosolization (Fischer, 2020). Chiang et al. (2020) deem EFRs to be safer than N95s because of this, as particles can get trapped in EFR filters and die over several days, reducing the number of filter replacements needed. Furthermore, EFRs contain separate inhale and exhale vents, preventing exhaled air to pass through the filter and aerosolize viral particles. This reduces the risk of transferring viral particles to others without PPE. One caveat of EFR use during sterile procedures is the need for a disposable surgical mask covering the exhale valve to maintain sterility (Howard, 2020, p. 101).

2.2.3 COMMUNICATION

Other factors impacting patient and user experience have been investigated, such as the diminished speech intelligibility associated with different respirators by healthcare workers. By using the modified rhyme test, speech intelligibility was assessed in an intensive care unit environment and results showed that, a) respirators decreased speech intelligibility by a range of 1-17% (which the authors deemed to be insignificant), b) EFRs with voice augmentation equipment was associated with higher speech intelligibility and, c) powered air-purifying respirators (PAPR) produced hearing clarity of 79% compared with 90% with no PAPR (Radonovich, et al., 2010). Though results did not show significant impacts on communications in the study, it is important to consider speech and audibility requirements on a case-by-case basis. For example, Wentworth et al. (2020) considered a transparent EFR design to address hearing-impaired needs in the healthcare community. In their review of N95 use, Baig et al. (2009) indicate potential for job and communication interference. Whichever PPE is chosen, NIOSH (2007) requires at least a 70% pass rate for the modified rhyme test.

2.2.4 COMFORT

Comfort and Anxiety can have various impacts on patient care and the user experience and can be measured by the State-Trait Anxiety Inventory (STAI) (Julian, 2011). In a review by Johnson (2016) anxiety was stated as the “most important threat to equipment wear” (p. 8). A study by Wu et al (2011) investigated user experience by comparing anxiety metrics of EFRs in comparison with N95 respirators. Using the STAI, twelve volunteers with normal to mildly impaired respiratory conditions performed simulated work tasks wearing N95 and EFRs. The anxiety effect of the respirators was measured. It was found that N95 had no observed impacts, while the EFR increased state anxiety by 2.92 units, (P<0.01). Overall, the authors did not deem the increase to be significant. There are several causes for anxiety during the use of respirators in the study such as claustrophobia, laboratory testing and methods, workplace circumstances and some respirator designs. When comparing anxiety during use of each respirator, it was noted that it may have been possible that N95s reduced anxiety, while EFRs increase anxiety. One drawback of the study was that the sample size was small, however it provides evidence that measuring anxiety in individuals may help PPE selection processes.

Similar findings concerning comfort have been discovered when investigating EFR modifications in attempt to handle N95 supply shortages during pandemic settings. For example, Liu et al. (2020) studied the new design of EFRs using custom anaesthesia circuit filters to address possible EFR filter shortages when N95s are replaced with EFRs. The research was conducted on eight volunteers, while measuring their fit testing, respiratory rate, and end-tidal carbon dioxide using the circuit filters. The findings of the study indicated half of the volunteers felt discomfort, while a small portion felt facial pressure and one participant felt dizziness. The study concluded that the adapted EFR may be a suitable substitute for disposable N95 respirators. However, future recommendations for research exploration were offered. It was recommended that a larger sample size be used, more than one filter be tested and modifications for larger users be investigated. Ultimately, EFRs and circuit filters may replace N95s during pandemics, but comfort factors still need to be addressed.

2.2.5 OTHER

Some studies have investigated other user functions of N95 and EFRs. Given SARS-CoV-2, the Centre of Disease and Control provided guidelines for the reuse of N95s to combat PPE shortages (CDC, 2020). N95 respirators should be used for no longer than eight hours of continuous use, while a single EFR may replace thousands of new reusable N95 masks. Design improvements for EFRs were investigated and three different filtering facepieces in comparison to 3M 1860 and 1870 N95 respirators. Participants were asked to self-report tolerability on comfort, wearing experience and function of the new PPE prototypes after simulated healthcare work tasks. All prototypes had high tolerability except for the EFR hybrid improvement that was designed with centralized, vertical filter housing and no exhalation valve. Communication and function capabilities interference were cited as the leading causes for low tolerability of EFRs in comparison to controls and other filtering facepieces (Radonovich, 2019).

2.3 COST CONSIDERATIONS

There are several functional benefits and drawbacks of EFRs compared to N95s, as discussed in the previous section. However, when determining whether to invest in EFRs, costs must also be considered. There are a few studies on the cost differentiation between respirators and several studies have explained the need for more comprehensive economic evaluations of respirator alternatives to guide decision-makers (Mukerji, MacIntyre & Newall, 2015). Comparisons may be made for EFRs and the prolonged or repeated use of N95s. Likewise, comparisons may be made if N95 disinfection protocols are adopted. The prolonged use and reuse of N95s reduces the quantity required, subsequently reducing upfront and inventory costs. Generally, the costs used for comparisons can be categorized into three groups: equipment, inventory, or program expenses. A study by Baracco et al. (2015) determined the circumstances in which using EFRs, N95s or a mixed strategy was most costly. Factors and costs that were considered for Baracco's analyses can be found in Table 3.

Factors in Table 2.4 include those impacting equipment, inventory, and program implementation. As discussed, N95s may be used repeatedly or for extended use to alleviate shortages. In addition, the size of the target population, number of healthcare workers, and frequency of patient interactions should be known to estimate the quantity of EFRs or N95s for a respiratory protection program. Once demand is known, inventory costs must be considered. Storage requirements can be estimated by determining size and volume of PPE and filters. Lastly, program costs that include training, fit testing and disinfecting must be considered. Cost factors for the PPE program include materials and time needed to plan, implement, and evaluate training, testing, and disinfection.

Table 2.4: Summary of drivers of cost to consider when comparing respirators

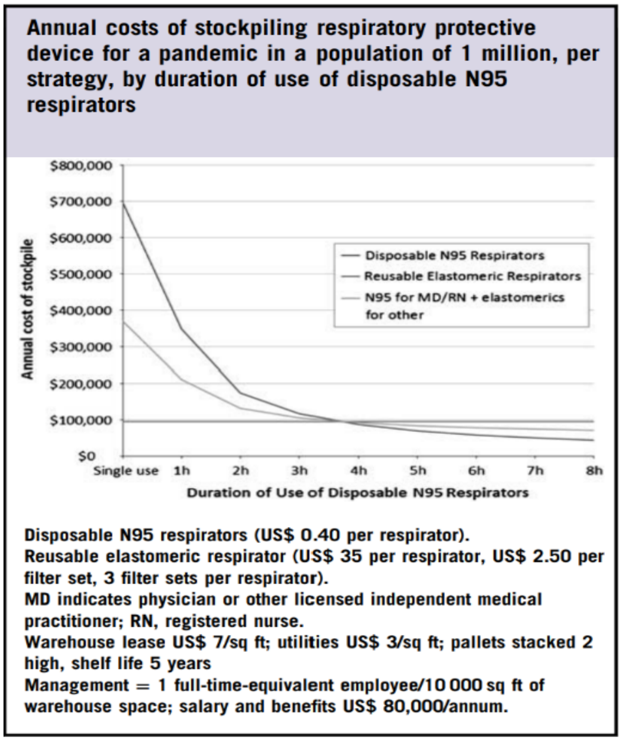
Category	Type	Item	Drivers of Cost
Equipment	Upfront	Unit cost of N95	Extended use of N95
Equipment	Upfront	Unit cost of EFR	Repeated use of N95
Equipment	Variable	Filter costs	Size of target population
Inventory	Fixed	Lease cost	Shelf life
Inventory	Fixed	Insurance cost	Dimensions of PPE storage

Category	Type	Item	Drivers of Cost
Inventory	Fixed	Inventory management salary	Dimensions of filter storage
Program	Variable	Mixed strategy costs	Number of filter sets required per EFR
Program	Variable	Fit testing costs	Fit test duration
Program	Variable	Training costs	Number of healthcare practitioners
Program	Variable	Disinfection costs	Number of patient interactions
Program	Variable	Disposal costs	Data-driven policy development

2.3.1 STUDIES COMPARING COSTS OF EFR AND N95 RESPIRATORS

There are several studies that share the same objective in comparing EFRs with N95s to reduce costs. It is apparent that there are possible instances in which it may be advantageous to use one PPE over another due to financial constraints.

Baracco (2015) determined the costs and benefits of stockpiling EFRs and N95s in a pre-SARS-Cov-2 and theoretical pandemic setting. Assumptions made were that healthcare workers worked 40-hour weeks for 12 pandemic weeks, with two infected patient contacts per hour on average; a 40% attrition rate to account for the loss of healthcare workers due to illness, refusal to work or familial reasons; 40% and 20% infection rates in adults and children respectively, and an average stay at a hospital of five days and ten days for patients requiring intensive care unit treatment. Overall, findings showed that EFR respirators were least costly when used for extended periods of time. Otherwise, an N95 program is least costly when the equipment is used between 4 and 8 hours.



Annual costs of stockpiling respiratory protective device for a pandemic in a population of 1 million, per strategy, by duration of use of disposable N95 respirators

Disposable N95 respirators (US$ 0.40 per respirator).
Reusable elastomeric respirator (US$ 35 per respirator, US$ 2.50 per filter set, 3 filter sets per respirator).
MD indicates physician or other licensed independent medical practitioner; RN, registered nurse.
Warehouse lease US$ 7/sq ft; utilities US$ 3/sq ft; pallets stacked 2 high, shelf life 5 years
Management = 1 full-time-equivalent employee/10 000 sq ft of warehouse space; salary and benefits US$ 80,000/annum.

Figure 2.2. Annual costs of stockpiling respiratory protective device for a pandemic in a population of 1 million, per strategy, by duration of use of disposable N95 respirators (Baracco, 2015).

Extensions to Baracco (2015)'s model are necessary to account for what was learned and experienced during the current SARS-COV-2 pandemic. These could include the costs of the disinfection, training, and testing components of an elastomeric respirator program. The costs associated with the reuse of N95 masks after decontamination through UV light or alternative methods which were developed for SARS-Cov-2. Lastly, salvage costs can be considered, as it may be necessary to investigate the disposal costs of PPE. The additional costs associated with new alternatives can be incorporated into an improved comparison model.

Chalikonda et al. (2020) investigated the implementation of a new cost-effective EFR program as well, as many healthcare facilities were challenged with N95 shortages during the SARS-CoV-2 pandemic. Chalikonda used a clinical allocation strategy to replace N95s with EFRs using P100 filters. The strategy consisted of an operational plan to educate users, fit, test, and sterilize masks. Within one month, 90% of N95 respirators were replaced at a cost that was ten times less than the original N95 program. In addition, the cost benefits increased the longer the EFRs were used. One challenge in the study was that staff members who did not pass seal checks did not graduate to fit testing and were required to continue wearing N95 respirators or powered air purifying respirators. The authors concluded that further research is needed to ensure successful seal checks for all staff members. Additionally, user preferences, physiological and psychological factors associated with wearing EFRs were not considered.

2.3.2 EQUIPMENT AND INVENTORY COSTS

For further considerations of respirator costs, the following section provides a breakdown of research that considers inventory, equipment, or PPE program costs but does not directly compare EFRs and N95s.

A study by Mukerji (2017) investigated N95 cost effectiveness in a Chinese healthcare facility. The analysis was done to determine whether the continuous use of N95s should be chosen over general face masks. Continuous use means use of an N95 respirator for an entire shift. The metric of interest was the incremental cost-effectiveness ratio per clinical respiratory illness (CIR) case prevented. Costs included for analysis were absenteeism, intervention, and healthcare worker CIR case costs. The majority of the considered costs were related to N95 program implementation and equipment requirements. For example, productivity costs related to time for fit testing for different healthcare workers (doctors, nurses, and administrative staff) were considered which impact comparisons of PPE programs. Notable results from the research indicate that the incremental cost to prevent a CRI case in a healthcare worker using N95s ranges between $490 - $1,230 USD ($611.48-$1,534.95 CAD). If fit testing is included in the program, the cost doubles. It was also cautioned that the results from the study may not be transferable between countries due to differences in factors such as productivity.

A study by Patel (2020) is a more recent cost analysis for reusable respirators. A comparison was completed for reusable respirators and single-use filtering facepiece code 3 (fluid resistant) masks. Initial outlay, recurring costs, patient costs, weekly costs, and cumulative costs were identified and totalled to underscore the savings in adopting a reusable respirator program. Patient costs considers whether a disposable mask is used per patient or continuously for a maximum of one hour. If a reusable respirator is used, wipes are required for disinfection and prevention of disease spread. The cost savings were found to be £150 ($261.50 CAD) per month.

One prominent functional factor (not already discussed) was the utilization of hydrocolloid dressing to improve comfort during prolonged use of reusable respirators.

2.3.3 PROGRAM COSTS

To outline common program costs, we overview the National Institute for Occupational Safety and Health's (2015) toolkit which provides a guide in forming a respiratory protection program (RPP). Each component of the RPP incurs costs due to time for planning and implementation, as well as material requirements. A first step of the RPP is to identify a program administrator responsible for hazard evaluations and procedure and policy adoption. The second section of the toolkit covers hazard evaluation. The purpose of the evaluation is to identify if there are hazards in the workplace, how often the hazards are present and whether respiratory protection is needed.

The last section of the program development covers policies guiding the general operations of a respiratory protection program. Respirators require routine inspection, as well as routine training/inspection to ensure proper use (donning and doffing). Similarly, it is important to determine storage, maintenance, repair, and disposal procedures. Are respirators repaired in house? Who has the responsibility of disposing of equipment?

The policies section also summarizes considerations for RPP training, recordkeeping, and program evaluation. Training is necessary for the success of the RPP. The program should provide an outline of the training curriculum and how principles of the program will be taught. The main objectives of the course should be to educate on hospital practices and program risks, how to properly use respiratory equipment, and how to determine when respirators or filters need to be disposed. In regard to recordkeeping, several documents should be maintained. The documents are the written program itself which should be available to all participants, the medical evaluations of those using (and not using) PPE, fit tests, checklists, changes to the program and evaluation records. Program evaluation records are the last consideration of the RPP development section of the NIOSH toolkit. A checklist is offered but serves as a starting point for any developing RPP. The evaluation should consider feedback from respirator users and document any aspects of the program that is not being followed. It must also offer a section on how the program will be assessed and how the program will be re-evaluated as necessary (does not need to be at set intervals).

2.3.4 INTANGIBLE COSTS

In addition to a well functioning respiratory protection program, successful implementation depends on staff participation and buy-in. These have costs but they are typically considered intangible costs because they are difficult to quantify or estimate. Brown et al (2018) outlines five key findings related to RPP evaluations and success. The first finding was that safety climate is a prominent indicator of the success of hospital RPPs. The second finding was that annual fit test tracking was lacking. This is an important finding, as ongoing evaluation is needed to ensure continued success. Point-of-care PPE monitoring is suggested to ensure proper use of respiratory equipment. Another finding was that end-user feedback was lacking, indicating failure to implement a mechanism for routine evaluation. Lastly, it was found that users were unclear on choosing and using equipment, as well as when to use equipment. This may reflect on the hazard assessment and program training components of the RPP.

A leading indicator of RPP success is the organizational safety climate. An insufficient safety climate can result in social, emotional, and human costs such as those related to stress or loss of employee morale, to name a few. According to a report by Clever et al. (2019) safety culture is perceived differently by different people in different roles. However, there are several ways in which safety culture can be strengthened and standardized. The first is to strengthen leadership and management commitment to safety. In addition, it is important to ensure safety resources and alternatives are easily accessible. An organization that fosters open conversations about safety and promotes learning from past mistakes establishes a safety culture founded on continuous improvement. There are other components of safety culture change discussed in the report, which are: investment, participation, assessment, capacity, and communication (Clever, 2019, p. 142). Investment considers notable aspects such as setting share priorities. Without participation of employees and management, a safety culture cannot be established. Goals, problems, and progression are also important in the assessment of the RPP and safety culture. Lastly, capacity encompasses the training and facilitation of safety procedures, while communication must be regular, reliable, and complete.

Establishing an RPP and a safety climate helps to ensure the success of the chosen respiratory equipment. When determining when EFRs are suitable substitutes for N95s, considering additional program factors is necessary to ensure successful implementation and administration. Though there is not a lot of literature on EFR programs, current toolkits and standards can act as templates for unique case-by-case program development.

2.4 SUMMARY

To summarize findings of the articles reviewed in Section 2.2 and 2.3, three tables are presented. Table 2.5 overviews 12 papers considering both N95 and EFRs. Five articles considering only EFRs are overviewed in Table 2.6 and likewise, 14 articles considering only N95s are overviewed in Table 2.7. The tables summarize study methodology, and findings on costs, safety, communication, and comfort. An additional column indicates gaps in the literature and list either the limitations identified in the research or opportunities for further investigation.

Table 2.5 provides a summary of the literature on comparisons of EFRs and N95s. Given the summary, it is apparent that studies are either attentive to functionality or cost of PPE, but do not extensively investigate both. Further, comparison studies on functional factors of respirators are more frequent than those comparing costs. Each study considers equipment, program, and inventory costs of stockpiling EFRs, N95s and alternatives.

Similar results are evident for all three cost-comparing studies, indicating EFRs can be more cost-effective than N95s. However, a common theme among study limitations is that functional factors such as comfort and protocol adherence negatively impact the roll-out of EFR stockpiling programs. Furthermore, estimation methods for PPE demand often do not consider needs for additional healthcare workers during peak pandemic demands. Demand of PPE was estimated using different respirator utilization strategies such as comparing EFR use with prolonged use (8 hours) of N95s. Each model is different in demand assumptions and respirator utilization strategies. For models that consider both functionality and feasibility, no applications were available to calculate the cost and functional benefits of both EFR and N95 investments.

The remaining comparative studies in Table 2.5 focus on safety, communication and comfort factors impacting the usage of N95s and EFRs. A theme among functional comparison studies is that fit testing and training are essential safety factors in respiratory protection programs in healthcare. For both N95s and EFRs, periodic fit testing is required to ensure protocol adherence. Continuous education is also considered to ensure PPE is used safely and effectively. A prominent finding in safety comparisons is that EFRs are preferred in emergency settings due to better sense of protection against facial seal leakage.

There are several trends for comfort and communication factors in the comparison studies. First, healthcare workers prefer N95s over EFRs due to comfort and communication. With regard to comfort factors, EFRs have a higher negative impact on users and patient anxiety due to design. Additionally, skin irritation and prolonged use discomfort are cited as contributors to N95 preference over EFRs. Secondly, though EFRs pass NIOSH modified rhyme test requirements, poor speech intelligibility appears several times in the literature as a factor negating EFR use. Recommendations in comparison studies list EFR design improvements or alterations to enhance comfort and communication. When choosing a respirator program, it is important to consider functional requirements on a case-by-case basis.

Table 2.5: Summary of research considering N95s and EFRs

Paper	**Methodology**	**Cost**	**Function**			**Limitations/ Gaps**
			Safety	**Comm.**	**Comfort**	
Considers EFRs and N95s						
Baracco, 2015	- Pandemic modelling - Cost comparisons	- Mixed strategy (N95 and EFR) vs EFR vs N95 vs powered APR - Extended vs mixed use	- Fit tests - Training	--	--	- Only considers a constant number of disease cases and healthcare practitioners
Chalikonda, 2020	- Multimodal training approach - Hood and sensitivity solution fit testing - Cost-ratio assessment	- Comparing N95 and EFR with filters - Phased program approach	- Fit tests - Dis-infection flowcharts - Training	--	--	- Does not consider user functions
Chiang, 2020	- Descriptive research	--	- Fit and seal comparisons - Reuse and disinfection comparisons	--	- Extended EFR use causes discomfort	- Lacks clinical workplace settings investigation
Duling, 2007	- Simulated workplace protection - Bitrex Solution Aerosol Qualitative Fit Test - Saccharin Solution Aerosol Protocols - Ambient Aerosol Condensation Nuclei Counter Quantitative Fit Testing Protocol factor testing	--	- Fit testing - Duration of use and type of movements	--	--	- Simulated workplace exercises may not reflect real workplace and respirator protection
He, 2015	- Simulated workplace protection factor testing	--	- Fit test and leakage	--	--	- Study aerosol may not have same properties as flu

Hines , 2017	-Interviews to determine adoption and continued use of EFRs in hospital settings	--	- Success of EFR program depended on safety culture and certified safety professionals	- Communication impairment with EFRs	- Less skin irritation with N95s - EFRs recorded to be more constraining	- Small sample size - Interviewed authoritative figures only - No extensive cost analysis
Hines, 2019	- Cross-sectional survey for evaluation of healthcare practitioner EFR, N95 & powered AFR use	--	- Sense of protection evaluation - Fit testing and training	- Survey response evaluation of communication	- Survey response evaluation of comfort - Confidence evaluation	- Evaluation of different sites: different training programs - No extensive cost evaluation
Hines, 2020	- Interviews and electronic surveys	--	- Respirator interference with patient care	--	- Responses reflected patient anxiety	- No information of specific tasks or emergency settings
Howard, 2020	- Considerations of different PPE	--	- Protection against aerosol-generating procedures	--	--	- Missing cost considerations
Patel, 2020	- Cost analysis - Comparison of cumulative costs	- Initial outlay - Recurring costs	- Fit testing - Wipes for disinfection	- Suggested EFR use: short phrases and low noise	- Suggested EFR use: hydrocolloid dressing	- Does not include healthcare worker costs
Radonovich, 2010	- Modified rhyme test result comparisons	--	- Training and fit testing (NIOSH)	- Evaluation of intelligibility of words	--	- Small sample size - No cost analysis
Wu, 2011	- Simulated work task analysis - State-Trait Anxiety Inventory - Trait anxiety measurements	--	--	--	- Comparison of anxiety between N95 and EFR (EFR induces greater anxiety)	- Larger population needed to determine if subpopulation has differing responses

Table 2.6 provides a review of EFR research and identifies unique research focussing on EFRs alone. Literature on EFRs often investigates safety factors. One safety factor under scrutiny in many EFR studies is disinfection. Disinfection protocols are not reliable without training and periodic testing as noted in Table 2.5. Standardized processes are necessary to ensure consistent and effective disinfection necessary for preventing spread of contaminants. In relation to protocol standardisation, the literature continues to emphasize the importance of ongoing training and program auditing to prevent protective respiratory program failure.

Additional functional and feasibility trends are seen in EFR literature. As discussed, EFR design changes are often recommended when considering comfort and communication factors impact user experience. Clever (2019) dedicates a section of their consensus study to research and design of EFRs to enhance speech intelligibility and reduce design aspects that cause discomfort. Aspects include size and weight of respirators, and ease of donning and doffing the equipment. With regard to feasibility, EFRs generally cost more than most other PPE but can have considerable benefits as indicated by comparison studies. Though there is research offered on costs of new EFR designs to address N95 shortages during SARS-CoV-2, further investigation into communication is necessary.

Table 2.6. Summary of literature on EFRs.

Paper	**Methodology**	**Cost**	**Function**			**Limitations/ Gaps**
			Safety	**Comm.**	**Comfort**	
Considers EFRs only						
Bessesen, 2015	- Disinfection standard operating procedure (SOP) development - Error rate comparison of manufacturer instructions and SOPs		-Disinfection protocols - Fit testing (Occupational Safety and Health Admin)	--	--	- Bleach concentrations are not consistent across products
Brown, 2018	-Respiratory Protection Program admin questionnaire - Walk-through questionnaire	--	- No structured auditing process for protocols - Disinfection and fit testing protocols not standardized	--	--	- Only one hospital out of nine in the study used EFRs consistently

Paper	Methodology	Cost	Function			Limitations/ Gaps
			Safety	Comm.	Comfort	
Considers EFRs only						
	- Discussion Group Questions		across hospitals			
Clever, 2019	- Consensus study - Case studies compilation	- Stock-piling costs - Compare costs	- Safety culture changes - Fit testing - Disinfection - Training and testing	- Factors impacting comfort and tolerability - User tolerability	- R&D: next generation of EFRs to improve comm.	- Indicates expansion of research on cost-analysis training, fitting, use
Liu, 2020	- Design feasibility study - Quantitative fit testing: end-tidal CO_2 and respiratory rate	- New design - Custom production costs	- Fit tests	- Muffled communication	- Dis-comfort	- Need for investigation of higher BMI users
Wentworth, 2020	- Multi-institutional trial of transparent EFR	--	- Design allows for better seal	- Design for hearing-impaired persons	- Design improves comfort and maintains seal	- Sample size of study was small

Table 2.7 provides a review of literature on N95s. Literature on N95s is predominantly based on safety. For example, a theme in N95 research is determining optimal methods for decontamination to reduce the quantity used and subsequent costs (utilization strategies). With decontamination methods, N95s can be used for longer periods of time, and repeatedly. However, though decontamination methods are offered in the literature, there is no standard, universally used method and respirator durability is not guaranteed. Another safety trend in N95 investigations is the success of fit testing. N95s are not effective if worn incorrectly and require routine fit reassessments to prevent leakage. This theme aligns with the EFR and comparisons findings. Finally, while safety plays a large role in PPE, much of the studies listed in Table 6 are clinically based. Further investigation of usage in the workplace is suggested.

Of the N95 literature, there are two studies that investigate feasibility of N95 programs. Studies often use cost-effective analyses as methodology, though they use different metrics to estimate benefits. Metrics include total program cost, level of intervention acceptability, incremental cost of preventing a clinical respiratory illness or net savings compared to no intervention, to name a few. A limitation of these metrics and economic evaluations is that results or methodology are often not transferable between settings. A comparative analysis among respirator types is preferred due to this, as PPE comparisons do not require factors such as country-specific levels of intervention acceptability. One limitation of N95 costing related to safety is utilization strategies that allow for repeated use or prolonged use of N95s. Decontamination of N95s is still in research phases and there are no publicly accepted standards. N95s are typically used once per patient or up to 8 hours if the seal does not break.

Table 2.7. Summary of literature on N95s.

Paper	Methodology	Cost	Function			Limitations/ Gaps
			Safety	Comm.	Comfort	
Considers N95s only						
Baig, 2010	- 63-item survey	--	- Preference for disposable respirators	- Little interference in comm. With patients	- Preference for respirators that do not interfere with breathing	- Findings indicate need for research into new design of N95
Bergman, 2010	- Decontamination methods (3 cycles): ultraviolet germicidal irradiation, ethylene oxide, hydrogen peroxide gas plasma, hydrogen peroxide vapor, microwave oven generated steam, bleach, liquid hydrogen peroxide and moist heat incubation	--	- Disinfection and respirator degradation	--	--	- Did not test FFR filtration efficiency of actual bioaerosols following a treatment
de Perio, 2020	- Descriptive study design	--	- Fit tests	--	--	- Expired equipment effectiveness - No cost analysis
Fischer, 2020	- Decontamination methods: ultraviolet radiation (260 – 285 nm), 70ºC heat, 70% ethanol and vaporized hydrogen peroxide (VHP) -Fit factor measurements	--	- Fit tests - De-contamination durations - VHP likely best method	--	--	- Did not study different models of N95s
Heimbuch, 2011	- Decontamination methods: microwave-generated steam, warm moist heat, and ultraviolet germicidal irradiation (UVGI) at 254 nm - H1N1 influenza contamination	--	- Fit testing and impact on protection after treatment	--	--	- Properties such as biocidal efficacy, pressure drop, residual toxicity needs to be evaluated - No cost analysis
Lee, 2005	- Prospective observational cohort study - Standard fit-test protocol analysis - Qualitative fit-test protocol employing denatonium benzoate	--	- Impacts of training and fit testing on respirator protection	--	--	- Small sample size and no cost analysis
Liao, 2020	- Heat under various humidities vs steam, vs 75% alcohol vs chlorine vs UV germicidal irradiation	--	- Heat is most effective	--	--	- Did not test on respirators

Paper	Methodology	Cost	Function			Limitations/ Gaps
			Safety	Comm.	Comfort	
Considers N95s only						
						contaminated with SARS-Cov-2
Mukerji, 2015	- Scopus database literature search - Inclusion of cost-effectiveness studies	- Productivity costs - Healthcare provider costs - Economic costs of productivity losses	- Studies including assigned protective factor	--	--	- Inclusion criteria limited number of studies
Mukerji, 2017	- Cost-effectiveness analysis - Incremental cost-effectiveness ratio (ICER)	- Equipment - Admin. - Product. Costs -Fit test costs	- Continuous use of N95s - Fit testing vs no fit testing	--	--	- Costs and factors may not be similar across countries
Ontiveros, 2020	- UV disinfection system	--	- UV penetration - Disinfection	--	--	- Layer disinfection does not reflect reality
Qian, 1998	- Filtration efficiency testing	--	- Filtration protection - Patient care interference	--	- Testing with low pressure drop for breathing	- Testing was limited to two bacteria
Radonovich, 2019	- Randomized simulated workplace study	--	- Fit test - Effect on attention	- Muffled speech - Difficulty hearing	- Dizziness - Fatigue -Breathing -Skin irritation	- Other costs and market considerations impact respirator adoptability
Suen, 2017	- Quantitative fit test - Ambient air particle concentration measurements	--	- Face seal leakage and fit testing	--	-Workload induced heavy breathing	- Need for frontline workers investigation
Zhuang, 2015	- Simulated workplace protection factor testing - Facial measurements - Sex-stratified analysis	--	- Face seal leakage and fit testing	--	--	- Only considers respirator and facial dimensions as design factors

2.5 CONCLUSION

The functional and feasibility findings summarized in this chapter provide an overview of the current literature. There are several major themes. First, EFRs may be preferred in emergency settings when protection is priority. Secondly, further research is needed for disinfection of N95s. Programs that consider different PPE utilization strategies must consider training, protocols and costs associated with required materials and time. Moreover, cost analyses often omit factors such as materials and time required to disinfect PPE. Lastly, a common theme among studies that implement new protective respirator programs, is that education and auditing systems are necessary for ensuring procedure adherence and continued program support. These themes indicate the importance of combining functional and financial considerations when developing cost-effectiveness models for PPE comparisons.

The purpose of this chapter is to review literature comparing the capability and cost considerations for determining whether organizations should invest in EFR and N95 respirators. There are several important aspects of the existing body of literature discussed. Aspects include accepted N95 disinfection methods, clinical allocation strategies that reduce costs by implementing EFR programs, user functional weaknesses such as fit test, communication challenges and time consumption during PPE disinfection. In addition, N95 users highly favour N95 respirators due to better comfort but prefer EFRs under circumstances when better protection is needed. Lastly, studies have concluded that EFRs tend to be safer than N95 respirators and EFRs typically do not have significant negative impacts on patient care. If N95s and EFRs are to be compared in research, it is important to understand the functional strengths and weaknesses of each, including the shelf-life, decontamination methods and limitations in previous research.

The Baracco (2015) study was the most comprehensive that was identified. The model considered moderate and severe pandemic circumstances based on the 1918 H1N1 pandemic (severe) and 1968 H3N2 pandemic (moderate). The features of the model can also be used to help determine pre-SARS-CoV-2 and post-SARS-CoV-2 circumstances such as fatality rate, average length of hospital stay, etc. The model could be updated to reflect SARS-CoV-2 attack rates and hospital conditions that impact the number of healthcare worker and patient contacts. For example, many health providers postponed elective surgeries in preparation of the expected pressures of SARS-CoV-2 on the healthcare system (Cooke, 2020). A comparison of N95 and elastomeric respirator use should be conducted for the SARS-CoV-2 pandemic setting and post-pandemic setting in which respirators will continue to be necessary. According to a primary care professor at the university of oxford, masks will be a requirement until there are no new cases (Greenhalgh, 2020 as cited in Khazan, 2020).

The current state of the literature reviewed is quickly developing as SARS-CoV-2 persists and new challenges in healthcare continue to put pressures on resources and patient care. Many new studies (published in 2020) provide insights into immerging functional and financial requirements of PPE. However, there are some significant gaps in existing knowledge. Models discussed use dated data from previous pandemics. New factors such as disinfection methods extensively researched and policy changes such as disinfecting N95 masks should be considered. Furthermore, many studies are completed in controlled environments. It is important to conduct user case studies in clinical environments to better understand potential design improvements of EFRS for better program acceptance and maintenance. In conclusion, areas for future study include feasibility analyses that take a system approach at investigating combined financial and functional factors of EFR and N95 respirators. Existing research sets the path for development of a new feasibility model for EFRS based on SARS-CoV-2.

3. METHODS

This section discusses methods for determining if EFRs are efficacious substitutes for N95 respirators by comparing their functionality and cost. Multiple data sources were elicited for model inputs, and several different methods were used to complete comparative studies on financial and functional aspects of EFRs and N95s.

A model based on Baracco et al.'s (2015) was developed to contribute an extended modelling approach. This was done by adding new metrics, scenario investigation and dynamic modelling. Sections 3.1.1 and 3.1.2 introduce Baracco et al.'s (2015) equipment and inventory costs used in the base model framework. Section 3.1.2.1 introduces base model extensions such as the addition of program costs. Section 3.2 introduces a dynamic model that uses the base model framework and incorporates the susceptible-infected-recovered (SIR) compartmental model. A final model is introduced in Section 3.3 which also uses the base model framework and incorporates the susceptible-exposed-infected-recovered (SEIR) compartmental model. Lastly, Section 3.5 introduces the TOPSIS analyses used to investigate both functional and financial criteria together. Figure 3.1 illustrates the relationships between each of the financial analysis models that will be presented in this chapter.

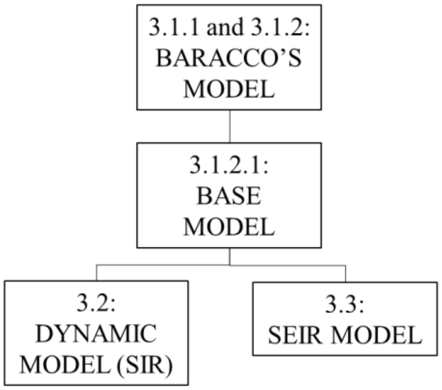


Figure 3.1: Modelling flowchart

As Baracco et al. (2015) considered only stockpiling respirators according to equipment and inventory costs, the new models in this chapter incorporate additional costs, specifically respiratory protection program management, disinfection, and respirator utilization strategies. We define stockpiling as accumulating respirators for all healthcare workers for a defined pandemic duration. Further, the model takes a different approach to calculating stockpiling requirements by using a dynamic model to estimate daily infections. This enables recommendations for daily respirator purchasing based on epidemiological characteristics of several pandemic scenarios.

Lastly, functional aspects of N95s and EFRs were investigated using the multi-criteria decision analysis method, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS suggests an optimal alternative (respirator option) based on criteria rankings which are ratings for different functional and financial aspects of N95s and EFRs in this application. Recommendations for when to use each respirator option are provided based on the functional and financial findings. Table 3.1 lists all notation used throughout Sections 3.1-3.4.

Table 3.1: Notation related to Methods chapter

Baracco's Equipment Costs			
R_x	*Respirators required,* where $x \in \{N95, EFR\}$	$\mathcal{S}$	*Patients seek healthcare*
C	*Total contacts for a given population*	HU	*Healthcare utilization rate*
CPP	*Number of contacts per respirator*	h	*Hospitalization rate*
P	*Number of HCWs involved in pandemic*	H	*Hospitalized*
K	*Number of patient contacts per HCW per hour*	$t_{non-ICU}$	*Average duration a patient stays in a hospital (non-ICU)*
ω	*Employee attrition rate*	i	*ICU admission rate*
T	*Duration of pandemic*	J	*Individuals needing ICU care*
$c_{i,j}$	*Average daily contacts in department i for HCW type j*	t_{ICU}	*Average stay in ICU*
I	*Infected individuals (see SIR)*	m	*Mechanical ventilation rate*
N	*Target population*	t_{MV}	*Average mechanical ventilation duration*
A	*Attack rate*	M	*Duration on mechanical ventilation*
MV	*Mechanical ventilation total*	$APR_{x,\tau}$	*Respirator x accessory* τ
Inventory Costs			
TP	*Total number of pallets*	MCY	*Management cost per year*
F	*Footprint of pallets*	MS	*Management salary per full-time equivalent employee*
SP	*Number of stacked pallets*	$FTEE$	*Number of full-time managers*
TSF	*Total sq ft needed*		
Base Model Extensions			
$\mathcal{R}_x$	*Number of reprocessing cycles*	$\mathcal{R}_{EFR,\delta}$	*EFR reprocessing cycles depending on reprocessing strategy*

$\mathcal{B}$	*Batch size (respirators/cycle)*	δ	*Index for the reprocessing strategy where* $\delta \in \{contact, shift, clean\}$
$\mathcal{M}$	*Maximum number of reprocessing cycles for each N95*		
SIR Model			
S	*The total number of susceptible individuals*	B	*Infection rate*
I	*The total number of infected individuals*	N	*Population*
R	*The total number of recovered individuals*	γ	*Recovery rate*
SEIR Model			
μ:	*Per-capita death and birth rate independent of disease.*	γ:	*Recovery rate. Reciprocal of infectious period.*
β:	*Infection rate.*	α:	*Virus-induced average death rate.*
ϵ:	*Incubation rate. Reciprocal of incubation period.*		
TOPSIS			
$(x_{ij})_{m\times n}$	*Matrix of ratings for the* m^{th} *alternative and* n^{th} *criteria*	w_j	*Weighting for* j^{th} *criteria*
x'_{ij}	*Matrix rating with adjusted scale*	t_{ij}	*Weighted normalized rating*
a	*Research rating value*	A_w	*Negative ideal solution*
t_{min}	*TOPSIS target minimum scale value*	A_b	*Ideal solution*
t_{max}	*TOPSIS target maximum scale value*	J_+	*Criteria having a positive impact*
r_{min}	*Research minimum scale value*	J_-	*Criteria having a negative impact*
r_{max}	*Research maximum scale value*	S^*	*Ideal solution*
$(r_{ij})_{m\times n}$	*Normalized matrix of ratings*	S'	*Negative ideal solution*
r_{ij}	*Normalized rating*	x''_{ij}	*Adjusted performance scale rating*

3.1 BASE MODEL

The base model uses Baracco et al.'s (2015) methods, but with added sophistication of additional metrics and a new respirator equipment utilization strategy. The model estimates total stockpiling costs for each respirator utilization strategy for a predetermined pandemic duration. The base case assumes a pandemic length of 12 weeks. The base model and Baracco et al.'s (2015) model calculate the total cost of each strategy alternative as shown in (3.1):

$$Total\ cost = Equipment\ costs + Inventory\ Costs \tag{3.1}$$

However, there are several differences between the base case model and Baracco et al.’s (2015) as summarized in Table 3.2. Disinfection costs for both EFRs and N95s are added which include time and materials. Additionally, disinfection costs depend on how often respirators are processed. In the base model, N95s can be disinfected by two possible methods: low temperature plasma vaporized hydrogen peroxide sterilization method (Holdsworth, 2021), and ultraviolet germicidal irradiation (UVGI) (Lowe, 2020) which are explained in more detail in Section 3.1.2.1. EFRs can be disinfected once after each contact, or after each shift, or cleaned after each contact and disinfected after each shift. Cleaning requires less steps and time but is less effective than disinfection methods.

Table 3.2: Comparison of base model with Baracco et al. (2015).

Baracco et al., 2015	**Base Model**
Equipment costs	Equipment costs
Inventory costs	Inventory costs
N95 utilization strategies	N95 utilization strategies
EFR utilization strategies	EFR utilization strategies
One mixed N95 and EFR utilization strategy	Disinfection costs
	EFR disinfection strategies
	N95 disinfection strategies
	Program costs
	One mixed N95 and EFR utilization strategies

3.1.1 BARACCO’S EQUIPMENT COSTS

As stated, the base model considers both equipment and inventory costs as calculated using Baracco et al.’s (2015) methods. Total equipment costs ($) depend on respirators and accessories required to protect all healthcare workers during the length of the pandemic. In addition, the costs are prorated to the shelf-life of the equipment (years). Using Baracco et al.’s (2015) method,

$$Total\ annual\ equipment\ costs = \frac{Total\ equipment\ costs}{Shelflife} \tag{3.2}$$

Where,

$$Total\ equipment\ costs\ =\ respirator\ costs\ +\ accessories\ costs \tag{3.3}$$

Respirator costs=respirator price *R_x

Respirator prices are known, and the number of *respirators required* (R_x) depend on *total contacts* (which is not dependent on the duration of the pandemic when using Baracco's static method) and *number of contacts per product.*

R_x = *Respirators required,* where $x \in \{N95, EFR\}$ (respirators)

C = Total contacts for a given population (contacts) and attack rate

CPP = Number of contacts per respirator (contacts/respirator)

Where the *number of contacts per respirator* depends on use strategies:

1. Discarded after one contact : *CPP* = 1.
2. Multiple contacts before being discarded (max 5 contacts and then discarded) : *CPP = 5.*

For N95s, the number of *respirators required* is:

$$R_{N95} = \frac{C}{CPP} \tag{3.4}$$

For EFRs, the *respirators required* depends on the number of healthcare personnel involved in the pandemic as each healthcare provider requires one EFR. *Healthcare workers (HCWs) needed* during the pandemic depends on *total contacts, number of HCW-patient contacts per hour, employee attrition rate* and the *duration of the pandemic.* Without the duration of the pandemic, the number of HCWs per week can only be estimated. All patients must be seen (all contacts must be addressed) at a given HCW-patient contact rate per hour during the pandemic. The number of *HCW-patient contacts per hour, employee attrition rate,* and *duration of pandemic* are known. It is also assumed that all HCWs work 40 hours per week.

P = Number of HCWs involved in pandemic (HCWs)

K = Number of patient contacts per HCW per hour (contacts/HCW/hour)

ω = Employee attrition rate (% of HCWs)

T = Duration of pandemic (weeks)

And,

$$P = \frac{C}{T \times K \times (1 - \omega) \times 40} \tag{3.5}$$

Therefore,

$$R_{EFR} = P \tag{3.6}$$

For both models, *total contacts for a given population (C)* depend on *MD contacts, RN contacts, Respiratory therapist (Resp ther) contacts, Radiology technologist (Rad tech) contacts, Phlebotomists (Phleb), Housekeepers (Housek), Other HCWs (mental health, clergy, etc.), Registration (Ref) contacts* and *Porter contacts.* Table 3.3 summarizes the approximate number of daily contacts each HCW experiences per patient in five general hospital settings. The approximate daily contacts of each HCW can be adjusted.

Table 3.3: Daily contacts inputs for HCW in each healthcare setting (Baracco et al., 2015)

Setting	**HCWs**								
	MD	RN	Resp ther	Rad tech	Phleb	MH	Housek	Reg	Porter
Outpatient visit (Ambulatory)	$c_{1,1}$	$c_{1,2}$				$c_{1,6}$		$c_{1,8}$	
Hospitalized (ED requiring admission)	$c_{2,1}$	$c_{2,2}$	$c_{2,3}$	$c_{2,4}$			$c_{2,7}$	$c_{2,8}$	$c_{2,9}$
Hospitalized (non-ICU) (Ward)	$c_{3,1}$	$c_{3,2}$	$c_{3,3}$	$c_{3,4}$	$c_{3,5}$	$c_{3,6}$	$c_{3,7}$		
ICU not on MV	$c_{4,1}$	$c_{4,2}$	$c_{4,3}$	$c_{4,4}$		$c_{4,6}$	$c_{4,7}$		
ICU on MV	$c_{5,1}$	$c_{5,2}$	$c_{5,3}$	$c_{5,4}$		$c_{5,6}$	$c_{5,7}$		

The number of *Porter contacts* depends on those *hospitalized.* The number of *Hospitalized* depends on those who *Seek healthcare* and *Hospitalization utilization rate.* The number of *those who seek healthcare* depends on those who are *ill* and *hospital utilization rate*. *Illness* depends on *target population and attack rate. Population of interest in study (target population), attack rate and hospitalization rate are known.* Figure 3.2 summarizes the relationships between each of the population health conditions.

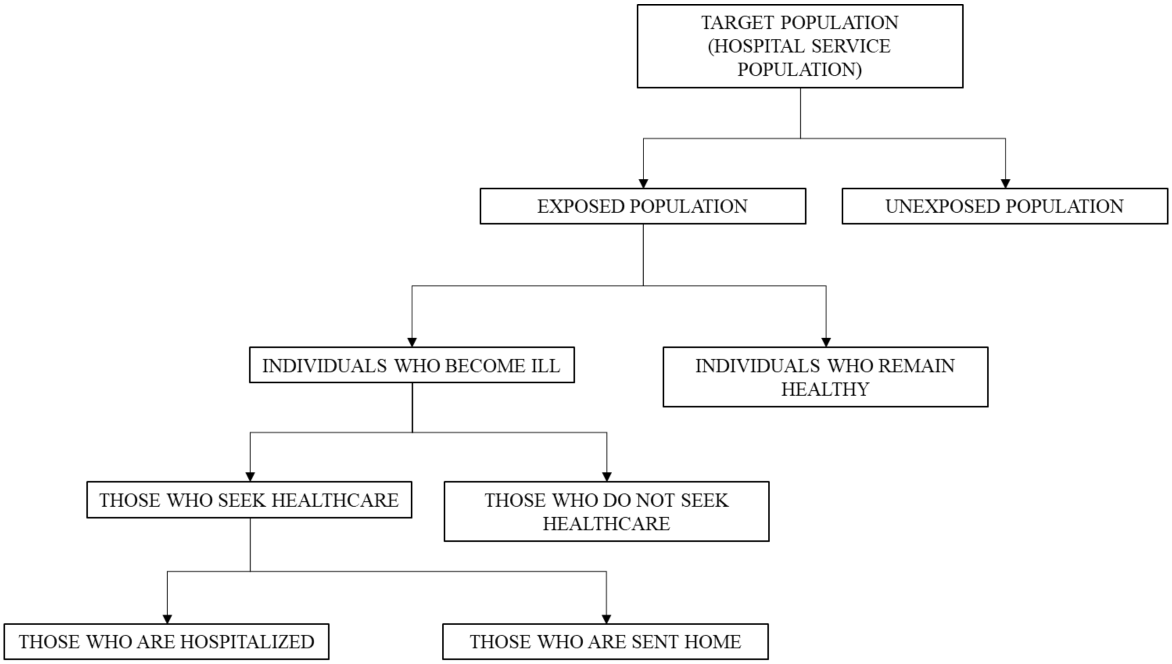


Figure 3.2: Flowchart of population health conditions.

I = *Individuals who become ill (sick population)*
N = *Target population (service population of hospital)*
A = *Attack rate (sick population/total exposed population)*
$\mathcal{S}$ = *Seek healthcare (sick population who become patients)*
HU = *Healthcare utilization rate (% of those ill)*
h = *Hospitalization rate (hospitalizations/day)*
H = *Hospitalized (patients)*

$$I = A \times N \tag{3.7}$$

$$\mathcal{S} = I \times HU \tag{3.8}$$

$$H = \mathcal{S} \times h \tag{3.9}$$

The total number of porter contacts is equivalent to the total number of hospitalized individuals. *Registration contacts* depend on those who *Seek healthcare, hospitalization rate and average daily number of a registrar contacts with hospitalized patients.*

$c_{2,8}$ = *Registration contacts (contacts)*

$$Registration\ contacts\ = (H \times \mathcal{S}) + (H \times c_{2,8}) \tag{3.10}$$

Other contacts depend on *Outpatient visits (non-hospitalized), non-ICU days, ICU days and days on mechanical ventilation. Other contacts* are not summarized in Table *3.3*, as they can be calculated using the following equations. *Outpatient visits* depend on *the number of those seeking healthcare* and those who are actually *hospitalized.*

$$Outpatient\ visits, not\ hospitalized\ = \mathcal{S} - H \tag{3.11}$$

The total number of *hospital days in non-ICU* of all patients who are admitted to the hospital but do not need ICU resources depend on the number of those who are *hospitalized,* and *average duration of hospital stays (non-ICU).*

$t_{non-ICU}\ = Average\ hospital\ duration\ (days) of\ a\ patient\ that\ is\ not\ in\ ICU$

$$Hospital\ days, non-ICU\ = H \times t_{non-ICU} \tag{3.12}$$

Hospital days in ICU depend on the number of those needing *ICU care, the average duration of hospital stays in ICU care, and the number of those needing mechanical ventilation. Individuals needing ICU care* depend on those who are *hospitalized and the ICU admission rate* (% of all those who are hospitalized). *ICU admission rate* is known.

i = ICU admission rate (admissions/day)
J =Individuals needing ICU care (patients)
t_{ICU} *= Average stay in ICU (days)*

Therefore,

$$J = H \times i \tag{3.13}$$

Hospital days in ICU can be calculated once *mechanical ventilation days* is formulated. The number of *mechanical ventilation days* depends on total patients who need *mechanical ventilation* and *average duration of mechanical ventilation. Mechanical ventilation duration* is known, and *mechanical ventilation demand* depends on *ICU care* and *mechanical ventilation rate. Mechanical ventilation rate* is known.

m = mechanical ventilation rate (% of patients in ICU)
t_{MV} = *Average mechanical ventilation duration (days)*
M = Duration on mechanical ventilation (days)
MV = Mechanical ventilation total (patients)

And,

$$MV = J \times m \tag{3.14}$$

$$Mechanical\ days = MV \times t_{MV} \tag{3.15}$$

$$Hospital\ days\ in\ ICU = (J - MV) \times t_{ICU} \tag{3.16}$$

Therefore, Eq. 3.17 encompasses equations 3-11, 3-12, 3-15, and 3-16 to calculate *other contacts.*

$$Other\ contacts = (S - H) + (H \times t_{non-ICU}) + ((J - MV) \times t_{ICU}) + (MV \times t_{MV}) \tag{3.17}$$

Housekeeper contacts depend on days spent in *non-ICU and ICU, days spent on mechanical ventilation and total hospitalized:*

$$Housekeeper\ contacts = Non - ICU\ days + ICU\ days + mechanical\ ventilation\ days \tag{3.18}$$

$$Housekeeper\ contacts = (H \times t_{non-ICU}) + ((J - MV) \times t_{ICU}) + (MV \times t_{MV}) + H \tag{3.19}$$

Phlebotomist contacts depends on days spent in hospital (non-ICU):

$$Phlebotomist\ contacts = H \times t_{non-ICU} \tag{3.20}$$

Radiology tech contacts depend on number of *hospitalized, days spent in non-ICU and ICU, and days spent on mechanical ventilation.* Radiology contacts also depend on how often radiology techs visit patients in the ICU and patients on ventilation.

Therefore,

$$\begin{aligned} &Radiology\ contacts \\ &\quad = H + (H \times t_{non-ICU}) + ((J - MV) \times t_{ICU} \times c_{4,4}) \\ &\quad + (MV \times t_{MV} \times c_{5,4}) \end{aligned} \tag{3.21}$$

Respiratory tech contacts depend on number of individuals *hospitalized, days spent in non-ICU, ICU and on mechanical ventilation.* Respiratory contacts also depend on how often respiratory therapists visit patients who are first hospitalized, then either in non-ICU, ICU or on mechanical ventilation.

Therefore,

$$\begin{aligned} Respiratory\ contacts = (H \times c_{2,3}) + (H \times t_{non-ICU} \times c_{3,3}) + ((J - \\ MV) \times t_{ICU} \times c_{4,3}) + (MV \times t_{MV} \times c_{5,3}) \end{aligned} \tag{3.22}$$

RN contacts depend on number of *hospitalized, outpatient visits, hospital days in non-ICU and ICU, and days spent in mechanical ventilation.* Nurse contacts also depend on number of contacts with outpatients, those who are hospitalized, and supplementary contacts once patients are admitted and sent to non-ICU, ICU, or mechanical ventilation.

Therefore,

$$\begin{aligned} RN\ contacts = ((\mathcal{S} - H) \times c_{1,2}) + (H \times c_{2,2}) + (H \times t_{non-ICU} \times c_{3,2}) + ((J \\ - MV) \times t_{ICU} \times c_{4,2}) + (MV \times t_{MV}) \times c_{5,2} \end{aligned} \tag{3.23}$$

MD contacts are similar to *RN contacts.* However, doctors only see each outpatient once:

$$\begin{aligned} MD\ contacts = (\mathcal{S} - H) + (H \times c_{2,1}) + (H \times t_{non-ICU} \times c_{3,1}) + ((J - \\ MV) \times t_{ICU} \times c_{4,1}) + (MV \times t_{MV} \times c_{5,1}) \end{aligned} \tag{3.24}$$

Finally, *total contacts* are the sum of all previous contacts. *Total contacts* are the number of HCW contacts with patients who become sick for given viral epidemiological characteristics. *Total contacts* do not depend on time but are calculated given a target population. Table 3.4 summarizes the summation of HCW contacts to calculate *Total costs.*

C = Total Contacts

Table 3.4: Summation of contacts

Summation of C	**Description**
$H\times \mathcal{S} + Hc_{28}$	Registration contacts
+ $(\mathcal{S} - \mathrm{H}) + (\mathrm{H}\times \mathrm{t}_{\mathrm{non-ICU}}) + ((\mathrm{J}-\mathrm{MV})\times \mathrm{t}_{\mathrm{ICU}}) + (\mathrm{MV}\times \mathrm{t}_{\mathrm{MV}})$	Other contacts
+ $(H\times t_{non-ICU}) + ((J\text{-}MV)\times t_{ICU}) + (MV\times t_{MV} + H)$	Housekeeper contacts
+ $H\times t_{non-ICU}$	Phlebotomist contacts
+ $H + (H\times t_{non-ICU}) + ((J\text{-}MV)\times t_{ICU}\times c_{4,4}) + (MV\times t_{MV}\times c_{5,4})$	Radiologist contacts
+ $(H\times c_{2,3}) + (H\times t_{non-ICU}\times c_{3,3}) + ((J\text{-}MV)\times t_{ICU}\times c_{4,3}) + (MV\times t_{MV}\times c_{5,3})$	Respiratory therapist contacts
+ $((\mathcal{S}\text{-}H)\times c_{1,2}) + (H\times c_{2,2}) + (H\times t_{non-ICU}\times c_{3,2}) + ((J-MV)\times t_{ICU}\times c_{4,2}) + (MV\times t_{MV}\times c_{5,2})$	Registered nurse contacts
+ $(\mathcal{S}\text{-}H) + (H\times c_{2,2}) + (H\times t_{non-ICU}\times c_{3,2}) + ((J-MV)\times t_{ICU}\times c_{4,2}) + (MV\times t_{MV}\times c_{5,2})$	Medical doctor contacts

Continuing with equipment costs, accessories are also considered. Accessory costs depend on number of accessories needed and their prices. *Accessory prices* are known, and *number of accessories needed per respirator* ($APR_{x,c}$) depends on respirator type and their use.

Let x be an index for the type of respirator where $x \in \{N95, EFR\}$

Let τ *be an index for the type of accessory needed for a respirator where* $c \in \{1,2,3\}$

Index $\tau = 1$ for eyewear, $\tau = 2$ filters, and $\tau = 3$ is for tear away visors.

For N95s:

Accessories needed for a defined respirator type depends on the *number of respirators multiplied by the number of accessories needed per respirator*. Eyewear is the only accessory needed for N95s, therefore, for N95s

$$Accessories\ needed = \frac{C}{CPP} \times APR_{N95,1} \tag{3.25}$$

And for EFRs

$$Accessories\ needed = \sum_{\tau \in \{1,2,3\}} R_{EFR} \times APR_{EFR,\tau} \tag{3.26}$$

3.1.2 BARACCO'S INVENTORY COSTS

Baracco et al.'s (2015) inventory costs consider both the costs associated with equipment taking up space, and inventory management. In general,

$$\begin{aligned} &\text{Total annual inventory costs} \\ &\quad = Space\ cost\ per\ year + Management\ cost\ per\ year \end{aligned} \tag{3.27}$$

Where,

$$\begin{aligned} &\text{Space cost per year} = \\ &\quad Total\ square\ feet\ needed \times (Warehouse\ lease\ cost\ per\ sq\ ft \\ &\qquad + Cost\ of\ warehouse\ utilities\ and\ insurance\ per\ sq\ ft) \end{aligned} \tag{3.28}$$

Total square ft needed (and 20% aisle) depends on the *footprint of pallets. Footprint of pallets* depends on *the total number of pallets* and *number of stacked pallets. Total number of pallets* depends on the total number of pallets in the inventory cache.

TP = Total number of pallets

Therefore,

$$TP = respirator\ pallets\ in\ cache + accessory\ pallets\ in\ cache + disinfection\ equipment\ pallets\ in\ cache. \tag{3.29}$$

The general case for pallets in cache is as follows:

$$Pallets\ in\ cache = \frac{Equipment\ needed}{Number\ of\ boxes\ per\ pallet} \tag{3.30}$$

Number of boxes per pallet depends on *box volume* and *equipment per box. Equipment per box* and *box volume* are known. To calculate items per pallet, the standard pallet size is needed which is 48” x 40”, or 1920 in^2. The pallet size helps determine how many equipment boxes can be stored on each pallet.

$$Items\ per\ pallet = \left(\frac{\frac{1920}{MAX(box\ surface\ area) \times MIN(box\ dimension)}}{Box\ volume} \right) \times Equipment\ per\ box \tag{3.31}$$

And,

F = Footprint of pallets (square feet)
SP = Number of stacked pallets
TSF = Total sq ft needed

The total footprint of pallets can be calculated by determining the surface area that pallets consume if pallets can be stacked (Eq. 3.32). Following Baracco et al.’s (2015) assumption, two pallets can be stacked. Each stack of pallets covers 40” x 48” or 40/3 ft^2 of warehouse area. The total square footage of inventory needed to stockpile all equipment is equivalent to the footprint of pallets in the warehouse, with 20% additional space for walking aisles (Eq. 3.33). This is then multiplied by the utilities, insurance, and lease costs per square foot to calculate annual space cost.

$$\mathrm{F} = \frac{TP}{IF(SP > 0, SP, 2)}\left(\frac{40}{3}\right) \tag{3.32}$$

$$TSF = 1.2 \times F \tag{3.33}$$

Total annual inventory costs also consider *management costs per year. Management costs per year* depend on Management salary per full-time equivalent employee and number of full-time equivalent managers. *Management salary* is known. And *number of full-time managers* depends on how many square feet a manager must manage (assumed 10,000 sq ft) (Baracco et al., 2015).

MCY = Management cost per year
MS = Management salary per full-time equivalent employee
FTEE = Number of full-time equivalent employees

Therefore,

$$FTEE = \frac{TSF}{10{,}000} \tag{3.34}$$

$$MCY = FTEE \times MS \tag{3.35}$$

3.1.2.1. Base Model Cost Extensions

The base model differs from Baracco et al.'s (2015) model by incorporating the additional costs associated with disinfection methods, respiratory protection program implementation and maintenance. Disinfection costs impact both equipment and inventory costs. A detailed approach to calculating disinfection equipment is provided. Inventory cost calculations will not be reiterated for disinfection equipment, as the method follows the same steps as previously introduced.

Total equipment costs depend on *disinfection equipment needed* and *disinfection equipment price. Disinfection equipment prices* are known. *Disinfection equipment needed* depends on *total contacts* and *number of contacts per product*.

For N95s:

The *Number of contacts per product* depends on the utilization strategy. When disinfecting N95s, the number of contacts per product is 10. N95s must be disinfected after each contact, and they can only be disinfected 10 cycles. A disinfection cycle encompasses all the sub-tasks required to sterilize multiple N95s at a time. Disinfection equipment required per respirator each disinfection cycle depends on the disinfection method:

1. Low temperature plasma vaporized hydrogen peroxide sterilization method which requires one peel pack and one chemical indicator (Holdsworth, 2021).
2. Ultraviolet Germicidal Irradiation (UVGI) Process which requires (Lowe, 2020):
    a. Mask
    b. Gloves
    c. Gown
    d. Oxivir wipe
    e. Brown and white paper bags

N95s cannot be disinfected more than 10 times. If $CPP \neq 10$ in the model, *disinfection equipment needed* is equivalent to zero since it indicates that a different N95 utilization strategy is chosen.

Otherwise,

$$\textit{Disinfection equipment needed} = \frac{C}{CPP}\ peel\ packs + \frac{C}{CPP}\ chemical\ indicators \tag{3.36}$$

For EFRs:

Disinfection equipment needed depends on the disinfection strategy. The three strategies considered are 1) *Disinfect per contact, 2) Disinfect once per shift and 3) Disinfect once per shift and interim cleaning once per contact. HPP* is the number of hours a product is used at once. *HPP* is used for calculating the disinfection strategies 2 and 3:

1. *Disinfect per contact : disinfection supplies needed =* $C \times$*disinfection equipment.*
2. *Disinfect once per shift : disinfection supplies needed =* $(\frac{T\times(40)}{HPP}) \times$*disinfection equipment.*

3. *Disinfect once per shift, interim clean once per contact = (C-* $(\frac{T\times(40)}{HPP})$ *) wipes +* $(\frac{T\times(40)}{HPP})$ $\times$*disinfection equipment.*

The disinfection equipment required each time a respirator is disinfected includes:

- 2 Gloves
- 1 Face mask
- 15 mL mild detergent
- 750 mL disinfectant

The interim disinfection equipment required each time a respirator is interim cleaned is:

- Disinfection wipe (x 2)

Program costs are also added to the model and include activities that require time and resources. The burden rate, or hourly rate of pay of HCW helps estimate costs for program activities such as:

- Program development
- Medical surveillance
- Training – development
- Training – delivery
- Fit testing
- Maintenance
- Auditing

Generally,

$$Program\ activity\ cost = Burden\ rate\ \times Hours \tag{3.37}$$

For disinfection costs:

$$\begin{aligned}&Disinfection\ cost\\ &\qquad = Burden\ rate\ \times \frac{Hours}{Reprocessing\ cycle}\\ &\qquad \times Number\ of\ reprocessing\ cycles\end{aligned} \tag{3.38}$$

The number of reprocessing cycles (or disinfecting cycles) is different for N95s and EFRs.

$\mathcal{R}_x$ = *Number of reprocessing cycles*
$x \in \{N95, EFR\}$

For N95s, the number of reprocessing cycles depends on three factors: total number of contacts, the number of respirators that can be reprocessed at once, and the total number of times a respirator can be reprocessed. If 100 contacts are expected, 10 respirators can be reprocessed at a time (batch size), and they can only be disinfected 5 times (maximum number of reprocessing cycles), the total number of reprocessing cycles is ($R_{N95} = \left(\frac{100}{10}\right) * (5) = 50$).

Therefore, let:

$\mathcal{B}$ = *Batch size (respirators/cycle)*
$\mathcal{M}$ = *Maximum number of reprocessing cycles for each N95 (cycles/respirator)*

And,

$$\mathcal{R}_{N95} = \left(\frac{C}{\mathcal{B}}\right) * (\mathcal{M}) \tag{3.39}$$

For EFRs, the number of reprocessing cycles $\mathcal{R}_{EFR}$ depends on how often EFRs are disinfected. They can be disinfected after each contact, after each shift or after each shift and interim cleaned after each contact. Interim cleans require less time and supplies, but do not provide the same insurance against cross-contamination as disinfecting.

Let $\mathcal{R}_{EFR,\delta}$ represent the number of EFR reprocessing cycles depending on the reprocessing strategy. The three strategies are to disinfect after each contact, after each shift, or to disinfect after each shift and clean after each contact.

Let δ be an index for the reprocessing strategy where $\delta \in \{contact, shift, clean\}$

For EFRs, the total number of reprocessing cycles if EFRs are disinfected after each patient contact is equivalent to the total expected contacts (Eq. 3.40). If EFRs are disinfected after each shift, the total number of reprocessing cycles is equivalent to the total number of shifts during the length of the pandemic. This can be estimated by dividing the total pandemic duration in hours by the number of hours EFRs are used per shift (Eq. 3.41). Lastly, Equation 3.42 presents the total number of reprocessing cycles required if EFRs are interim cleaned after each contact. EFRs are cleaned after each contact, and then disinfected after a HCW's last contact, at the end of their shift. This is why the total number of shifts during the pandemic are subtracted from the total number of expected contacts.

$$\mathcal{R}_{EFR,Contact} = C \tag{3.40}$$

$$\mathcal{R}_{EFR,Shift} = (\frac{T \times 40}{HPP}) \tag{3.41}$$

$$\mathcal{R}_{EFR,Clean} = C - (\frac{T \times 40}{HPP}) \tag{3.42}$$

Finally, a mixed strategy similar to Baracco et al.'s (2015) is used in the base model. Baracco et al. (2015) allocated N95s to doctors, nurses, and respiratory therapists, as they have frequent daily patient contacts. EFRs are allocated to remaining staff. In the base model mixed strategy, EFRs are allocated to doctors, nurses, and respiratory therapists and remaining staff use N95s. Equipment, inventory and program costs are calculated similarly to before, but depend on new calculations for total contacts which impact respirator quantity requirements.

For N95s, the number of respirators required depends on the total contacts calculated for HCW excluding doctors, nurses, and respiratory therapists:

$$
\begin{aligned}
R_{N95} ={}& \\
&(((\mathcal{S} - H) + (H \times t_{non-ICU}) + \left((J - MV) \times t_{ICU}\right) + (MV \times t_{MV}) \\
&\quad + (H \times t_{non-ICU}) + \left((J - MV) \times t_{ICU}\right) + (MV \times t_{MV} + H) \\
&\quad + H \times t_{non-ICU} + H + (H \times t_{non-ICU}) \\
&\quad + \left((J - MV) \times t_{ICU} \times c_{4,4}\right) + \left(MV \times t_{MV} \times c_{5,4}\right))/CPP
\end{aligned}
\tag{3.43}
$$

For EFRs, the number of respirators required depends on the number of doctors, nurses and respiratory therapists needed:

$$
\begin{aligned}
&R_{EFR} = \\
&+(H \times t_{non-ICU} \times c_{3,3}) + ((J\text{-}MV) \times t_{ICU} \times c_{4,3}) + \left((J - MV) \times t_{ICU} \times c_{4,2}\right) \\
&+ ((H \times c_{2,3}) + (MV \times t_{MV} \times c_{5,3}) \\
&+ \left((\mathcal{S} - H) \times c_{1,2}\right) + \left(H \times c_{2,2}\right) + \left(H \times t_{non-ICU} \times c_{3,2}\right) \\
&+ \left(MV \times t_{MV} \times c_{5,2}\right) + (\mathcal{S} - H) + (H \times c_{2,2}) + (H \times t_{non-ICU} \times c_{3,2}) \\
&+ ((J - MV) \times t_{ICU} \times c_{4,2}) + (MV \times t_{MV} \times c_{5,2}))/(T \times K \times (1 - \alpha) \times 40)
\end{aligned}
\tag{3.44}
$$

3.2 DYNAMIC MODELLING

The following section introduces the use of the SIR compartmental model to forecast daily contacts and hospitalizations. Understanding the dynamics of disease transmission helps to predict daily respirator requirements which can reduce costs of stockpiling. By predicting daily demands, the SIR model can be used to calculate the quantity and cost of respirators needed over the duration of a pandemic. This reduces risks of overstocking and expiring equipment.

The base model was extended to allow a phased approach using the SIR model. This new model will be referred to as the dynamic model henceforth. The dynamic model calculates costs of the phased approach that allocates N95s to some HCWs and then allocates EFRs to all staff after a number of weeks. The number of weeks before transitioning all HCWs to EFRs is up to decision-makers. The phased approach allows for healthcare facilities to use N95s and train and prepare for the implementation of an EFR respiratory protection program. The benefits of this, is that it allows HCWs to prototype the program in specialized departments to understand strengths and challenges of using EFRs. Baracco et al. (2015) did not use daily case and respirator requirements information to estimate respirator stockpiling requirements. However, Baracco et al.'s (2015) mixed strategy was used to increase comparisons between alternatives. A brief recap of the respirator utilization strategies can be found in Table 3.5.

Table 3.5: Summary of respirator utilization strategies

Strategy	Description	Model
Phased Approach	EFRs for MDs, RNs, and respiratory therapists for first 10 weeks, EFRs for remaining HCWs for remaining duration of pandemic	Dynamic, SEIR
Mixed Strategy #2	N95s for MDs, RNs, and respiratory therapists, EFRs for remaining HCWs for entire pandemic	Base Model, Dynamic, SEIR
Mixed Strategy #1	EFRs for MDs, RNs, and respiratory therapists, N95s for remaining HCWs for entire pandemic	Dynamic, SEIR

The SIR compartmental model helps to forecast spread of disease and estimate daily cases which helps to determine daily respirator requirements. The variables are separate populations from those introduced in Section 3.1 The three variables are:

$S = \textit{The total number of susceptible individuals}$
$I = \textit{The total number of infected individuals}$
$R = \textit{The total number of recovered individuals}$

The SIR model helps to achieve several objectives such as predicting the spread of disease, estimating epidemiological parameters, and predicting the duration of a pandemic, to name a few. The SIR model estimates the number of new ill individuals per day at a hospital which helps to calculate the number of respirators needed in a phased approach. Specifically, in this thesis the SIR model provides data on when contacts occur during a pandemic, allowing the respirator requirements to also be determined during the pandemic. The SIR model parameters are as follows (Roda et al., 2020):

$B = \textit{Infection rate}$
$N = \textit{Population}$
$\gamma = \textit{Recovery rate}$

With the differential equations describing the SIR model:

$$\frac{dS}{dt} = \frac{-(B \times S \times I)}{N} \tag{3.45}$$

$$\frac{dI}{dt} = \frac{B \times S \times I}{N} - (\gamma \times I) \tag{3.46}$$

$$\frac{dR}{dt} = \gamma \times I \tag{3.47}$$

The phased approach assumes that doctors, nurses, and respiratory therapists use EFRs for the first ten weeks, while the remaining HCWs use N95s. After ten weeks, all personnel are allocated EFRs. The total EFRs required depends on the number of HCWs needed over a pandemic of 12 weeks. The total number of N95s required depends on the total contacts between remaining HCWs and patients.

$$\begin{aligned}
&R_{N95} = \\
&(((\mathcal{S}(t) - H(t)) + (H(t) \times t_{non-ICU}(t)) + \left((J(t) - MV(t)) \times t_{ICU}(t)\right) + \\
&+(MV(t) \times t_{MV}(t)) + (H(t) \times t_{non-ICU}(t)) + \left((J(t) - MV(t)) \times t_{ICU}(t)\right) \\
&+ (MV(t) \times t_{MV}(t) + H(t)) + H(t) \times t_{non-ICU}(t) + H(t) \\
&\qquad\qquad + (H(t) \times t_{non-ICU}(t)) \\
&+ \left((J(t) - MV(t)) \times t_{ICU}(t) \times c_{4,4}\right) + (MV(t) \times t_{MV}(t) \times c_{5,4}))/CPP
\end{aligned} \tag{3.48}$$

And,

$$R_{EFR} = \sum_{t=0}^{84} P(t) \tag{3.49}$$

Where parameters are now time-dependent:

$$\mathcal{S}(t) = I(t) \times HU \tag{3.50}$$

$$H(t) = \mathcal{S}(t) \times h \tag{3.51}$$

$$J(t) = H(t) \times i \tag{3.52}$$

$$MV(t) = J(t) \times m \tag{3.53}$$

And the total daily contacts can be found by:

$$\begin{aligned}
&C(t) = \\
&(H(t) \times c_{2,3}) + (H(t) \times t_{non-ICU}(t) \times c_{3,3}) \\
&+ \big(H(t) \times t_{non-ICU}(t) \times c_{3,2}\big) + \Big(\big(J(t) - MV(t)\big) \times t_{ICU}(t) \times c_{4,2}\Big) \\
&+ ((J(t)-MV(t)) \times t_{ICU}(t) \times c_{4,3}) \\
&+ (MV(t) \times t_{MV}(t) \times c_{5,3}) + \Big(\big(\mathcal{S}(t) - H(t)\big) \times c_{1,2}\Big) + \big(H(t) \times c_{2,2}\big) \\
&+ \big(MV(t) \times t_{MV}(t) \times c_{5,2}\big) + (\mathcal{S}(t) - H(t)) + (H(t) \times c_{2,2}) \\
&+ (H(t) \times t_{non-ICU}(t) \times c_{3,2}) + ((J(t) - MV(t)) \times t_{ICU}(t) \times c_{4,2}) \\
&+ (MV(t) \times t_{MV} \times c_{5,2})
\end{aligned} \tag{3.54}$$

Therefore,

$$P(t) = \frac{C(t)}{T \times K \times (1 - \alpha) \times 40} \tag{3.55}$$

The dynamic model also includes a second mixed strategy that was initially introduced by Baracco et al. (2015). For N95s, the number of respirators required depends on the total contacts calculated for doctors, nurses, and respiratory therapists:

$$\begin{aligned}
&R_{N95} = \\
&((H(t) \times c_{2,3}) + (H(t) \times t_{non-ICU}(t) \times c_{3,3}) + ((J(t)-MV(t)) \times t_{ICU}(t) \times c_{4,3}) \\
&+ (MV(t) \times t_{MV}(t) \times c_{5,3}) + \Big((\mathcal{S}(t) - H(t)) \times c_{1,2}\Big) + \big(H(t) \times c_{2,2}\big) \\
&+ \big(H(t) \times t_{non-ICU}(t) \times c_{3,2}\big) + \Big((J(t) - MV(t)) \times t_{ICU}(t) \times c_{4,2}\Big)
\end{aligned}$$

$$\begin{aligned}&+ \big(MV(t) \times t_{MV}(t) \times c_{5,2}\big) + \ (\mathcal{S}(t) - H(t)) \ + \ (H(t) \ \times c_{2,2}) \\ &\qquad\qquad + (H(t) \times t_{non-ICU}(t) \times c_{3,2}) \\ &+ ((J(t) - MV(t)) \times \ t_{ICU}(t) \times \ c_{4,2}) \ + \ (MV(t) \times t_{MV}(t) \times c_{5,2}))/CPP\end{aligned} \tag{3.56}$$

For EFRs, the number of respirators required depends on the number of HCW contacts excluding doctors, nurses and respiratory therapists needed (the second mixed strategy allocates N95s to doctors, nurses, and respiratory therapists instead):

$$\begin{aligned}&R_{EFR} = \\ &(((\mathcal{S}(t) - H(t)\big) + \big(H(t) \times t_{non-ICU}(t)\big) + (\ H(t) \ \times t_{non-ICU}(t)) \\ &+(MV(t) \times t_{MV}(t)) \ + \ (H(t) \times t_{non-ICU}(t)) \\ &+ \Big(\big(J(t) - MV(t)\big) \times \ \ t_{ICU}(t)\Big) + \ \big(MV(t) \ \times t_{MV}(t) + \ H(t)\big) + \\ &+ \Big(\big(J(t) - MV(t)\big) \times \ t_{ICU}(t)\Big) H(t) \ \times t_{non-ICU}(t) + \ H(t) \\ &+ \Big((J(t) - MV(t)) \times \ t_{ICU}(t) \times c_{4,4}\Big) \\ &+ \big(MV(t) \ \times t_{MV}(t) \times c_{5,4}\big))/(T \times K \times (1-\alpha) \times 40)\end{aligned} \tag{3.57}$$

The first mixed strategy introduced in the base model is calculated in the same manor, but with the same time-dependent parameters as shown in (3.56) and (3.57). Program costs are calculated as before, with a new category for the phased approach which uses time-dependent SIR outputs such as total number of contacts (infected individuals who are hospitalized) over 84 days or 12 weeks (Eq. 3.58). Pandemic waves generally do not last longer than 12 weeks due to population characteristics, or policy implementation such as social distancing, isolating, quarantining.

$$Total\ contacts = \sum_{t=0}^{84} C(t) \tag{3.58}$$

3.2.1. PANDEMIC SCENARIOS

The dynamic model was used to introduce two new pandemic scenarios. The 20th century H1N1 influenza A virus, commonly known as the “Spanish Flu” was investigated to examine stockpiling requirements for an extreme pandemic case. Conversely, the 2009 H1N1, or

A/H1N1pdm09 was introduced to investigate a case in which fewer respirators may be needed in comparison to SARS-CoV-2. The different pandemic scenarios are modelled by changing the attack rates, death rates and recovery rates. The scenarios were used to determine surpluses and shortages of respirators if one scenario is planned for, and another actually occurs. For each pandemic scenario, a case study on Dartmouth General hospital was completed by using the healthcare facility's population statistics for inputs such as its patient population.

3.3. SEIR MODEL

The SEIR Model utilizes SEIR outputs entirely to estimate total costs for five respirator utilization strategies introduced earlier. Specifically, outputs estimate daily contacts which help to determine respirator requirements for a pandemic. Costs are calculated using the inventory, equipment and program cost frameworks discussed in Section 3.1. The SEIR model is a more advanced SIR compartmental model that incorporates the latent phase of a viral infection. The latent phase encompasses the period in which an individual is infected, but not yet infectious. The model reflects the latent phase by considering a latent/exposed population (E). Furthermore, the SEIR model with vital statistics allows for new opportunities for spread due to the introduction of new births, increasing the susceptible population.

According to Roda et. al. (2020), there are some advantages of the SEIR model, as COVID-19 does have latency period. SIR model is inappropriate to model SARS-CoV-2 because it does not consider the latency period. However, there is evidence to suggest that the SEIR's additional parameters complicate the model enough for it to potentially underperform in comparison to the SIR model (Roda et al., 2020). Generally, the latency period and initial latent population parameters are hard to estimate, reducing accuracy. For example, according to CDC (2021), the incubation period for SARS-CoV-2 has a wide range that is between 1 and 14 days, while the infectious period lasts an estimated 10 days. However, Carcione et al. (2020) indicated the importance of using the SEIR model to explore disease spread of SARS-CoV-2. If the dynamics of the pandemic can be approximately quantified, effects of lockdown, quarantine and other factors can be measured.

Vital statistics such as birth and death rates are assumed to be equal, maintaining a constant population. The total initial population is assumed to be equal to the combined number of susceptible, exposed, infected, and recovered populations. The model parameters are as follows:

μ: *Per-capita death and birth rate independent of disease.*
β: *Infection rate.*
ϵ: *Incubation rate. Reciprocal of incubation period.*
γ: *Recovery rate. Reciprocal of infectious period.*
α: *Virus-induced average death rate.*

The governing differential equations are shown in (3.59), (3.60), (3.61) and (3.62).

$$\frac{dS}{dt} = \mu N - \mu S - \frac{\beta S I}{N} \tag{3.59}$$

$$\frac{dE}{dt} = \frac{\beta S I}{N} - (\mu + \epsilon)E \tag{3.60}$$

$$\frac{dI}{dt} = \epsilon E - (\gamma + \mu + \alpha)I \tag{3.61}$$

$$\frac{dR}{dt} = \gamma I - \mu R \tag{3.62}$$

Where $N = S + E + I + R \leq N_0$ is the total population. The differential equations are subject to the initial conditions, S(0), E(0), I(0), and R(0). The parameters have time units of $\frac{1}{T}$, with T representing time in days. The model scheme is provided in Figure 3.3 where the arrows represent rates at which individuals move from one compartment to the next.

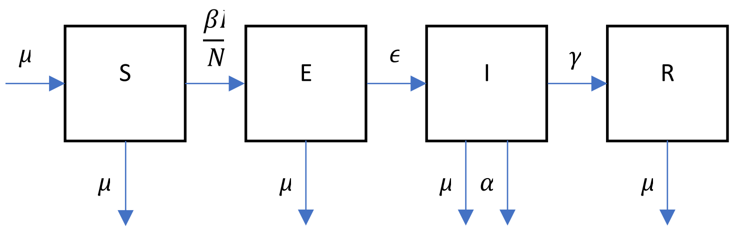


Figure 3.3: SEIR model scheme

As shown, the birth rate creates new susceptible individuals who can become exposed. They either remain healthy, or become infected and can recover, or succumb to the illness of interest.

Additionally, two death rates are considered. One death rate specifies the natural death rate of the population, while the second represents the illness-specific death rate. Individuals do not re-enter the susceptible population compartment, as it was assumed that SARS-CoV-2 can not be contracted several times.

3.4. TOPSIS METHOD

Finally, a multi-criteria decision analysis method is used to quantify qualitative criteria such as breathability, muffling, etc. Specifically, it allows functional investigations of N95s and EFRs which were not included in previous respirator comparison studies. TOPSIS was chosen according to the steps for selecting the most appropriate multi-criteria decision analysis method as defined by (Wątróbski et al., 2019). Following their decision tree, TOPSIS can handle decision problems with total ranking to determine a solution. TOPSIS has several advantages such as its universality, usability, and ability to determine relative performance of each alternative. In addition, the aggregation function minimizes the distance to the ideal solution and maximizes the distance from the anti-ideal solution. However, a notable disadvantage of TOPSIS is its subjectivity. This can inhibit the approximation of the objective world and impact the integrity of the study. Subjectivity in TOPSIS appears in criteria and alternative selection which is up to the analyst. Ultimately, TOPSIS helps to provide a prescriptive solution that can be considered in respiratory protection program decision-making and implementation if appropriate criteria are selected, and accurate rankings of each criterion are provided. The procedure is as follows:

1. A matrix of m alternatives and n criteria is developed. The matrix can be denoted by $(x_{ij})_{m\times n}$ where x_{ij} are ratings for each alternative i with respect to criterion j. Furthermore, alternatives are the options that are evaluated and selected and are N95s and EFRs. Criteria impact selection of alternatives and must be:
    a. Complete: All important criteria must be included.
    b. Non-redundant: Duplicate and similarities must be removed.
    c. Operational: All alternatives must be evaluated on each criterion.

    The selected criteria in this study follow from the literature review and include:

I. Temperature discomfort: Subjective discomfort of skin temperatures using respirator.
II. Vision obstruction: respirator interferes with visibility.
III. Skin irritation: Respirator causes skin irritation.
IV. Breathing difficulty: Respirator interference with breathing ability.
V. User anxiety: Subjective feelings of apprehension, tension, nervousness, worry, and activation/ arousal of the autonomic nervous system.
VI. Muffling: Reduced speech transmission.
VII. Cost: Total respirator protection program costs.
VIII. Protection: Filter performance.
IX. User acceptability: Sense of protection.
X. Confidence in training

2. The matrix $(x_{ij})_{m\times n}$ was normalized to form the matrix:

$$\mathrm{R} = (r_{ij})_{m\times n} \text{ where } r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}{}^2}}, i = 1,2, \dots., m,\ j = 1,2, \dots, n \qquad (3.63)$$

3. A new weighted normalized decision matrix was formed by using weights (w_j) of importance for each criterion as defined by subject matter experts:

$$t_{ij} = r_{ij} \times w_j\ , i = 1,2, \dots, m, j = 1,2, \dots, n \qquad (3.64)$$

4. The ideal solution A_b and negative ideal solution (A_w) were found:

$$A_w = \{[max(t_{ij}|i = 1,2,..m,)\ j \in J_-], [min(t_{ij}\mid i = 1,2,..m,)\ j \in J_+]\} \equiv \{t_{wj} \mid j = 1,2,..,n\}, \qquad (3.65)$$

$$A_b = \{[min(t_{ij}|i = 1,2,..m,)\ j \in J_-], [max(t_{ij}\mid i = 1,2,..m,)\ j \in J_+]\} \qquad (3.66)$$

$$\equiv \{t_{wj} \mid j = 1,2,\ldots,n\},$$

Where,

$J_{+} = \{j = 1,2,..,n \mid j\}$ are criteria having a positive impact.

$J_{-} = \{j = 1,2,..,n \mid j\}$ are criteria having a negative impact.

5. Calculated the separation from the ideal (S*) and negative ideal (S’) solutions:

$$S^{*} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{bj}\right)^{2}} \quad i = 1,2,\ldots,m. \tag{3.67}$$

$$S' = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{wj}\right)^{2}} \quad i = 1,2,\ldots,m. \tag{3.68}$$

6. Using ideal and negative ideal solutions, the relative closeness to the ideal solution was calculated:

$$\frac{S_i'}{(S_i^{*} + S_i')} \tag{3.69}$$

7. The alternatives were ranked according to their relative closeness. Max is best solution.

The models, scenario testing and TOPSIS analyses presented in this chapter were completed in Excel. To validate the base case model, its outputs were compared to those of Baracco et al.’s (2015) outputs. This required omitting program costs initially. Once outputs were consistent with previous research, program costs and additional respirator utilization strategies were introduced. To validate the dynamic and SEIR models, sensitivity analyses to understand the relationships between inputs and outputs were completed. Chapter 5 presents the sensitivity analyses between duration of respirator use and total costs, and the number of HCWs required during the pandemic and total cost. Verification was completed by setting parameters to zero to ensure base case costs could be achieved at each phase of modelling. Total costs were also manually calculated and compared with model outputs to monitor performance and reduce errors.

4. DATA

4.1. BASE MODEL

Initial parameter values can be found in Table 4.1 which are consistent with Baracco et al. (2015). Initial comparisons of the base model with Baracco et al.'s (2015) model were completed with identical inputs.

Table 4.1: Base model assumptions.

Assumptions	**Inputs**
Average length of non-ICU hospital stay for influenza-related illness (days)	5
Average length of ICU stay for influenza-related illness (days)	6
Average length of ventilator usage for influenza-related illness (days)	7
Average proportion of admitted influenza patients will need ICU care	15%
Average proportion of admitted influenza patients will need ventilators	8%
Average proportion of influenza deaths assumed to be hospitalized	70%
Shelf-life of inventory (yrs)	5
How many sq ft managers are responsible for	10000
Healthcare worker attrition rate	40%
Daily percentage increase in cases arriving compared to previous day	3%

To investigate total costs that could arise during SARS-CoV-2, inputs were changed in the model. Table *4.2* lists epidemiological characteristics of SARS-CoV-2 such as attack and death rates that were used. A study on the effects of non-pharmaceutical interventions on attack rates indicates that the attack rate in Canada can range between 1.6% to 76.6% (Ogden et al., 2021). The attack rate was set to 8.54% (Mao et al., 2020) in the model and the SARS-CoV-2 death rate was set to 3% (Wang, et al., 2020). In addition, the target population of interest is Dartmouth General Hospital which serves approximately 120,000 individuals (DGHF, n.d.). The attrition rate during a generic influenza outbreak was set to 40% (OSHA, 2009). The duration of the pandemic can be set to any length of time, but for simplicity, was set to three months (12 weeks). The remaining parameters were drawn from Baracco et al.'s (2015) work.

Table 4.2: Epidemiological characteristics of SARS-CoV-2 and healthcare facility inputs.

Epidemiological and Healthcare Characteristics	Inputs
Target population	120,000
Attack rate	8.54%
Healthcare utilization rate	50%
Hospitalization rate	22%
ICU admission rate	20%
Mechanical ventilation rate	100%
Average duration of hospital non-ICU	10
Average duration of hospital ICU	15
Average duration of mechanical ventilation	10
Death rate	3%
Duration of pandemic (weeks)	12

4.1.1. RESPIRATOR UTILIZATION AND DISINFECTION STRATEGY DATA

There are several utilization strategies for N95s and three disinfection strategies for EFRs. Table *4.3* summarizes utilization strategies for N95s. N95s can be disinfected after each contact for a maximum of 10 contacts, they can be disposed after each contact, or they can be used for an extended period of time. EFRs can be disinfected after each contact, shift, or cleaned post-contacts and disinfected after each shift. If N95s are disinfected, 10 can be disinfected at once. EFRs require a longer process and can only be disinfected one at a time. Table 4.4 summarizes utilization inputs for number of hours per use per respirator and number of contacts per hour.

Table 4.3: N95 disinfection and utilization strategies data

N95 Utilization Strategy	Number of Contacts per Respirator
Discard after each contact	1
Discard after multiple contacts	4
Discard after 10 disinfection cycles	40

Table 4.4: Inputs for hours of use for each respirator (N95s and EFRs) and number of contacts per hour

Utilization	Inputs
Number of hours per use of respirator	2
Number of HCW-patient contacts per hour	2

The number of contacts depends on the average number of HCW interactions with patients in each healthcare department. The model uses the following assumptions in Table 4.5 which are consistent with those used by Baracco et al. (2015).

Table 4.5: Average daily HCW-patient contacts in each department

Setting	**HCWs**									
	MD	RN	RT	RadT	Phleb	MH	HK	Admin	Porter	Total
Ambulatory	1	2				1		1		1
ED requiring admission	3	5	3	1			1	2	1	5
Inpatient day, non-ICU	2	6	6	1	1	1	1			16
Inpatient day, ICU	4	24	12	2		1	1			18
ICU, on MV	4	24	6	2		1	1			38

4.1.2. EQUIPMENT DATA

Equipment costs consist of purchasing requirements for respirators, accessories, and disinfection supplies. All costs and dimensions were determined by considering those from a major wholesaler. Table 4.6 lists N95 and EFR unit costs and quantities per box. Table 4.7 and Table 4.8 provide similar information on N95 disinfection supplies for the UVGI method and low temperature plasma vaporized hydrogen peroxide sterilization method, respectively.

Table 4.6: Respirator costs for N95s and EFRs

Respirator	**Quantity Per Box**	**Unit Cost**
N95	1	$0.50
EFR	1	$25.00

Table 4.7: N95 disinfection supplies costs and inventory inputs for low temperature plasma vaporized hydrogen peroxide sterilization

N95 Disinfectant Supplies	**Supplies Required Per Sterilization**	**Quantity Per Box**	**Cost Per Cycle**
Mask	1	1	$0.50
Gloves	4	1	$0.50
Gown	1	75	$0.67
Oxivir wipe	10	160	$1.69
Brown paper bag	10	100	$4.30
White paper bag	10	100	$4.40

Table 4.8: N95 disinfection supplies costs and inventory inputs for ow temperature plasma vaporized hydrogen peroxide sterilization

N95 Disinfectant Supplies	Supplies Required Per Sterilization	Quantity Per Box	Cost Per Cycle
Peel pack	10	100	$4.99
Chemical Indicator	1	1	$0.10

Table 4.9 summarizes inputs for EFR accessory costs and inventory requirements. Table 4.10 summarizes the costs and inventory inputs for EFR disinfection and interim cleaning. If interim cleaning is not required, costs and inventory inputs for the disinfection wipe are omitted.

Table 4.9: EFR accessory costs and inventory inputs

EFR Accessories	Number of Accessories Per Respirator	Quantity Per Box	Cost per
Filters	3	1	$2.50
Eyewear	NA	NA	$0.00
Tear away visor	NA	NA	$0.00

Table 4.10: EFR disinfection supplies costs and inventory inputs for both disinfecting and interim cleaning

EFR Disinfectant Supplies	Supplies Required Per Sterilization	Quantity Per Box	Cost per sterilization
Gloves	2	100	$0.50
Facemask	1	50	$0.50
Detergent (mL)	15	18927	$0.07
Disinfectant (mL)	100	10734	$0.34
Disinfection wipe	1	100	$0.69

4.1.3. INVENTORY DATA

Warehouse space and management costs are considered when stockpiling respirators. To determine space required, box dimensions of supplies are needed. Defaults length, width and height of respirator and inventory cases are 12 inches. Table 4.11 lists box dimensions of EFR accessories. Table 4.12 and Table 4.13 provide box dimensions for supplies required for the two N95 disinfection methods.

Table 4.11: Box dimensions for EFR disinfection supplies

EFR Disinfection Supplies Inputs	Gloves	Mask	Detergent	Disinfectant	Disinfectant wipes
Box length (in)	9	7.06	11.9	19.56	3.7
Box width (in)	3.9	4.72	11.9	6.81	6
Box height (in)	5.5	3.54	14.5	11.94	10.5

Table 4.12: Box dimensions for ultraviolet germicidal irradiation disinfection supplies

N95 Disinfection Supplies Box Volume Inputs	Mask	Gloves	Gown	Oxivir wipe	Brown paper bag	White paper bag
Box length (in)	21	9	21	5	12	12
Box width (in)	9	3.9	8	5	12	12
Box height (in)	6	5.5	10	7.5	12	12

Table 4.13: Box dimensions of low temperature plasma vaporized hydrogen peroxide sterilization supplies

N95 Disinfection Supplies Box Volume Inputs	Peel pack	Chemical Indicator
Box length (in)	7.06	8.3
Box width (in)	4.72	1.7
Box height (in)	3.54	1.2

Lastly, Table 4.14 lists warehouse lease, utilities, insurance, and management cost inputs. Warehouse inputs can be changed according to local storage market and management salary trends.

Table 4.14: Warehouse lease, utilities, and management cost inputs

Management Costs	Input	Citation
Warehouse lease cost per sq ft	$7.00	Turner Drake & Partners, LTD., 2020
Cost of warehouse utilities and insurance per sq ft	$3.00	Baracco et al., 2015
Management salary per year	$80,000.00	Baracco et al., 2015

4.1.4. PROGRAM DATA

Table 4.15 lists program inputs such as number of personnel, hours requirement to complete a task and hourly burden rate. Data are from Safety Services Nova Scotia (Curts, n.d.).

Table 4.15: Inputs for determining costs of program development, program surveillance, delivery, and maintenance (Safety Services NS, n.d.)

Factor	Hours	Number of people	Burden rate ($/hr)
Program development	80	1	75
Medical Surveillance	2	1992	43
Training - Development	24	1	75
Training - Delivery	2	1993	60
Fit Testing	1	1993	60
Maintenance	40	1	60
Audit	24	1	60

4.2. DYNAMIC MODELLING DATA

Initial SIR values are presented in Table 4.16. According to the Nova Scotia government, there were three initial presumptive cases in Nova Scotia in March 2020 (First Presumptive Cases of COVID-19 in Nova Scotia; New Prevention Measures - Government of Nova Scotia, Canada, 2020).

Table 4.16: Initial SIR conditions for population, susceptible, infected, and recovered individuals

N_0	50,000
S_0	49,997
I_0	3
R_0	0

System parameters are found in Table 4.17. The infection rate was found to be about 0.2 for SARS-CoV-2 (Carcione et al., 2020). The recovery rate of infectious individuals is the reciprocal of the infectious period of each illness. The infectious period is 10 days (NCIRD, 2021).

Table 4.17: SIR model rates for SARS-CoV-2

SIR Model Data	SARS-CoV-2
Infection rate	0.217352
Recovery rate	0.1
Death rate	3%

4.3. PANDEMIC SCENARIO DATA

To determine stockpiling respirator requirements for each pandemic scenario, data in Table 4.18 was used in the model. Hospitalization rates chosen for inputs are based on findings from previous research. Consistent data was lacking in the research and rates were estimated. There is approximately a 0.5% difference between SARS-CoV-2 and Spanish Flu death rates: 3% (Wang, et al., 2020) and 2.5% (Taubenberger & Morens, 2006). The Swine Flu was found to have the lowest death rate of 0.02% (Lovelace, 2020).

Table 4.18: Hospitalization and death rates for SARS-CoV-2, 20th cent. H1N1, and A/H1N1pdm09

	SARS-CoV-2	**20th Cent. H1N1**	**A/H1N1pdm09**
Hospitalization rate	22% (Canadian Institute for Health Information, 2021)	30% (Acquah et al., 2017)	0.02% (Truelove, et al., 2011)
Death rate	3%	2.5%	0.02%

Initial SIR values are presented in Table 4.19.

Table 4.19: Initial SIR values for each pandemic

	SARS-CoV-2	**20th Cent. H1N1**	**A/H1N1pdm09**
N_0	120,000	120,000	120,000
S_0	119,997	119,997	119,997
E_0	0	0	0
I_0	3	3	3
R_0	0	0	0

To determine respirator requirements with a phased approach for each scenario, data in Table 4.20 were inputted into three separate SIR models. Death rates are used from the stockpiling calculations. The infection rates are 0.5 (Fraser et al., 2011) for 20th century H1N1 and 0.11 (Roos, 2011) for A/H1N1pdm09. The infectious periods are 12.5 days (Soucheray, 2020), and 5 days (Jilani et al., 2021) 20th century H1N1 and A/H1N1pdm09respectively. An initial population of 120,000 was set for each scenario, with 3 individuals infected on the first day. No individuals are set to be recovered since infections only occur on day one.

Table 4.20: SIR model rates for each pandemic

SIR Model Data	SARS-CoV-2	20th Cent. H1N1	A/H1N1pdm09
Infection rate	0.217352	0.5	0.24
Recovery rate	0.1	0.08	0.2
Death rate	3%	2.5%	0.02%

4.4. SEIR MODEL DATA

Initial SEIR values are presented in Table 4.21.

Table 4.21: Initial SEIR model conditions

N_0	120,000
S_0	119,997
E_0	0
I_0	3
R_0	0

Systems parameters of SEIR model are presented in Table 4.22. The SEIR model uses vital statistics to predict daily cases. Vital statistics and initial conditions in Table 4.21 are based on Nova Scotia. The per-capita death rate and birth rates are equal and can be calculated by finding the inverse of the average life-expectancy. The average life expectancy is 80.5 years (Life Expectancy at Birth Nova Scotia 2018 | Statista, 2021).

Table 4.22: SEIR input parameters for estimating number of susceptible, infected, exposed and recovered individuals

Parameters	SARS-CoV-2	20th Cent. H1N1	A/H1N1pdm09
Per-capita death and birth rate independent of disease	0.07849	0.07849	0.07849
Infection rate	0.21735209	0.5	0.24
Incubation rate: reciprocal of incubation period	0.2	0.192308	0.5
Recovery rate: reciprocal of infectious period	0.1	0.08	0.1667
Virus-induced average death rate	0.03	0.025	0.0002

4.4.1. TOPSIS DATA

Table 4.23 summarizes scores for each TOPSIS criteria found from literature. Though many studies investigated the same criteria such as temperature discomfort of N95s or EFRs, methods and metrics were often different. In order to make scores comparable, results from each study were normalized. In real world applications, these metrics should be investigated at the specific site for which the model is being used (Dartmouth General Hospital in this case).

Table 4.23: Normalized TOPSIS criteria scores from secondary research sources

	N95		**EFR**	
Criteria	**Ref**	**Rating**	**Ref**	**Rating**
Temperature discomfort (10=low, 1=high)				
	J. Powell, J. Kim & R. Roberge, 2017	8.15 (N=12) Low discomfort	J. Powell, J. Kim & R. Roberge, 2017	6.04 (N=12) High discomfort
	Scarano, A., Inchingolo, F., & Lorusso, F., 2020	7.86 (N=20) Low discomfort	-	-
	Baig, Knapp, Eagan, et al., 2010	10 (N=159) Low discomfort	-	-
	-	-	Roberge, R. J., Coca, A., Williams, W. J., et al., 2010	1 (N=10) High discomfort
Average		8.67		3.52
Vision obstruction (10=low, 1=high)				
	Baig, Knapp, Eagan, et al., 2010	8.875 (N=159) High visibility	-	-
	-	-	Schumacher, J., Arlidge, J., Dudley, et al., 2020	3.25 (N=25) Low visibility
Average		8.875		3.25
Skin irritation (10= low, 1=high)				
	Baig, Knapp, Eagan, et al., 2010	10 (N=159) Low skin irritation	-	-
	-	-	Roberge, R. J., Coca, A., Williams, W. J., Powell, J. B., & Palmiero, A. J., 2010	5.5 (n=10) Some skin irritations
Average		10		5.5
Breathing difficulty (10 = good, 1=bad)				
	Baig, Knapp, Eagan, et al., 2010	10 (N=159) Good breathing	-	-

	N95		EFR	
Criteria	**Ref**	**Rating**	**Ref**	**Rating**
			A. Wentworth, J. Byrne & S. Orguc, et al., 2020	7 (N=42) Good breathing
Average		10		7
User anxiety (10=low, 1 = high)				
	Julian, 2011	9.78 (N=12) Low anxiety	Julian, 2011	1.22 (n=12) High anxiety
Average		9.78		1.22
Muffling (10 = low, 1 = high)				
	Baig, Knapp, Eagan, et al., 2010	5.5 (N=159) High muffling)	-	-
	Hines, S. E., Brown, C., Oliver, M., et al., 2019	4.847 (N=606) High muffling	Hines, S. E., Brown, C., Oliver, M. et al., 2019	6.04 (N=280) Mediocre
	L. Radonovich Jr. , R. Yanke, J., et al., 2009	8.5 (N=16) Low muffling 2.5	L. Radonovich Jr. , R. Yanke, J., et al., 2009	7.2 (N=16) Low muffling 3.8
Average		5.33		5.68
Cost (10=low cost, 1=high cost)				
	Baracco, et al., 2015	2.655 High Cost	Baracco, et al., 2015	9.03 Low cost
	Research findings (base case, only N95 and EFR)	5.8	Research findings (base case, only N95 and EFR)	5.5
Average		4.22		7.26
Protection (10=good, 1=bad)				
	Zhuang, 2015	2.78 (N=25) Poor filter performance	Zhuang, 2015	8.7 (N=25) Poor filter performance
Average		2.78		8.7
Sense of protection (10=high, 1=low)				
	Hines, Brown, Oliver et al., 2019	6.74 (N=606)	Hines, Brown, Oliver et al., 2019	8.02 (N=280)
Average		6.74		8.02
Confidence in training (10=high, 1=low)				

	N95		EFR	
Criteria	**Ref**	**Rating**	**Ref**	**Rating**
	Hines, Brown, Oliver et al., 2019	6.895 (N=606)	Hines, Brown, Oliver et al., 2019	7.615 (N=280)
Average		6.895		7.615

To determine TOPSIS ratings (x'_{ij}), rating values (a) from previous research, with a range $[r_{min}, r_{max}]$ were converted to a target range $[t_{min}, t_{max}]$ by using the Eq. 4.1.

$$x'_{ij} = \frac{(t_{min} - t_{max})(a - r_{min})}{r_{max} - r_{min}} + t_{min} \qquad (4.1)$$

For example, if a TOPSIS range is selected to be [1,10] and a study reports a rating of 2 given a range [1,3], the new study rating would be 5.5 out of 10 to be consistent with the TOPSIS scale:

$$x'_{ij} = \frac{(1 - 10)(2 - 1)}{3 - 1} + 1 = 5.5$$

Unlike most TOPSIS analyses, the interpretations of ratings were not consistent. For example, a low score out of ten may mean that the respirator being investigated induced little to no anxiety, which should be considered a positive outcome. TOPSIS requires that the score should be high to represent good performance. In order to adjust the score to reflect TOPSIS requirements, Eq. 4.2 was used, where x''_{ij} denotes the adjusted score, and x'_{ij} denotes the original score.

$$x''_{ij} = t_{max} - x'_{ij} + t_{min} \qquad (4.2)$$

5. RESULTS

5.1. OVERVIEW OF RESULTS CHAPTER

The following chapter presents and examines the results of each model. A comparison of Baracco et al.'s (2015) model and the base model using identical inputs is discussed. Subsequently, SARS-CoV-2 inputs are used in the new base model. Following the base model, the dynamic model presents total costs associated with using the SIR model. The same method is used to investigate several pandemic scenarios. Lastly, the SEIR model is used to explore total costs, trends, and a sensitivity analysis.

Finally, TOPSIS results are provided. Three different weighting schemes are used to investigate whether EFRs are preferred over N95s according to functional characteristics introduced in the literature review, and costs.

5.2 BASE MODEL

The following section provides total costs estimated by the base model. Firstly, results will be provided that were determined by using Baracco et al.'s (2015) inputs in the base model. Those findings will be compared with Baracco et al.'s (2015). Secondly, results will be presented that were outputted by using SARS-CoV-2 inputs.

5.2.1 BARACCO'S INPUTS WITH ADDED PROGRAM COSTS AND STRATEGIES

As discussed, the base model differs from Baracco's model in several ways. This section investigates how the changes impact total costs of each respirator alternative over 12 weeks (84 days) using the base model (Baracco et al. (2015) used 12 weeks). Table 5.1 summarizes total costs calculated using Baracco et al.'s (2015) method in comparison with the totals outputted by the base case model. When reprocessing costs are not considered, total annual costs are equivalent across models. However, if reprocessing is considered, EFRs become extremely costly. This is due to the time and material required to disinfect EFRs after 830 contacts.

Notably, the additional costs associated with disinfecting EFRs make an EFR respiratory protection program less cost-effective than opting for single-use N95s in the base model. Additionally, using N95s multiple times before disposal achieves the lowest cost of $563,367.30, 189% greater than Baracco et al.'s (2015) findings. Evidently, the base model outputs larger total annual costs, as it includes program and disinfection costs.

Table 5.1: Total costs comparisons of Baracco et al. (2015) and base model outputs

Strategy	Baracco et al. (2015)	Base Case Model
N95: Dispose after contact	$1,323,325.00	$1,555,388.20
N95: Dispose after multiple contacts	$331,471.30	$563,367.30
N95: Reprocessed	NA	Low temp: $3,146,812.77 UVGI: $7,482,314.88
EFR: Without reprocessing	$7,030.00	$7,030.00
EFR: With reprocessing	NA	$7,560,285.09

The base model also uses other combinations of settings that are not found in Baracco et al.'s (2015) model. Total costs are calculated according to the N95 utilization strategy, EFR disinfection strategy and N95 disinfection strategy. Table 5.2 summarizes all combinations of model utilization and disinfection settings, indicated by a settings number: (N95 utilization strategy, EFR disinfection strategy, N95 disinfection strategy).

Table 5.2: Setting combinations and their meanings for respirator utilization and disinfection strategies

Settings	N95 Utilization Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy
(1,1,3)	Dispose after contact	Disinfect after contact	N/A
(2,1,3)	Dispose after multiple contacts	Disinfect after contact	N/A
(3,1,1)	Disinfect	Disinfect after contact	UVGI
(3,1,2)	Disinfect	Disinfect after contact	Low temp
(1,2,3)	Dispose after contact	Disinfect after each shift	N/A
(2,2,3)	Dispose after multiple contacts	Disinfect after each shift	N/A
(3,2,1)	Disinfect	Disinfect after each shift	UVGI
(3,2,2)	Disinfect	Disinfect after each shift	Low temp
(1,3,3)	Dispose after contact	Disinfect and clean	N/A
(2,3,3)	Dispose after multiple contacts	Disinfect and clean	N/A
(3,3,1)	Disinfect	Disinfect and clean	UVGI
(3,3,2)	Disinfect	Disinfect and clean	Low temp

Table 5.3 summarizes total costs for each respirator alternative when each respirator is used for two hours at a time, either before disposal or reprocessing. Refer to Table 5.2 for each combination of settings. As shown in Table 5.4, N95s accomplish the minimum total cost in

most cases. However, EFRs are least costly ($247,050) when they are disinfected after each shift. The mixed strategy is never the best solution but does achieve a minimum cost of $322,490 when N95s are used for multiple contacts, and EFRs are disinfected after each shift. For this combination of settings, the mixed strategy costs less than using N95s alone.

Table 5.3: Total costs of each respirator strategy according to each combination of model settings

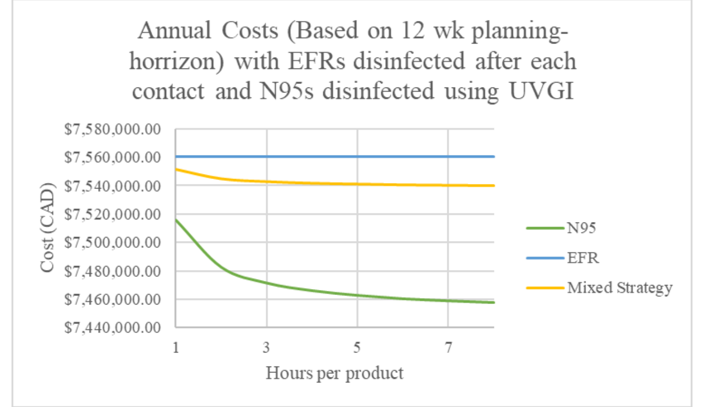
Setting	N95 (1000s)	EFR (1000s)	Mixed (1000s)
(1,1,3)	$1,555.39	$7,560.29	$6,315.37
(2,1,3)	$563.37	$7,560.29	$6,109.50
(3,1,1)	$3,146.81	$7,560.29	$6,645.36
(3,1,2)	$7,482.31	$7,560.29	$7,544.79
(1,2,3)	$1,555.39	$247.05	$528.36
(2,2,3)	$563.37	$247.05	$322.49
(3,2,1)	$3,146.81	$247.05	$2,536.84
(3,2,2)	$7,482.31	$247.05	$5,954.02
(1,3,3)	$1,555.39	$2,743.77	$8,178.17
(2,3,3)	$563.37	$2,743.77	$7,972.30
(3,3,1)	$3,146.81	$2,743.77	$10,186.65
(3,3,2)	$7,482.31	$2,743.77	$13,603.84

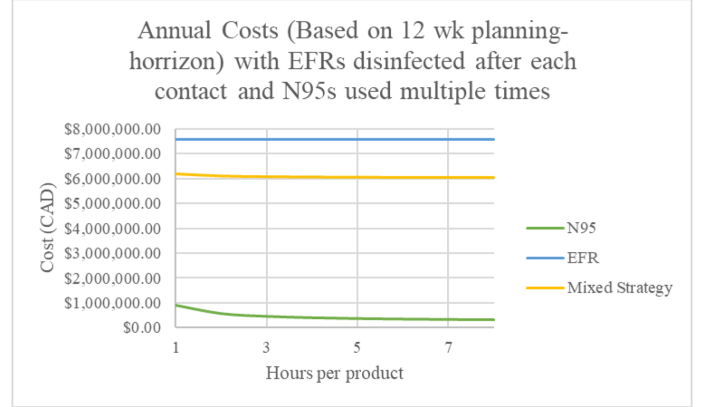
Table 5.4: Summary of most cost-effective alternatives for each combination of settings

Settings	N95 Utilization Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy	Most Cost-Effective Strategy
(1,1,3)	Dispose after contact	Disinfect after contact	N/A	N95
(2,1,3)	Dispose after multiple contacts	Disinfect after contact	N/A	N95
(3,1,1)	Disinfect	Disinfect after contact	UVGI	N95
(3,1,2)	Disinfect	Disinfect after contact	Low temp	N95
(1,2,3)	Dispose after contact	Disinfect after each shift	N/A	EFR
(2,2,3)	Dispose after multiple contacts	Disinfect after each shift	N/A	EFR
(3,2,1)	Disinfect	Disinfect after each shift	UVGI	EFR
(3,2,2)	Disinfect	Disinfect after each shift	Low temp	EFR
(1,3,3)	Dispose after contact	Disinfect and clean	N/A	N95
(2,3,3)	Dispose after multiple contacts	Disinfect and clean	N/A	N95
(3,3,1)	Disinfect	Disinfect and clean	UVGI	EFR

(3,3,2)	Disinfect	Disinfect and clean	Low temp	EFR

Figure 5.1 summarizes notable findings when completing sensitivity analysis on each combination of mixed utilization strategies, and EFR and N95 disinfection strategies. The figures show total costs as the duration of product use is changed from 1 to 10 hours. N95s achieve the lowest total costs, except when EFRs are disinfected after each shift only. EFRs are most costly when they are disinfected after each contact. The mixed strategy is the costliest option when EFRs are disinfected after each shift and cleaned after each contact, while N95s are used for multiple contacts at a time.





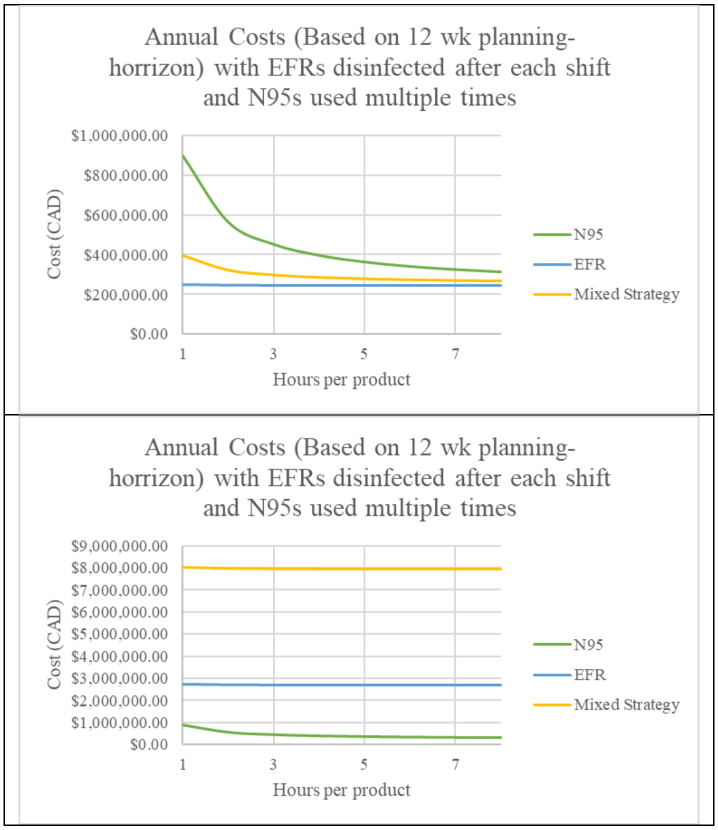


Figure 5.1: Sensitivity analysis of total costs based on hours per product with four combinations of settings

5.2.2. SARS-COV-2 INPUTS

The base case model was run with a different attack rate to reflect SARS-CoV-2. According to a study by Mao et al. (2020) the primary attack rate of SARS-CoV-2 is approximately 8.54%. Table 5.5 summarizes total costs for each respirator alternative when each respirator is used for two hours at a time, and the pandemic has an attack rate of 8.54%. Table *5.6* summarizes the most cost-effective respirator alternatives given each combination of settings.

Table 5.5: Total costs of each respirator strategy given each combination of model settings with SARS-CoV-2 inputs

Setting	N95 (1000s)	EFR (1000s)	Mixed (1000s)
(1,1,3)	$451.65	$2,161.20	$1,806.82
(2,1,3)	$169.29	$2,161.20	$1,748.24
(3,1,1)	$904.68	$2,161.20	$1,900.98
(3,1,2)	$2,139.07	$2,161.20	$2,157.27
(1,2,3)	$451.65	$82.23	$162.07

Setting	N95 (1000s)	EFR (1000s)	Mixed (1000s)
(2,2,3)	$169.29	$82.23	$103.50
(3,2,1)	$904.68	$82.23	$734.04
(3,2,2)	$2,139.07	$82.23	$1,707.06
(1,3,3)	$451.65	$791.81	$2,336.32
(2,3,3)	$169.29	$791.81	$2,277.74
(3,3,1)	$904.68	$791.81	$2,908.29
(3,3,2)	$2,139.07	$791.81	$3,881.30

Table 5.6: Summary of most cost-effective respirator alternative for each combination of settings when SARS-CoV-2 inputs are used

Settings	N95 Utilization Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy	Most Cost-Effective Strategy
(1,1,3)	Dispose after contact	Disinfect after contact	N/A	N95
(2,1,3)	Dispose after multiple contacts	Disinfect after contact	N/A	N95
(3,1,1)	Disinfect	Disinfect after contact	UVGI	N95
(3,1,2)	Disinfect	Disinfect after contact	Low temp	N95
(1,2,3)	Dispose after contact	Disinfect after each shift	N/A	EFR
(2,2,3)	Dispose after multiple contacts	Disinfect after each shift	N/A	EFR
(3,2,1)	Disinfect	Disinfect after each shift	UVGI	EFR
(3,2,2)	Disinfect	Disinfect after each shift	Low temp	EFR
(1,3,3)	Dispose after contact	Disinfect and clean	N/A	N95
(2,3,3)	Dispose after multiple contacts	Disinfect and clean	N/A	N95
(3,3,1)	Disinfect	Disinfect and clean	UVGI	EFR
(3,3,2)	Disinfect	Disinfect and clean	Low temp	EFR

Two findings are noted. Firstly, EFRs achieve a minimum cost of $82,230 when they are disinfected after each shift. This is the minimum total annual cost achieved out of all setting combinations and respirator strategies. However, there is an important caveat regarding disinfection of EFRs once after each shift. The Centre for Disease and Control suggests EFRs should be disinfected every time they are doffed. In the instance that EFRs are only disinfected after each shift, HCWs have to wear their EFR for the duration of their shift which can last 8 hours or longer. Lastly, N95s achieve a minimum cost of $169,290 when they are used for multiple contacts before disposal. This is similar to EFRs, as the N95 must be worn continuously for each contact.

5.3. DYNAMIC MODEL

The dynamic model uses SARS-CoV-2 inputs to estimate the total costs for N95s, EFRs, two mixed strategies and a phased approach. The phased approach uses the SIR model with SARs-CoV-2-specific infection and recovery rates.

5.3.1. TOTAL COSTS

As before, scenarios are used to investigate total costs of each respirator alternative. Table 5.7 summarizes all combinations of each strategy, indicated by a new settings number: (N95 utilization strategy, mixed strategy, EFR disinfection strategy, N95 disinfection strategy). Table 5.8 summarizes the total costs of each strategy with each combination of settings. Table 5.9 summarizes which of the respirator strategies are most cost-effective for each combination of settings. Mixed strategy #1 allocates EFRs to MDs, RNs, and respiratory technologists, while mixed strategy #2 allocates N95s to EFRs to MDs, RNs, and respiratory technologists.

Table 5.7: Setting combinations and their meanings for respirator utilization and disinfection strategies

Scenario	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy
(1,1,1,3)	Dispose after contact	1: EFR for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A
(1,2,1,3)	Dispose after contact	2: N95s for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A
(2,1,1,3)	Dispose after multiple contacts	1	Disinfect after contact	N/A
(2,2,1,3)	Dispose after multiple contacts	2	Disinfect after contact	N/A
(3,1,1,1)	Disinfect	1	Disinfect after contact	UVGI
(3,2,1,1)	Disinfect	2	Disinfect after contact	UVGI
(3,1,1,2)	Disinfect	1	Disinfect after contact	Low temp

Scenario	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy
(3,2,1,2)	Disinfect	2	Disinfect after contact	Low temp
(1,1,2,3)	Dispose after contact	1	Disinfect after each shift	N/A
(1,2,2,3)	Dispose after contact	2	Disinfect after each shift	N/A
(2,1,2,3)	Dispose after multiple contacts	1	Disinfect after each shift	N/A
(2,2,2,3)	Dispose after multiple contacts	2	Disinfect after each shift	N/A
(3,1,2,1)	Disinfect	1	Disinfect after each shift	UVGI
(3,2,2,1)	Disinfect	2	Disinfect after each shift	UVGI
(3,1,2,2)	Disinfect	1	Disinfect after each shift	Low temp
(3,2,2,2)	Disinfect	2	Disinfect after each shift	Low temp
(1,1,3,3)	Dispose after contact	1	Disinfect and clean	N/A
(1,2,3,3)	Dispose after contact	2	Disinfect and clean	N/A
(2,1,3,3)	Dispose after multiple contacts	1	Disinfect and clean	N/A
(2,2,3,3)	Dispose after multiple contacts	2	Disinfect and clean	N/A
(3,1,3,1)	Disinfect	1	Disinfect and clean	UVGI
(3,2,3,1)	Disinfect	2	Disinfect and clean	UVGI
(3,1,3,2)	Disinfect	1	Disinfect and clean	Low temp
(3,2,3,3)	Disinfect	2	Disinfect and clean	Low temp

In most cases, N95s achieve minimum total costs. However, an EFR respiratory program is cheaper when disinfection is completed after each shift ($82,220). Additionally, if N95s are disinfected and are compared to EFRs that are cleaned and disinfected, EFRs are cheapest ($791,810). Further, a trend in the results show that the mixed respirator strategy # 2 is always more costly than the mixed strategy #1. This is because the second mixed strategy allocates N95s to all MDs, RNs and respiratory technologists who have the highest rates of patient contacts in the model. The second strategy was also investigated in Baraco's work and did not achieve minimum costs. Neither of the mixed strategies ever achieve a minimum total cost out of all alternatives. The phased approach also does not achieve minimum cost out of all alternatives, but it is cheaper than the mixed strategies when EFRs are cleaned and disinfected, and N95s are not disinfected ($2,219,190).

Table 5.8: Total annual costs of each respirator alternative including the new phased approach

Settings	N95 (1000s)	EFR (1000s)	Mixed 1 & 2 (1000s)	Phased (1000s)
(1,1,1,3)	$451.65	$2,161.20	$1,806.82	$6,472.95
(1,2,1,3)	$451.65	$2,161.20	$2,025.12	$6,472.95
(2,1,1,3)	$169.29	$2,161.20	$1,748.24	$6,390.48
(2,2,1,3)	$169.29	$2,161.20	$1,801.34	$6,390.48
(3,1,1,1)	$904.68	$2,161.20	$1,900.98	$6,605.56
(3,2,1,1)	$904.68	$2,161.20	$2,382.27	$6,605.56
(3,1,1,2)	$2,139.07	$2,161.20	$2,155.54	$6,965.80
(3,2,1,2)	$2,139.07	$2,161.20	$3,353.56	$6,965.80
(1,1,2,3)	$451.65	$82.23	$162.07	$198.93
(1,2,2,3)	$451.65	$82.23	$380.38	$198.93
(2,1,2,3)	$169.29	$82.23	$103.50	$116.46
(2,2,2,3)	$169.29	$82.23	$156.59	$116.46
(3,1,2,1)	$904.68	$82.23	$256.23	$331.54
(3,2,2,1)	$904.68	$82.23	$737.52	$331.54
(3,1,2,2)	$2,139.07	$82.23	$510.80	$691.78
(3,2,2,2)	$2,139.07	$82.23	$1,708.81	$691.78
(1,1,3,3)	$451.65	$791.81	$2,336.32	$2,301.66
(1,2,3,3)	$451.65	$791.81	$2,554.88	$2,301.66
(2,1,3,3)	$169.29	$791.81	$2,277.74	$2,219.19
(2,2,3,3)	$169.29	$791.81	$2,331.10	$2,219.19
(3,1,3,1)	$904.68	$791.81	$2,430.48	$2,434.27
(3,2,3,1)	$904.68	$791.81	$2,912.03	$2,434.27
(3,1,3,2)	$2,139.07	$791.81	$2,685.04	$2,794.51
(3,2,3,3)	$2,139.07	$791.81	$3,883.32	$2,794.51

Table 5.9: Summary of cost-effective strategies across each combination of settings when using the dynamic model

Scenario	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy	Most Cost-Effective Strategy
(1,1,1,3)	Dispose after contact	1: EFR for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A	N95
(1,2,1,3)	Dispose after contact	2: N95s for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A	N95

Scenario	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy	Most Cost-Effective Strategy
(2,1,1,3)	Dispose after multiple contacts	1	Disinfect after contact	N/A	N95
(2,2,1,3)	Dispose after multiple contacts	2	Disinfect after contact	N/A	N95
(3,1,1,1)	Disinfect	1	Disinfect after contact	UVGI	N95
(3,2,1,1)	Disinfect	2	Disinfect after contact	UVGI	N95
(3,1,1,2)	Disinfect	1	Disinfect after contact	Low temp	N95
(3,2,1,2)	Disinfect	2	Disinfect after contact	Low temp	N95
(1,1,2,3)	Dispose after contact	1	Disinfect after each shift	N/A	EFR
(1,2,2,3)	Dispose after contact	2	Disinfect after each shift	N/A	EFR
(2,1,2,3)	Dispose after multiple contacts	1	Disinfect after each shift	N/A	EFR
(2,2,2,3)	Dispose after multiple contacts	2	Disinfect after each shift	N/A	EFR
(3,1,2,1)	Disinfect	1	Disinfect after each shift	UVGI	EFR
(3,2,2,1)	Disinfect	2	Disinfect after each shift	UVGI	EFR
(3,1,2,2)	Disinfect	1	Disinfect after each shift	Low temp	EFR
(3,2,2,2)	Disinfect	2	Disinfect after each shift	Low temp	EFR
(1,1,3,3)	Dispose after contact	1	Disinfect and clean	N/A	N95
(1,2,3,3)	Dispose after contact	2	Disinfect and clean	N/A	N95
(2,1,3,3)	Dispose after multiple contacts	1	Disinfect and clean	N/A	N95
(2,2,3,3)	Dispose after multiple contacts	2	Disinfect and clean	N/A	N95
(3,1,3,1)	Disinfect	1	Disinfect and clean	UVGI	EFR
(3,2,3,1)	Disinfect	2	Disinfect and clean	UVGI	EFR
(3,1,3,2)	Disinfect	1	Disinfect and clean	Low temp	EFR
(3,2,3,3)	Disinfect	2	Disinfect and clean	Low temp	EFR

5.3.2. SIR MODEL

Figure 5.2 illustrates the SIR model for SARS-CoV-2. At 84 days (12 weeks) the SIR model predicts that the pandemic is still not complete. The basic reproduction number which estimates the cases of infection to occur in a homogeneous population as the result of a single infected individual, was found to be 2.17. This indicates that the SIR model predicts an epidemic will occur.

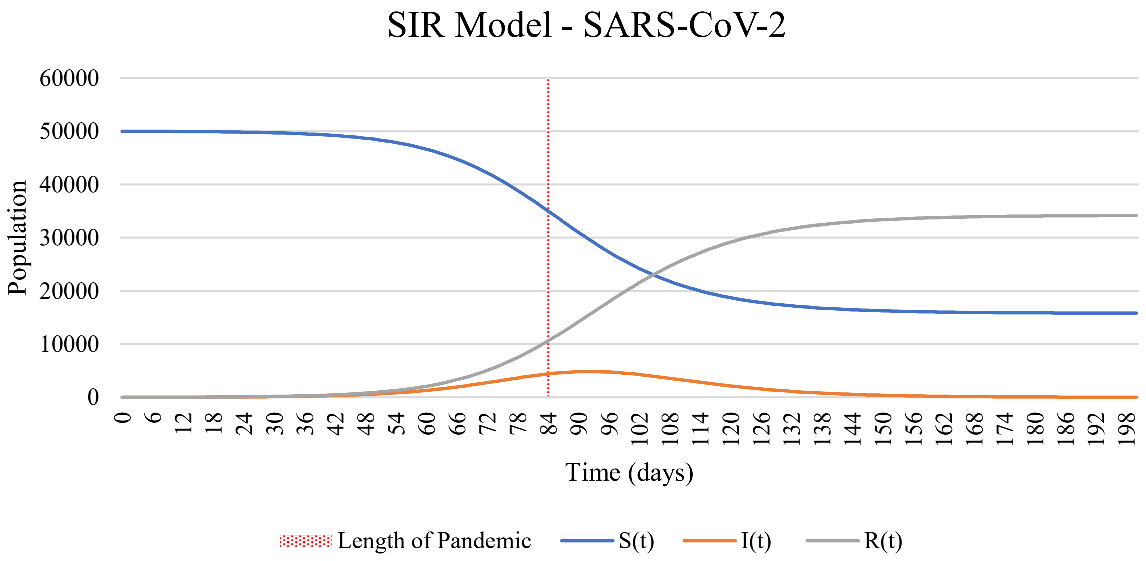


Figure 5.2: SIR Model for SARS-CoV-2

The SIR model is helpful beyond estimating N95 requirements in the phased approach. The model helps to track inventory by predicting number of contacts which determine how many N95s are required each day for the duration of the pandemic, or for any duration of interest. Figure 5.3 displays the respirator inventory tracker which is based on the number of infected individuals. If a single-use N95 respiratory program is chosen, over 450,000 masks are required to protect HCWs for the first 84 days of the pandemic.

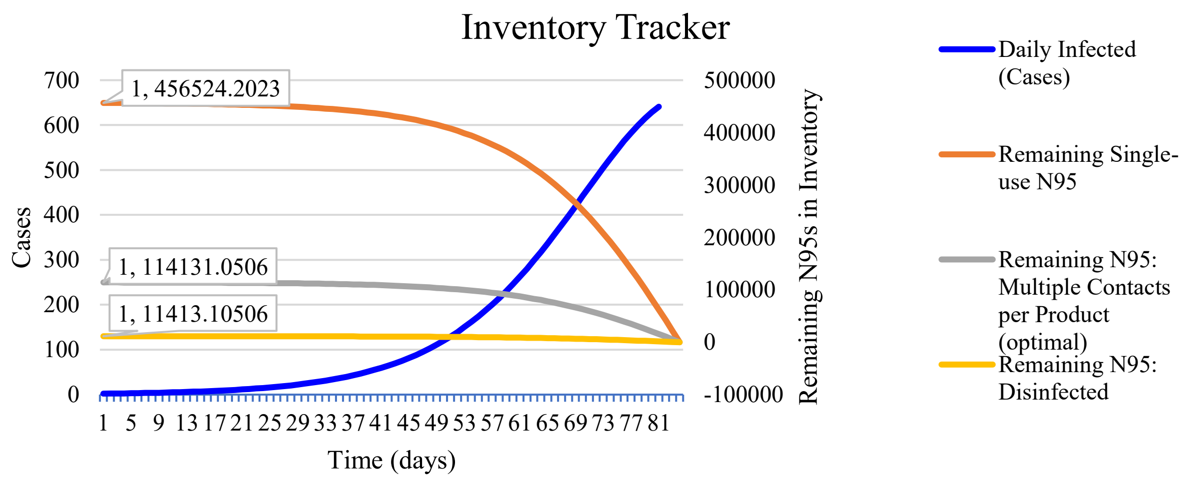


Figure 5.3: Single-use N95 inventory tracker

5.4. PANDEMIC SCENARIOS INVESTIGATION

5.4.1. TOTAL COSTS

Table 5.10 lists total costs for each combination of settings for each pandemic scenario at Dartmouth General Hospital. The minimum total costs of $82,220 and $103,990 were achieved for both SARS-CoV-2 and the 20th century H1N1, respectively, when EFRs are disinfected after each shift. However, when N95s are used multiple times before disposal and EFRs are disinfected after each contact, a phased approach achieves the lowest total cost of $28,680 during a A/H1N1pdm09 pandemic. Table 5.11 provides the most cost-effective respirator strategies for each combination of settings.

Table 5.10: Scenario investigation total costs for each pandemic and combination of model settings

Setting	Pandemic	N95 (1000s)	EFR (1000s)	Mixed 1 & 2 (1000s)	Phased (1000s)
(1,1,1,3)	SARS-CoV-2	$451.65	$2,161.20	$1,806.82	$3,345.52
	20th Cent. H1N1	$598.75	$2,899.28	$2,437.68	$44,742.09
	A/H1N1pdm09	$92.54	$405.75	$317.92	$53.14
(1,2,1,3)	SARS-CoV-2	$451.65	$2,161.20	$2,023.40	$3,345.52
	20th Cent. H1N1	$598.75	$2,899.28	$2,573.00	$44,742.09
	A/H1N1pdm09	$92.54	$405.75	$348.20	$53.14
(2,1,1,3)	SARS-CoV-2	$169.29	$2,161.20	$1,750.36	$3,315.94
	20th Cent. H1N1	$221.68	$2,883.44	$2,202.75	$43,837.68

Setting	Pandemic	N95 (1000s)	EFR (1000s)	Mixed 1 & 2 (1000s)	Phased (1000s)
	A/H1N1pdm09	$40.87	$405.75	$304.10	$52.24
(2,2,1,3)	SARS-CoV-2	$169.29	$2,161.20	$1,807.70	$3,315.94
	20th Cent. H1N1	$221.68	$2,883.44	$2,242.45	$43,837.68
	A/H1N1pdm09	$40.87	$405.75	$312.19	$52.24
(3,1,1,1)	SARS-CoV-2	$904.68	$2,161.20	$1,903.73	$3,393.32
	20th Cent. H1N1	$1,203.76	$2,878.97	$2,355.25	$48,096.88
	A/H1N1pdm09	$175.81	$405.75	$342.19	$55.05
(3,2,1,1)	SARS-CoV-2	$904.68	$2,161.20	$2,391.06	$3,393.32
	20th Cent. H1N1	$1,203.76	$2,878.97	$3,013.06	$48,096.88
	A/H1N1pdm09	$175.81	$405.75	$409.61	$55.05
(3,1,1,2)	SARS-CoV-2	$2,139.07	$2,161.20	$2,162.90	$3,522.53
	20th Cent. H1N1	$2,851.68	$2,879.60	$2,697.76	$54,891.86
	A/H1N1pdm09	$402.40	$405.75	$406.84	$59.85
(3,2,1,2)	SARS-CoV-2	$2,139.07	$2,161.20	$3,381.05	$3,522.53
	20th Cent. H1N1	$2,851.68	$2,879.60	$4,334.51	$54,891.86
	A/H1N1pdm09	$402.40	$405.75	$574.18	$59.85
(1,1,2,3)	SARS-CoV-2	$451.65	$82.23	$159.78	$174.07
	20th Cent. H1N1	$598.75	$124.31	$419.99	$1,382.62
	A/H1N1pdm09	$92.54	$28.19	$47.51	$29.59
(1,2,2,3)	SARS-CoV-2	$451.65	$82.23	$378.35	$174.07
	20th Cent. H1N1	$598.75	$124.31	$556.41	$1,382.62
	A/H1N1pdm09	$92.54	$28.19	$77.79	$29.59
(2,1,2,3)	SARS-CoV-2	$169.29	$82.23	$103.32	$144.49
	20th Cent. H1N1	$221.68	$108.47	$185.05	$478.20
	A/H1N1pdm09	$40.87	$28.19	$33.68	$28.69
(2,2,2,3)	SARS-CoV-2	$169.29	$82.23	$162.65	$144.49
	20th Cent. H1N1	$221.68	$108.47	$225.86	$478.20
	A/H1N1pdm09	$40.87	$28.19	$41.78	$28.69
(3,1,2,1)	SARS-CoV-2	$904.68	$82.23	$256.69	$221.87
	20th Cent. H1N1	$1,203.76	$103.99	$337.56	$4,737.41
	A/H1N1pdm09	$175.81	$28.19	$71.77	$31.50
(3,2,2,1)	SARS-CoV-2	$904.68	$82.23	$746.01	$221.87
	20th Cent. H1N1	$1,203.76	$103.99	$996.47	$4,737.41
	A/H1N1pdm09	$175.81	$28.19	$139.19	$31.50
(3,1,2,2)	SARS-CoV-2	$2,139.07	$82.23	$515.86	$351.08
	20th Cent. H1N1	$2,851.68	$104.63	$680.06	$11,532.38
	A/H1N1pdm09	$402.40	$28.19	$136.42	$36.29
(3,2,2,2)	SARS-CoV-2	$2,139.07	$82.23	$1,736.00	$351.08
	20th Cent. H1N1	$2,851.68	$104.63	$2,317.91	$11,532.38
	A/H1N1pdm09	$402.40	$28.19	$303.76	$36.29
(1,1,3,3)	SARS-CoV-2	$451.65	$791.81	$2,336.02	$1,236.36
	20th Cent. H1N1	$598.75	$842.02	$2,619.15	$15,970.73

Setting	Pandemic	N95 (1000s)	EFR (1000s)	Mixed 1 & 2 (1000s)	Phased (1000s)
	A/H1N1pdm09	$92.54	$712.95	$316.75	$37.48
(1,2,3,3)	SARS-CoV-2	$451.65	$791.81	$2,552.59	$1,236.36
	20th Cent. H1N1	$598.75	$842.02	$2,753.45	$15,970.73
	A/H1N1pdm09	$92.54	$712.95	$347.03	$37.48
(2,1,3,3)	SARS-CoV-2	$169.29	$791.81	$2,279.55	$1,206.78
	20th Cent. H1N1	$221.68	$826.18	$2,384.35	$15,066.31
	A/H1N1pdm09	$40.87	$712.95	$302.93	$36.58
(2,2,3,3)	SARS-CoV-2	$169.29	$791.81	$2,336.90	$1,206.78
	20th Cent. H1N1	$221.68	$826.18	$2,422.77	$15,066.31
	A/H1N1pdm09	$40.87	$712.95	$311.02	$36.58
(3,1,3,1)	SARS-CoV-2	$904.68	$791.81	$2,432.92	$1,284.15
	20th Cent. H1N1	$1,203.76	$821.70	$2,536.73	$19,325.52
	A/H1N1pdm09	$175.81	$712.95	$341.02	$39.39
(3,2,3,1)	SARS-CoV-2	$904.68	$791.81	$2,920.26	$1,284.15
	20th Cent. H1N1	$1,203.76	$821.70	$3,193.38	$19,325.52
	A/H1N1pdm09	$175.81	$712.95	$408.44	$39.39
(3,1,3,2)	SARS-CoV-2	$2,139.07	$791.81	$2,692.09	$1,413.37
	20th Cent. H1N1	$2,851.68	$822.34	$2,879.23	$26,120.49
	A/H1N1pdm09	$402.40	$712.95	$405.67	$44.18
(3,2,3,2)	SARS-CoV-2	$2,139.07	$791.81	$3,910.25	$1,413.37
	20th Cent. H1N1	$2,851.68	$822.34	$4,514.83	$26,120.49
	A/H1N1pdm09	$402.40	$712.95	$573.01	$44.18

Table 5.11: Summary of most cost-effective respirator strategies for each combination of settings for each pandemic scenario

Setting	Pandemic	Most Cost-Effective Strategy	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy
(1,1,1,3)	SARS-CoV-2	N95	Dispose after contact	1: EFR for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(1,2,1,3)	SARS-CoV-2	N95	Dispose after contact	2: N95s for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(2,1,1,3)	SARS-CoV-2	N95	Dispose after multiple contacts	1	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(2,2,1,3)	SARS-CoV-2	N95	Dispose after multiple contacts	2	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				

Setting	**Pandemic**	**Most Cost-Effective Strategy**	**N95 Utilization Strategy**	**Mixed Strategy**	**EFR Disinfection Strategy**	**N95 Disinfection Strategy**
(3,1,1,1)	SARS-CoV-2	N95	Disinfect	1	Disinfect after contact	UVGI
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(3,2,1,1)	SARS-CoV-2	N95	Disinfect	2	Disinfect after contact	UVGI
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(3,1,1,2)	SARS-CoV-2	N95	Disinfect	1	Disinfect after contact	Low temp
	20th Cent. H1N1	Mixed #1				
	A/H1N1pdm09	Phased				
(3,2,1,2)	SARS-CoV-2	N95	Disinfect	2	Disinfect after contact	Low temp
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(1,1,2,3)	SARS-CoV-2	EFR	Dispose after contact	1	Disinfect after each shift	N/A
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(1,2,2,3)	SARS-CoV-2	EFR	Dispose after contact	2	Disinfect after each shift	N/A
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(2,1,2,3)	SARS-CoV-2	EFR	Dispose after multiple contacts	1	Disinfect after each shift	N/A
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(2,2,2,3)	SARS-CoV-2	EFR	Dispose after multiple contacts	2	Disinfect after each shift	N/A
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(3,1,2,1)	SARS-CoV-2	EFR	Disinfect	1	Disinfect after each shift	UVGI
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(3,2,2,1)	SARS-CoV-2	EFR	Disinfect	2	Disinfect after each shift	UVGI
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(3,1,2,2)	SARS-CoV-2	EFR	Disinfect	1	Disinfect after each shift	Low temp
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(3,2,2,2)	SARS-CoV-2	EFR	Disinfect	2	Disinfect after each shift	Low temp
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	EFR				
(1,1,3,3)	SARS-CoV-2	N95	Dispose after contact	1	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(1,2,3,3)	SARS-CoV-2	N95		2		N/A

Setting	Pandemic	Most Cost-Effective Strategy	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy
	20th Cent. H1N1	N95	Dispose after contact		Disinfect and clean	
	A/H1N1pdm09	Phased				
(2,1,3,3)	SARS-CoV-2	N95	Dispose after multiple contacts	1	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(2,2,3,3)	SARS-CoV-2	N95	Dispose after multiple contacts	2	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	Phased				
(3,1,3,1)	SARS-CoV-2	EFR	Disinfect	1	Disinfect and clean	UVGI
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	Phased				
(3,2,3,1)	SARS-CoV-2	EFR	Disinfect	2	Disinfect and clean	UVGI
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	Phased				
(3,1,3,2)	SARS-CoV-2	EFR	Disinfect	1	Disinfect and clean	Low temp
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	Phased				
(3,2,3,2)	SARS-CoV-2	EFR	Disinfect	2	Disinfect and clean	Low temp
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	Phased				

5.4.2. SIR MODEL

The SIR model can also help guide preparations for future pandemics. Table 5.12 summarizes the respirators remaining if one type of pandemic (row) is prepared for, but a different pandemic (column) occurs. If SARS-CoV-2 is prepared for and a pandemic similar to the Spanish flu (20th century H1N1) occurs, a shortage of over 300 thousand single-use N95s will result. If A/H1N1pdm09 is prepared for, 2469 respirators will be needed if a similar pandemic to SARS-CoV-2 occurs. If a pandemic with the same severity of the 20th century H1N1 pandemic occurs, a shortage of over 3 million N95s will result.

Table 5.12: Respirator shortages and surpluses expected when preparing for each pandemic scenario

Prepared for	Reality		
	SARS-CoV-2	**20th Cent. H1N1**	**A/H1N1pdm09**
SARS-CoV-2	--	-311,203	2469
20th Cent. H1N1	311,203	--	3,150,912

A/H1N1pdm09	-2469	-3,150,912	--

Other information from the SIR model can also help plan inventory requirements. For example, reproduction numbers of each pandemic can help gauge the severity of a contagious viral outbreak. The basic reproduction number (R_0) for SARS-CoV-2 is 2.71 and the 20th century H1N1 pandemic R_0 is 6.25, while for the A/H1N1pdm09 pandemic, R_0 is 1.2. If the pandemics were to run their course given the initial conditions, instead of stopping analysis at 12 weeks, respirator requirements are summarized in Table 5.13. Since all reproduction numbers are above 1, it is predicted that future outbreaks resembling pandemics investigated, would develop into epidemics given no interventive policies such as social distancing, mask-wearing, and vaccinations.

Table 5.13: Estimated respirator requirements if pandemic scenarios occur without intervention

	SARS-CoV-2	**20th Cent. H1N1**	**A/H1N1pdm09**
Quantity of N95s	2,615,079.86	3,624,792.16	36,583.38
Quantity of EFRs	1893	2623	64
Duration (days)	366	177	1095

The accompanying SIR models for each pandemic are presented in Figure 5.4, Figure 5.5 and Figure 5.6. SIR models can help to predict peeks in incoming infectious patients. For example, the largest increase in patients seen at a hospital may be at 115 days into a pandemic resembling SARS-CoV-2. This provides the opportunity to use a phased approach in which a gradual transition to reusable respirators is strategic. However, the peek may be seen sooner for a pandemic resembling the Spanish flu. In which case, a large portion of respirators are needed at approximately 36 days into the pandemic. Lastly, for a pandemic resembling A/H1N1pdm09, a small portion of respirators would be required immediately.

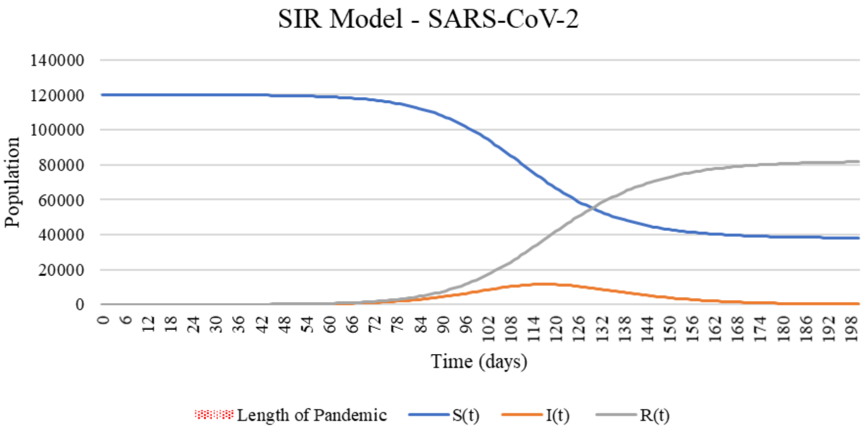


Figure 5.4: SARs-CoV-2 SIR model using Dartmouth General Hospital inputs

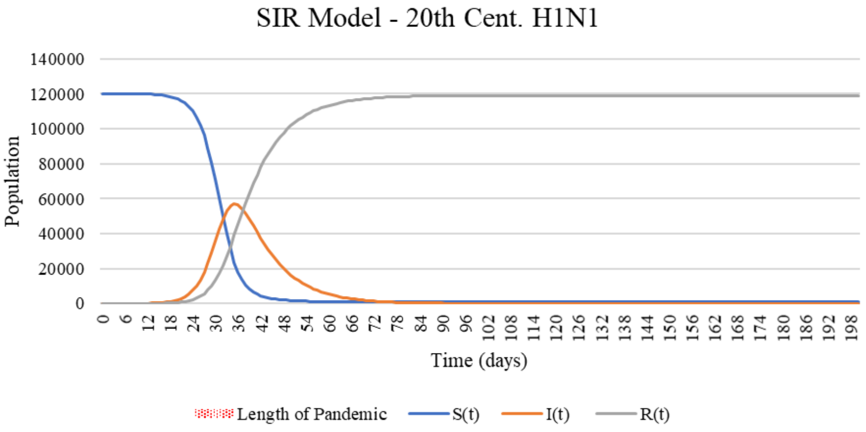


Figure 5.5: 20th Century H1N1 SIR model using Dartmouth General Hospital inputs

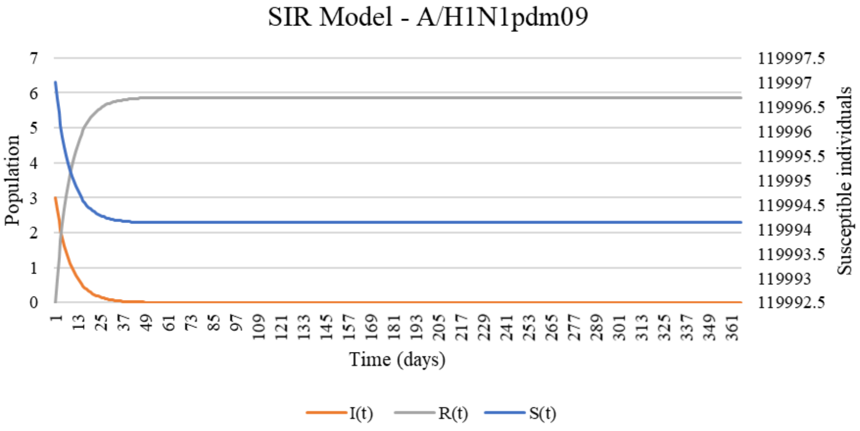


Figure 5.6: A/H1N1pdm09 SIR model with Dartmouth General Hospital inputs

5.5. SEIR MODEL

5.5.1. TOTAL COSTS

Table 5.14 lists total costs achieved from the SEIR model for each combination of settings and for each pandemic scenario at Dartmouth General Hospital. Table 5.15 summarizes the most cost-effective strategies for each combination of settings. A minimum total cost of $125,500 was achieved for SARS-CoV-2 if an N95 program is adopted when N95s are used multiple times before disposal. This is unlike previous results. Figure 5.7 shows that as the total number of HCWs needed during a pandemic increases, the total costs associated with disinfecting EFRs after each shift surpass those associated with using N95s multiple times before disposal. The program costs of disinfecting EFRs increase quickly after 100,000 HCWs are needed to address a pandemic resembling SARS-CoV-2 without social distancing, mask-wearing, and other disease transmission-limiting policies.

There are limitations of these findings because they are not realistic. Dartmouth General Hospital does not have the capacity for tens of thousands of HCWs. For Dartmouth General Hospital's purposes, disinfecting EFRs after each shift may still be the most cost-effective solution since SARS-CoV-2 cases did not spike in reality as they do in the SEIR model. This indicates that the SEIR model may not benefit analyses of smaller populations such as those studied within Nova Scotia. Ioannidis, Cripps, Tanner, (2020) have indicated that forecasting for the purposes of SARS-CoV-2 has failed due to several modelling challenges. Challenges include high sensitivity of estimates, poor modelling assumptions and poor data input.

The same strategy achieved a minimum cost of $75,700 in an A/H1N1pdm09 pandemic. Lastly, a minimum cost of $87,523,000 is achieved during a 20th century H1N1 pandemic when the phased approach is chosen, when N95s are used multiple times before disposal and EFRs are disinfected after each shift. Though disinfecting N95s does not yield the lowest cost in all pandemic scenarios, it is an appropriate alternative to using N95s multiple times before disposal. In a SARS-CoV-2 pandemic scenario, disinfecting only costs $1519 more than using N95s multiple times before disposal.

Table 5.14: Total costs of each respirator alternative using the SEIR model

Setting	Pandemic	N95 (1000s)	EFR (1000s)	Mixed 1 & 2 (1000s)	Phased (1000s)
(1,1,1,3)	SARS-CoV-2	$130.34	$136.97	$175.91	$453.53
	20th Cent. H1N1	$96,083.86	$96,721.99	$128,086.33	$131,783.79
	A/H1N1pdm09	$78.97	$80.12	$92.95	$98.11
(1,2,1,3)	SARS-CoV-2	$133.86	$136.97	$173.80	$453.53
	20th Cent. H1N1	$96,083.86	$96,721.99	$126,445.23	$131,783.79
	A/H1N1pdm09	$78.97	$80.12	$92.33	$98.11
(2,1,1,3)	SARS-CoV-2	$125.50	$136.97	$175.91	$250.64
	20th Cent. H1N1	$89,542.53	$96,721.51	$128,086.33	$131,513.37
	A/H1N1pdm09	$75.70	$80.12	$92.95	$97.53
(2,2,1,3)	SARS-CoV-2	$126.46	$136.97	$173.80	$250.64
	20th Cent. H1N1	$89,542.53	$96,721.51	$126,445.23	$131,513.37
	A/H1N1pdm09	$75.70	$80.12	$92.33	$97.53
(3,1,1,1)	SARS-CoV-2	$127.02	$136.97	$181.00	$193.08
	20th Cent. H1N1	$89,633.16	$96,721.51	$132,026.03	$132,804.04
	A/H1N1pdm09	$76.11	$80.12	$95.61	$99.28
(3,2,1,1)	SARS-CoV-2	$127.02	$136.97	$193.01	$193.08
	20th Cent. H1N1	$89,633.16	$96,721.51	$141,453.74	$132,804.04
	A/H1N1pdm09	$76.11	$80.12	$95.61	$99.28
(3,1,1,2)	SARS-CoV-2	$131.38	$136.97	$188.60	$205.16
	20th Cent. H1N1	$92,804.96	$96,721.83	$137,909.72	$134,861.60
	A/H1N1pdm09	$78.16	$80.12	$99.57	$102.06
(3,2,1,2)	SARS-CoV-2	$131.53	$136.97	$221.78	$205.16
	20th Cent. H1N1	$92,804.96	$96,721.83	$163,940.63	$134,861.60
	A/H1N1pdm09	$78.16	$80.12	$99.57	$102.06
(1,1,2,3)	SARS-CoV-2	$130.34	$133.18	$130.71	$403.86
	20th Cent. H1N1	$96,083.86	$90,875.52	$89,903.56	$87,793.52
	A/H1N1pdm09	$78.97	$80.89	$79.33	$81.77
(1,2,2,3)	SARS-CoV-2	$133.86	$133.18	$128.61	$403.86
	20th Cent. H1N1	$96,083.86	$90,875.52	$88,262.46	$87,793.52
	A/H1N1pdm09	$78.97	$80.89	$79.33	$81.77
(2,1,2,3)	SARS-CoV-2	$125.50	$133.18	$130.71	$200.98
	20th Cent. H1N1	$89,542.53	$90,875.04	$89,903.56	$87,523.11
	A/H1N1pdm09	$75.70	$80.89	$79.33	$81.19
(2,2,2,3)	SARS-CoV-2	$126.46	$133.18	$128.61	$200.98
	20th Cent. H1N1	$89,542.53	$90,875.04	$88,262.46	$87,523.11
	A/H1N1pdm09	$75.70	$80.89	$79.33	$81.19
(3,1,2,1)	SARS-CoV-2	$127.02	$133.18	$135.81	$143.42

Setting	**Pandemic**	**N95 (1000s)**	**EFR (1000s)**	**Mixed 1 & 2 (1000s)**	**Phased (1000s)**
	20th Cent. H1N1	$89,633.16	$90,875.04	$93,843.26	$88,813.77
	A/H1N1pdm09	$76.11	$80.89	$82.00	$82.95
(3,2,2,1)	SARS-CoV-2	$127.02	$133.18	$147.82	$143.42
	20th Cent. H1N1	$89,633.16	$90,875.04	$103,270.97	$88,813.77
	A/H1N1pdm09	$76.11	$80.89	$82.00	$82.95
(3,1,2,2)	SARS-CoV-2	$131.38	$133.18	$143.41	$155.49
	20th Cent. H1N1	$92,804.96	$90,875.36	$99,726.95	$90,871.33
	A/H1N1pdm09	$78.16	$80.89	$85.95	$85.72
(3,2,2,2)	SARS-CoV-2	$131.53	$133.18	$176.59	$155.49
	20th Cent. H1N1	$92,804.96	$90,875.36	$125,757.86	$90,871.33
	A/H1N1pdm09	$78.16	$80.89	$85.95	$85.72
(1,1,3,3)	SARS-CoV-2	$130.34	$153.27	$190.46	$420.76
	20th Cent. H1N1	$96,083.86	$107,270.66	$127,879.30	$102,469.37
	A/H1N1pdm09	$78.97	$81.48	$92.89	$87.52
(1,2,3,3)	SARS-CoV-2	$133.86	$153.27	$188.36	$420.76
	20th Cent. H1N1	$96,083.86	$107,270.66	$126,238.20	$102,469.37
	A/H1N1pdm09	$78.97	$81.48	$92.89	$87.52
(2,1,3,3)	SARS-CoV-2	$125.50	$153.27	$190.46	$217.88
	20th Cent. H1N1	$89,542.53	$107,270.18	$127,879.30	$102,198.96
	A/H1N1pdm09	$75.70	$81.48	$92.89	$86.94
(2,2,3,3)	SARS-CoV-2	$126.46	$153.27	$188.36	$217.88
	20th Cent. H1N1	$89,542.53	$107,270.18	$126,238.20	$102,198.96
	A/H1N1pdm09	$75.70	$81.48	$92.89	$86.94
(3,1,3,1)	SARS-CoV-2	$127.02	$153.27	$195.55	$160.32
	20th Cent. H1N1	$89,633.16	$107,270.18	$131,819.00	$103,489.62
	A/H1N1pdm09	$76.11	$81.48	$95.55	$88.69
(3,2,3,1)	SARS-CoV-2	$127.02	$153.27	$207.56	$160.32
	20th Cent. H1N1	$89,633.16	$107,270.18	$141,246.71	$103,489.62
	A/H1N1pdm09	$76.11	$81.48	$95.55	$88.69
(3,1,3,2)	SARS-CoV-2	$131.38	$153.27	$203.16	$172.39
	20th Cent. H1N1	$92,804.96	$107,270.50	$137,702.69	$105,547.18
	A/H1N1pdm09	$78.16	$81.48	$99.51	$91.46
(3,2,3,2)	SARS-CoV-2	$131.53	$153.27	$236.33	$172.39
	20th Cent. H1N1	$92,804.96	$107,270.50	$163,733.60	$105,547.18
	A/H1N1pdm09	$78.16	$81.48	$99.51	$91.46

Table 5.15: Summary of cost-effective strategies for each combination of settings using the SEIR model

Setting	Pandemic	Most Cost-Effective Strategy	N95 Utilization Strategy	Mixed Strategy	EFR Disinfection Strategy	N95 Disinfection Strategy
(1,1,1,3)	SARS-CoV-2	N95	Dispose after contact	1: EFR for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(1,2,1,3)	SARS-CoV-2	N95	Dispose after contact	2: N95s for doctors, nurses, and respiratory technologists	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(2,1,1,3)	SARS-CoV-2	N95	Dispose after multiple contacts	1	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(2,2,1,3)	SARS-CoV-2	N95	Dispose after multiple contacts	2	Disinfect after contact	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,1,1,1)	SARS-CoV-2	N95	Disinfect	1	Disinfect after contact	UVGI
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,2,1,1)	SARS-CoV-2	N95	Disinfect	2	Disinfect after contact	UVGI
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,1,1,2)	SARS-CoV-2	N95	Disinfect	1	Disinfect after contact	Low temp
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,2,1,2)	SARS-CoV-2	N95	Disinfect	2	Disinfect after contact	Low temp
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(1,1,2,3)	SARS-CoV-2	N95	Dispose after contact	1	Disinfect after each shift	N/A
	20th Cent. H1N1	EFR				
	A/H1N1pdm09	N95				
(1,2,2,3)	SARS-CoV-2	Mixed #2	Dispose after contact	2	Disinfect after each shift	N/A
	20th Cent. H1N1	Phased				
	A/H1N1pdm09	N95				
(2,1,2,3)	SARS-CoV-2	N95	Dispose after multiple contacts	1	Disinfect after each shift	N/A
	20th Cent. H1N1	Phased				
	A/H1N1pdm09	N95				
(2,2,2,3)	SARS-CoV-2	N95	Dispose after multiple contacts	2	Disinfect after each shift	N/A
	20th Cent. H1N1	Phased				
	A/H1N1pdm09	N95				
(3,1,2,1)	SARS-CoV-2	N95	Disinfect	1	Disinfect after each shift	UVGI
	20th Cent. H1N1	Phased				

Setting	**Pandemic**	**Most Cost-Effective Strategy**	**N95 Utilization Strategy**	**Mixed Strategy**	**EFR Disinfection Strategy**	**N95 Disinfection Strategy**
	A/H1N1pdm09	N95				
(3,2,2,1)	SARS-CoV-2	N95	Disinfect	2	Disinfect after each shift	UVGI
	20th Cent. H1N1	Phased				
	A/H1N1pdm09	N95				
(3,1,2,2)	SARS-CoV-2	N95	Disinfect	1	Disinfect after each shift	Low temp
	20th Cent. H1N1	Phased				
	A/H1N1pdm09	N95				
(3,2,2,2)	SARS-CoV-2	N95	Disinfect	2	Disinfect after each shift	Low temp
	20th Cent. H1N1	Phased				
	A/H1N1pdm09	N95				
(1,1,3,3)	SARS-CoV-2	N95	Dispose after contact	1	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(1,2,3,3)	SARS-CoV-2	N95	Dispose after contact	2	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(2,1,3,3)	SARS-CoV-2	N95	Dispose after multiple contacts	1	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(2,2,3,3)	SARS-CoV-2	N95	Dispose after multiple contacts	2	Disinfect and clean	N/A
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,1,3,1)	SARS-CoV-2	N95	Disinfect	1	Disinfect and clean	UVGI
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,2,3,1)	SARS-CoV-2	N95	Disinfect	2	Disinfect and clean	UVGI
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,1,3,2)	SARS-CoV-2	N95	Disinfect	1	Disinfect and clean	Low temp
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				
(3,2,3,2)	SARS-CoV-2	N95	Disinfect	2	Disinfect and clean	Low temp
	20th Cent. H1N1	N95				
	A/H1N1pdm09	N95				

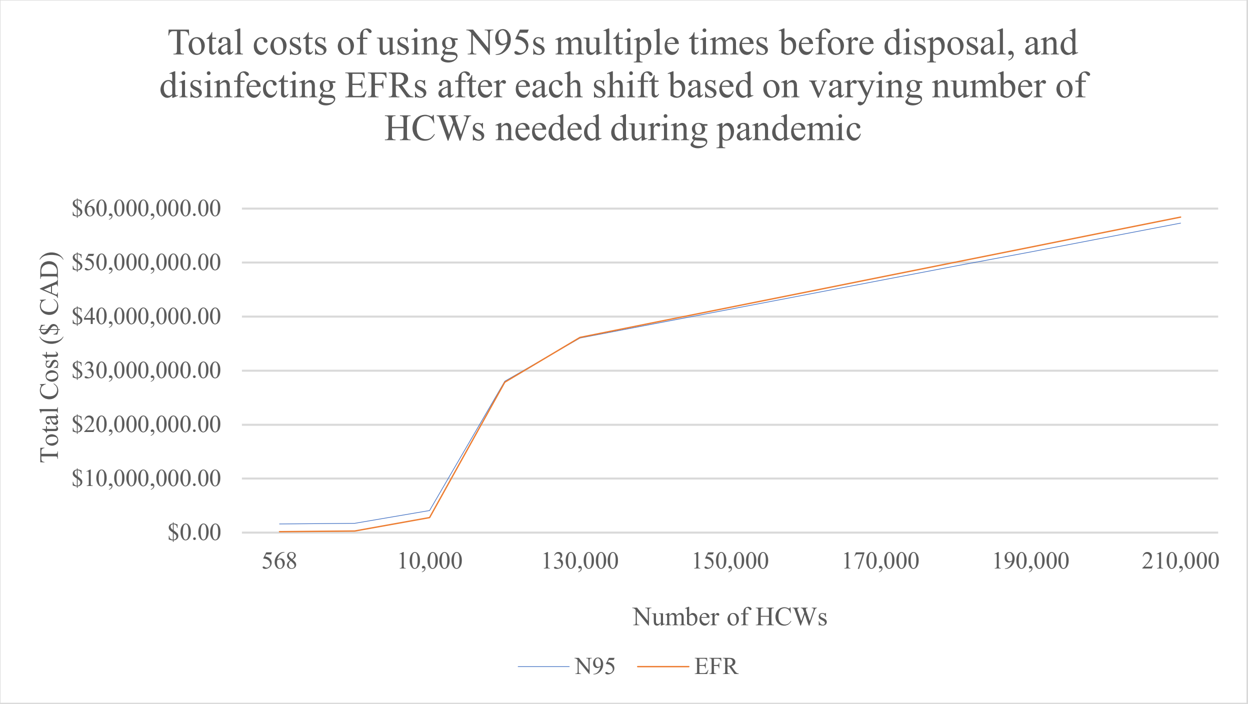


Figure 5.7: Total costs of disinfecting EFRs after each shift and disposing N95s after multiple contacts, depending on total number of HCW required during a 12-week pandemic

5.5.2. SEIR MODEL PANDEMIC SCENARIOS

Let us return to reproduction numbers to help accurately predict the infectiousness of each pandemic scenario. Table 5.16 lists the basic reproduction numbers for each outbreak. According to Al-Raeei M. (2021), the basic reproduction number of SARS-CoV-2 should be located in the range of 1.0011–2.7936 days. The 1918 influenza virus was estimated to have a basic reproduction number between 2.4–4.3 days (Vynnycky, E., Trindall, A., & Mangtani, P., 2007). Lastly, studies have shown that the A/H1N1pdm09 reproduction number falls within 1.30–1.70 days (Biggerstaff, M., et al., 2014). Given that the reproduction numbers for SARS-CoV-2, the 20th century H1N1 and A/H1N1pdm09 are 1.43, 3.99 and 1.3, respectively, all outbreaks are estimated to turn into epidemics and fall within each of the expected ranges. This validates the SEIR model estimates and helps to accurately predict respirator requirements.

Table 5.16: Reproduction numbers of each pandemic scenario using SEIR model inputs

	SARS-CoV-2	20th Cent. H1N1	A/H1N1pdm09
R_0	1.436	3.99	1.30
Expected	1.0011–2.7936	2.4–4.3	1.30–1.70

The accompanying SEIR models for each pandemic are presented in Figure 5.8, Figure 5.9, and Figure 5.10. It is estimated that peeks in incoming infected individuals occur at 287 days, 80 days, and 1 day in the SARS-CoV-2, 20th century H1N1 and A/H1N1pdm09 pandemics, respectively. It is apparent that the duration of the SARS-CoV-2 should last beyond a year, while the last infected individual in the A/H1N1pdm09 pandemic is expected before 84 days. The 20th century H1N1 pandemic exhibits similar behaviour as SARS-CoV-2 but has a greater peek in infections (35,101 vs 5949 individuals).

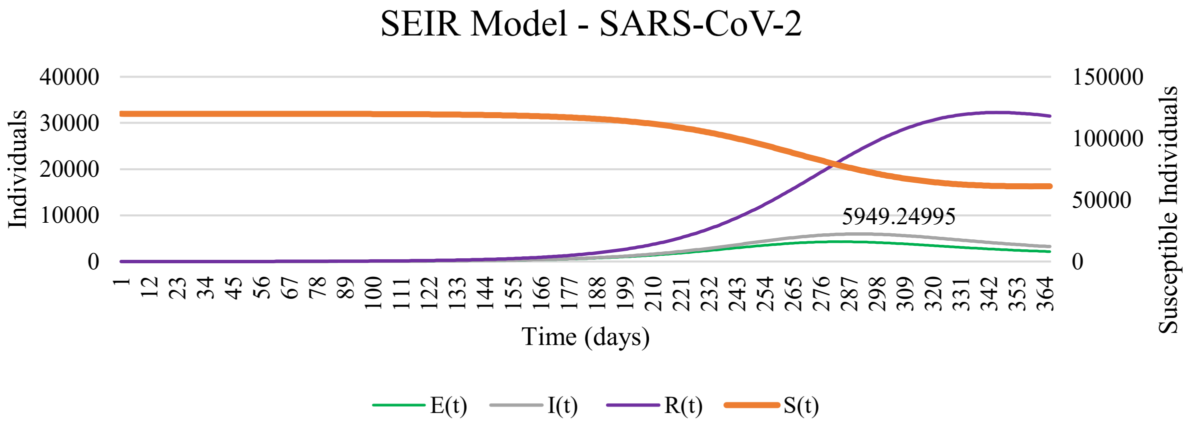


Figure 5.8: SEIR model of SARS-CoV-2 using Dartmouth General Hospital inputs

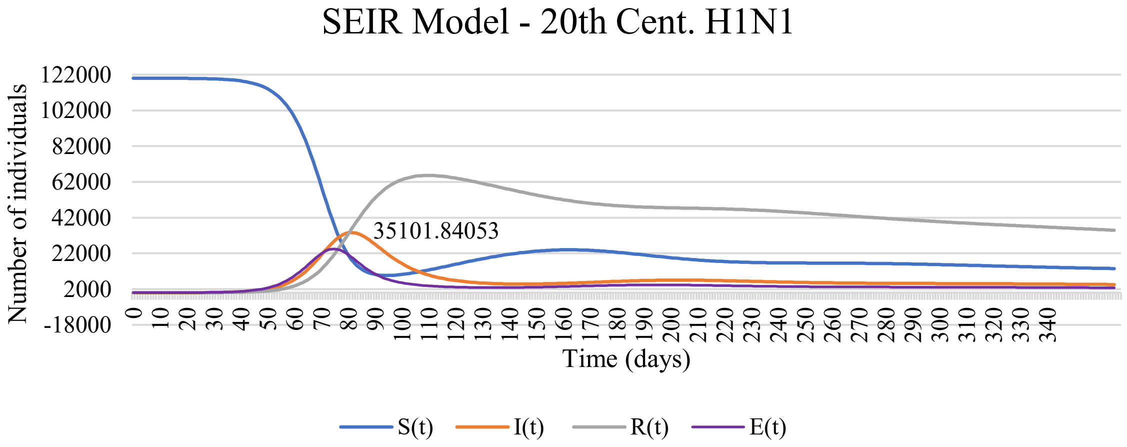


Figure 5.9: SEIR model of 20th Century H1N1 using Dartmouth General Hospital inputs

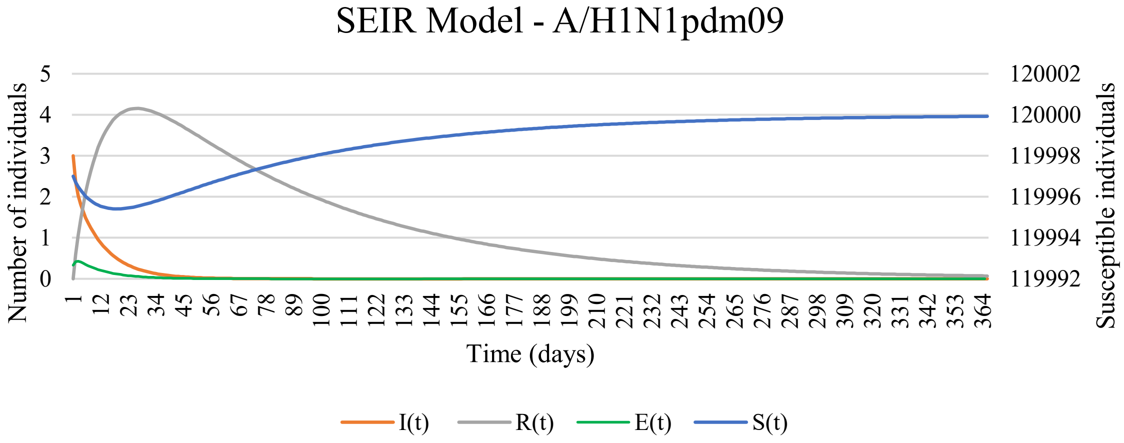


Figure 5.10: SEIR model of A/H1N1pdm09 using Dartmouth General Hospital inputs

One benefit of using the predictive SEIR model to help forecast pandemic behaviour is that it allows policymakers to plan for and adjust inventory requirements ahead of time. This is a significant improvement over other PPE cost analyses, as the application of the final model can address and avoid challenges during pandemics such as upstream disruptions in supply chain, high demands, and low supply due to hoarding and panic purchasing.

5.5.2.1. Stockpiling Comparisons

When N95 shortages became the norm during the SARS-CoV-2 pandemic, their prices skyrocketed. How much do shortages of PPE and subsequent increase in prices impact total annual costs using the SEIR model? Table 5.17 summarizes the stockpiling costs before and during SARS-CoV-2 if the cost of N95s changes from \$0.50 (Pre-SARS-CoV-2) apiece to \$7.50 (During SARS-CoV-2) apiece. Costs reflect the single-use N95 strategy and disinfection of EFRs after each contact. The phased approach is impacted the least (the cost increases by 0.15%) as it relies on completely switching to EFRs over 10 weeks. The 4.16% increase in total costs associated with the N95 respirator protection program reflects the risks associated with stockpiling N95s when they are in high demand. Though the cost of N95s still does not exceed the cost of EFRs (\$136,900), it is important to consider supply chain limitations of N95s when they are in high demand.

Table 5.17: Comparison of total annual costs if N95 costs change from \$0.5 to \$7.50

Strategy	**Pre-SARS-CoV-2 (1000s)**	**During SARS-CoV-2 (1000s)**	**Δ**

N95	$130.34	$136.00	4.16%
Mixed #1	$175.91	$177.09	0.67%
Mixed #2	$173.80	$178.28	2.57%
Phased	$453.53	$454.22	0.15%

Furthermore, the present value of the money saved is $3190 today if respirators are stockpiled five years prior to the next pandemic resembling SARS-CoV-2 (five years is the shelf-life of N95s) with a 10% interest rate.

5.5.2.2. Sensitivity Analysis: Contacts per Hour

A sensitivity analysis was completed on the number of contacts per hour per respirator. If N95s are used multiple times per product, and EFRs are disinfected after each shift and cleaned after each contact, EFRs are still more costly than N95s (see Table 5.21). Under normal circumstances for example, nurses are expected to see four contacts per hour (ThriveAP, 2016). However, many accounts during the pandemic suggested that nursing and doctor workloads were above average (Fernandez et al., 2020). As the relationship between cost and contacts per hour is negative, there are however, consequences of using N95s for multiple patient contacts before doffing as discussed previously. At four contacts per hour, EFRs are 37.91% more costly than N95s, but risk of structural integrity is lower, and sense of protection is higher.

Table 5.18: Total costs of each respirator alternative given contacts per hour

Contacts per Hour	N95	EFR	Mixed Strategy #1	Mixed Strategy #2	Phased Approach
1	$239.05	$270.38	$305.59	$301.16	$402.62
2	$125.50	$153.27	$190.46	$188.36	$217.88
3	$87.76	$114.31	$152.08	$150.76	$156.36
4	$68.67	$94.70	$132.89	$131.96	$125.48
5	$57.33	$83.10	$121.38	$120.68	$107.11
6	$49.86	$75.09	$113.70	$113.16	$94.61
7	$44.39	$69.57	$108.22	$107.79	$85.89
8	$40.39	$65.43	$104.11	$103.75	$79.31
9	$37.28	$62.21	$100.91	$100.62	$74.30
10	$34.66	$59.63	$98.35	$98.12	$70.19

5.6. TOPSIS RESULTS

Before TOPSIS results are discussed, a review of the final criteria evaluations is presented in Table 5.19. The literature suggests that N95s are more functional. Whereas, EFRs have been found to be the financially advantageous option but have the potential to induce user anxiety. However, upon discussions with HCWs, it is apparent that regular users who do not have pre-existing anxiety are generally unaffected by the use of EFRs. Furthermore, in many studies discussed in the literature review, study participants often indicated the increase in feelings of protection and safety when using EFRs. In comparison, N95s have poor evaluations for sense of protection.

It is important to note that each of the studies used to determine respirator evaluations have their own limitations. For example, there are many differences across makes and models of each type of respirator which can influence comparisons. A half-face EFR requires the use of goggles which can fog and may negatively impact vision greater than a full-face EFR. Furthermore, the length of time that participants are instructed to use each respirator type can vary across studies. The length of time that a user must use a respirator can have varying impacts on discomfort. As well, a combination of factors can negatively influence the functional aspects of respirators that may not be reflected in clinical studies because they do not resemble realistic emergency scenarios. In a case-control study, Lam (2020) indicated that the anxiety of SARS-CoV-2 caused HCWs to wear their N95s tighter than usual which caused skin ulcers the longer they wore the mask. The participants they examined for nose dorsum ulcers were HCWs who on average, wore their N95s for at least 5 hours after donning their mask.

Lastly, it is important to remember when reviewing TOPSIS results, the manor in which weighting is provided. Decision-makers often provide weighting in terms of whether the importance of each criterion is “high” or “low”, reflecting uncertainty and lack of precision.

Table 5.19: TOPSIS criteria evaluations for each respirator alternative

	Decision Matrix	**Evaluations ($x_{n.m}$)**	
n	Criteria	N95 (m=1)	EFR (m=2)
1	Temperature discomfort	8.67	3.52
2	Skin irritation	8.875	3.25

3	Vision obstruction	10	5.5
4	Breathing difficulty	10	7
5	User anxiety	9.78	1.22
6	Muffling	5.33675	5.68
7	Cost	4.2275	7.265
8	Protection	2.78	8.7
9	Sense of protection	6.74	8.02
10	Confidence in training	6.895	7.615

Using the evaluations in Table 5.19, TOPSIS analyses were completed using three different weighting schemes as presented in the following pages. All TOPSIS analyses were completed assuming that EFRs are disinfected after each contact, and N95s are disposed of after each contact. The first TOPSIS analysis uses an equal weighting scheme, while the last two use variable weighting schemes. One considers cost the highest of importance, while the last analysis provides results for weighting provided by HCWs input.

5.6.1. EQUAL CRITERIA WEIGHTING

The ranks for the alternatives using the TOPSIS method are shown in Table 5.20 and Figure 5.11. If all criteria weights are equal, N95s are ranked highest according to their relative closeness with the ideal solution. Generally, N95s are a shorter distance from the ideal solution ($S^* = 0.0028$) than EFRs. N95s have greater ratings for vision, breathing ability, skin irritability, skin temperature, muffling and anxiety.

Table 5.20: TOPSIS results for N95 and EFR alternatives

Criteria	**N95 (m=1)**	**EFR (m=2)**
Si*	0.002862491	0.008136614
Si'	0.008136614	0.002862491
Si'/Si'+Si*	0.739752369	0.260247631
Rank	1	2

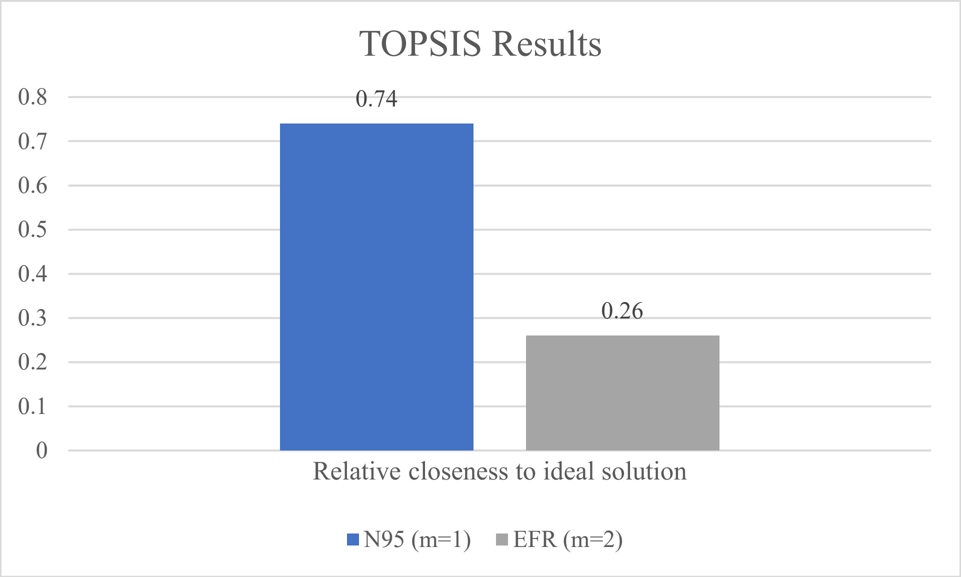


Figure 5.11: Relative closeness to the ideal solution for N95 and EFR alternatives

5.6.2. COST CRITERIA GIVEN HALF THE WEIGHT

The ranks for the alternatives are shown in Table 5.21 and Figure 5.12 when cost is given half the weight. If all criteria weights are equal, except for cost having a weight of 0.5, EFRs are ranked highest according to their relative closeness with the ideal solution. The EFR alternative has a greater distance from the negative ideal solution (S'=0.017 > 0.0025). Cost ratings are greatest for EFRs, despite N95s having advantages when used multiple times before disposal.

Table 5.21: TOPSIS results for N95 and EFR alternatives with greatest weight on cost

Criteria	**N95 (m=1)**	**EFR (m=2)**
Si*	0.017005644	0.002511301
Si'	0.002511301	0.017005644
Si'/Si'+si*	0.129	0.871
Rank	2	1

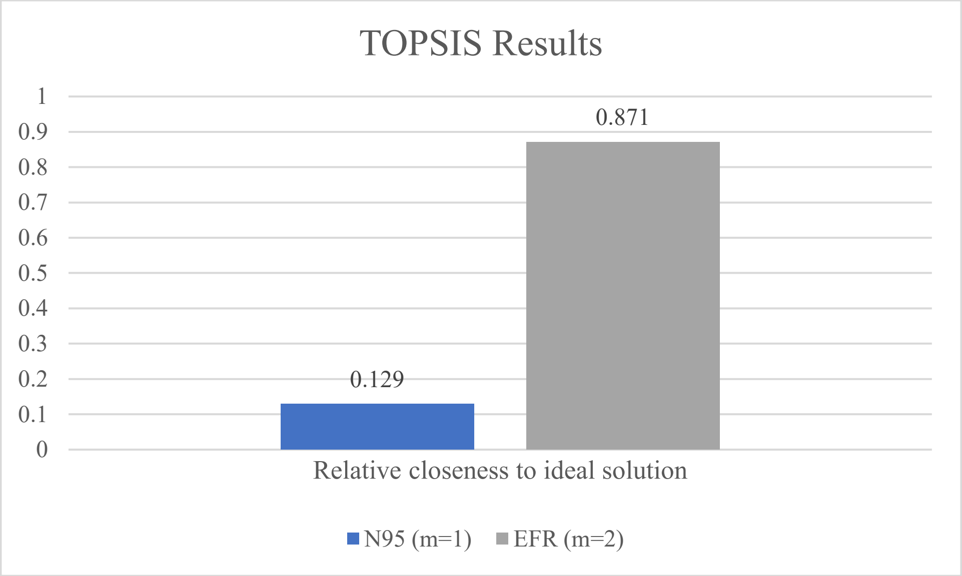


Figure 5.12: Relative closeness to the ideal solution for N95 and EFR alternatives with greatest weight on cost

5.6.3. EXTERNAL INPUT

Table 5.22 summarizes weights provided by HCWs. Several points were made when discussing criteria. Firstly, temperature discomfort is related to all PPE, so it was given a low score of importance. However, skin irritation was given a high weight of 0.3 by one subject matter expert because the difference in skin irritation between N95s and full-face EFRs is large after 20 minutes of use. EFRs cause less irritation for long periods of time, while N95s can are recounted to be uncomfortable. If half-face EFRs are considered, a much lower weight is preferred such as 0.05, as the relative difference between respirators is low. Visual obstruction was also weighted low, but it is important not to minimize the importance of visibility. If a half-face EFR is used, goggles can cause fogging, just as they do with N95s.

User anxiety was also scored low, as it was indicated that it is typically not an issue for HCWs. An average weight of 0.125 was given to the muffling criterion, as EFRs are typically worse that N95s. Cost was given the lowest weight of 0.01, because of beliefs that there are minimal differences between N95 and EFR respiratory protection programs.

Lastly, respirator protection, user acceptability and training were scored. Respirator protection was weighted high in importance. There are multiple protection qualifiers that matter such as the protection factor rating of each respirator, fit testing, and resistance to leakage. When discussing the importance of disinfecting respirators to prevent contamination, it was emphasized that though guidelines for sterilizing EFRs are thorough, they do not reflect realistic circumstances. For example, HCWs are not required to wash their hair and neck after each patient contact, nor are they responsible for disinfecting all counter surfaces after each appointment. Why consider disinfecting EFRs after every contact, when there are other risk factors that are not addressed?

Continuing with the last criteria, user acceptance was given a low score of 0.05, while training was given a score of 0.065. Though the last criteria were given low weights of importance, it was noted that personnel who do not feel protected are unhappy, and this is an important consideration in choosing a respiratory protection program. Lastly, training is important in maintaining skills and safety, and should not be minimized in importance despite the weight given.

Table 5.22: HCWs weights

Criteria	**Weights (w_n)**		**Average**
	Stakeholder 1	**Stakeholder 2**	
Temperature discomfort	0.05	0.05	0.05
Skin irritation	0.3	0.05	0.175
Vision obstruction	0.05	0.15	0.1
Breathing difficulty	0.05	0.15	0.1
User anxiety	0.05	0.2	0.125
Muffling	0.15	0.1	0.125
Cost	0.02	0	0.01
Protection	0.2	0.2	0.2
Sense of protection	0.05	0.05	0.05
Confidence in training	0.08	0.05	0.065

The ranks for the alternatives are shown inTable *5.21* Table 5.22 given the new weighting scheme provided by HCWs. N95s have the largest relative closeness to the ideal solution once again. Despite input from HCWs, EFRs performed poorly across studies used for rating skin irritation. The high weight given to skin irritation contributes to N95's greater relative closeness to the ideal solution. The importance of muffling also influences the TOPSIS results, as EFRs on average, have a greater negative impact on speech transmissibility than N95s.

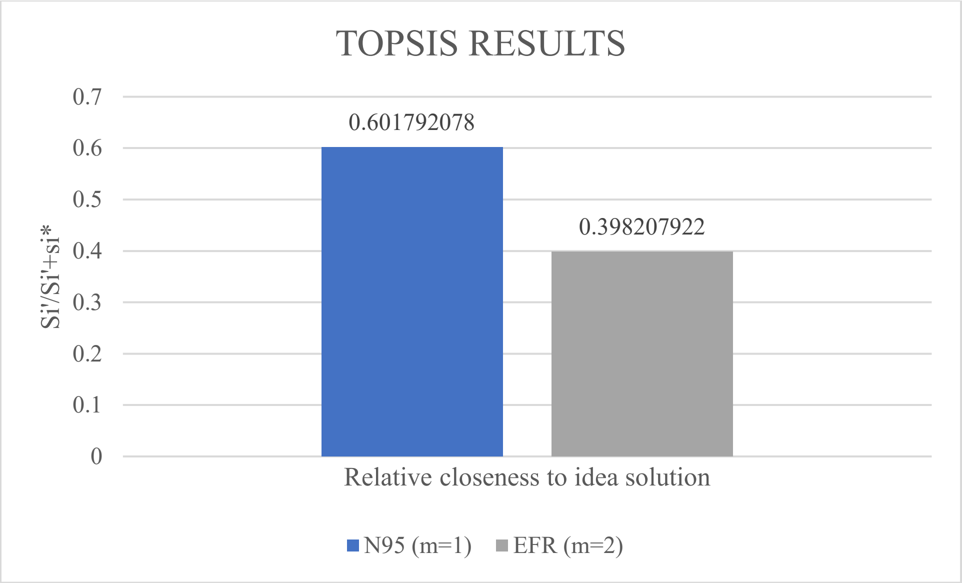


Figure 5.13: Relative closeness to the ideal solution result

6. CONCLUSION

6.1. SUMMARY

This thesis has contributed to the field of healthcare planning and decision making through theory development and application of innovative methods to determine whether EFRs are efficacious substitutes for N95s. By completing an extensive literature review, incorporating existing compartmental models into new financial predictive tools, and applying operational research methods, questions introduced in the introductory chapter were answered. The thesis explored the different circumstances in which EFRs and N95s should be selected, as there is no single respiratory protection program that fits all scenarios. Several major findings are worth returning to in this section which relate back to the thesis questions posed in the introduction chapter:

1. Are EFRs more financially advantageous than N95s, and do they meet user functional requirements such as comfort, communication, and safety? In the scenarios investigated, EFRs were found to be only financially advantageous if they are disinfected after each shift. Otherwise, N95s are cheapest when disposed after multiple contacts. However, it is important to be mindful that they can cause skin irritation and temperature discomfort.

2. Is a mixed strategy or phased approach to implementing EFRs less costly than using N95s alone? In comparison to other strategies, mixed strategies and phased approaches are not more cost-effective. However, mixed strategy #1 outperforms strategy #2, and the phased approach can be less costly for a small number of cases when EFRs are disinfected after each shift, and N95s are used multiple times before disposal.

3. Is there a financial advantage of disinfecting N95s? Disinfecting N95s proves to be the more cost-effective option when EFRs are disinfected after each shift, or when the estimated number of HCWs required during a pandemic is high, as illustrated in the SEIR model results. This is because the cost of disinfecting N95s is slightly less than the cost to disinfect EFRs.

4. Is there a financial advantage of disinfecting EFRs less frequently than after each patient interaction? There is a trend in the results that suggest disinfecting EFRs after each shift is most advantageous out of all options. The program costs associated with disinfecting EFRs are reduced when the number of reprocessing cycles decreases.

5. Is stockpiling N95s always more expensive than stockpiling EFRs? Stockpiling N95s for single use is always more expensive than most other respirator alternatives and utilization strategies. However, when used multiple times, they can be financially advantageous. As the number of hours of use of N95s increases, the less are required for stockpiling.

6. Are epidemiological compartmental models suitable for estimating respirator demands? The SIR and SEIR models were used. SIR models offer a simplistic approach to dynamic modelling ,while SEIR models more realistically reflect disease transmission since they consider latency periods and have the option to use vital statistics (birth and death rates of a population of interest).

7. How are the respirator demand requirements different across pandemics with varying epidemiological characteristics? More respirators are required for pandemics with greater infection rates and lower recovery rates. Specifically, the 20th century flu requires a greater stockpile than both SARs-CoV-2 and A/H1N1pdm09 combined.

8. If both functionality and costs are considered for each respirator alternative, in what circumstances are EFRs chosen over N95s and vice versa? EFRs are chosen if costs have the greatest importance in decision making. However, given HCW inputs and TOPSIS results, N95s should be chosen.

Overall, the literature reflects the challenges of selecting different respirator protection programs. The importance of adhering to and addressing limitations of respiratory protection program policies was emphasized, as program procedures such as sterilizing equipment, performing maintenance and following training are aspects that impact program success. Though cost studies typically favoured EFR programs, functional considerations such as communication and comfort must be further investigated for use in different contexts. It should also be reiterated that users preferred EFRs in situations in which better protection is desired, despite preference for N95s with respect to communication and comfort. Overall, the literature suggests that EFRs meet minimum functional requirements and in some cases, are not statistically different from N95s in performance.

The base model, dynamic model and SEIR model allowed for quantitative investigation to determine whether one respirator is financially advantageous over the other. The base model results indicated that EFRs are the best option when they are disinfected once per shift. This suggests that there is a potential financial advantage of disinfecting EFRs less frequently than after each contact. In fact, less frequent disinfection policies reflect real-world conditions and practices. Disinfecting EFRs after each shift also achieved minimum costs in the dynamic model and scenario investigation. In comparison to Baracco et al.'s (2015) model, the base model outputs greater costs because of equipment and time needed for disinfection and program implementation. Interestingly, the mixed strategy was not found to be cost-effective and achieved the highest price tag when N95s are disinfected and EFRs are cleaned and disinfected. There were no advantages of disinfecting N95s from a financial perspective in this case.

The dynamic model also produced several trends. One showed that disinfecting N95s can be less costly than disinfecting EFRs after each contact. Additionally, the mixed strategy #1 was found to always be less costly than the mixed strategy #2. The phased approach is less costly than both mixed strategies when N95s are not disinfected and EFRs are disinfected and cleaned. Surprisingly, in a A/H1N1pdm09 pandemic, the phased approach is the best option when EFRS are disinfected after each contact, and N95s are disposed of after multiple contacts. It was also evident that there are substantially different respirator demand requirements across different pandemics due to varying epidemiological characteristics. If a 20th century H1N1 pandemic was prepared for, and a different pandemic resembling A/H1N1pdm09 or SARS-CoV-2 occurred, a surplus of additional respirators in inventory would result.

The final model yielded different results from the previous models. Implementing a program that uses N95s multiple times before disposal was found to be the cheapest out of all options in SARS-CoV-2 and A/H1N1pdm09 pandemic scenarios. As discussed in the literature review, there are risks associated with using N95s for multiple patient contacts such as contamination and loss of mask integrity (soiling) which can break the face seal and result in leakage. Furthermore, these findings show that there is an intersection of costs of EFRs and N95s when 100,000 - 130,000 HCWs are needed. Unfortunately, these numbers do not reflect realistic circumstances, as Dartmouth General Hospital does not have that many staff. However, this result illustrates that there are exceptions to simply assuming the EFR programs are always more financially advantageous.

For the 20th century pandemic, the phased approach was found to be the best option when N95s are disposed after multiple contacts, and EFRs are disinfected after each shift. If N95s are purchased during a pandemic, the total cost of the program will still be less than that of an EFR program. However, there are risks associated with relying on supply chains during a worldwide state of emergency, as seen during SARS-CoV-2.

Finally, TOPSIS results provided insights that were not available with financial modelling. EFRs ratings below 5/10 were skin irritation, temperature discomfort and user anxiety. Despite this, EFRs ranked highest in closeness to the ideal solution when cost was given the highest weight. However, in all other cases, including the weighting scheme provided by healthcare personnel, N95s achieved highest rank. The lowest rating from the literature for N95s was for protection. There are limitations to this study such as the subjective responses provided by HCWs who provided weights for each criterion. In future research of respirator comparisons, Zadeh's (1965) method of using fuzzy sets to address uncertainty with systematic reasoning should be applied. Fuzzy TOPSIS assigns triangular fuzzy numbers to linguistic terms for alternative ratings. This allows analysis of criteria when decision makers have incomplete or uncertain knowledge and information (Nădăban, 2016).

Additional research extensions are also possible. Baracco et al.'s (2015) hospitalization rate was used in the base case, dynamic and SEIR models to estimate total HCW-patient contacts, and subsequent respirator requirements. The rate may not reflect those seen at Dartmouth General Hospital as the data was not readily available. One method for addressing this issue in future studies could be to estimate weekly influenza-related hospitalizations at the site of interest (Dartmouth General hospital) using an adaptive time-dynamic forecasting model. Huang et al. (2017) used dynamic linear modelling to estimate hospitalizations. Their approach used historical data to determine peak-week hospitalizations during previous pandemics and found their correlations with respirator demands. To address uncertainties in forecasting, they included additional predictors such as A/H1N1pdm09 influenza surveillance data (hospital admission, average hospitalization stay, etc.). Using dynamic linear modeling instead of the SEIR or SIR models may produce more accurate case estimates used for calculating stockpiling requirements and total annual costs.

6.2. POLICY EXTENSIONS

The feasibility of the following policies relies on economic and functional considerations that have been discussed in this thesis. Though there are limitations in the methods used to quantify total costs of each alternative, there are trends consistent throughout the models that should not be ignored, such as the cost of disinfection of EFRs after each shift instead of after each new patient contact. It is important to remember that these recommendations apply to emergency settings, in which there are N95 shortages. The following policies and recommendations should be reviewed:

1. In future forecasting, dynamic modelling should be used to prevent errors in predicting pandemic behaviour that can lead to underestimating respirator stockpiling requirements.
2. Consider disinfecting EFRs after each shift instead of each contact.
3. Consider stockpiling for a pandemic resembling SARS-CoV-2 to minimize respirator shortages and costs associated with expired inventory.
4. If a mixed strategy is preferred, it is recommended that EFRs be allocated to HCWs who are expected to have the most patient contacts. In our model, doctors, nurses, and respiratory therapists have the greatest number of patient interactions.
5. If a phased approach is preferred, it is recommended that N95s are disposed of after multiple contacts and EFRs are disinfected after each shift.
6. Due to TOPSIS results, healthcare facilities should consider improving EFR speech transmissibility or using N95s in instances in which clear communication is non-negotiable (ER rooms).

The worldwide outbreak of SARS-CoV-2 has posed implications for the supply of personal protective equipment such as N95 respirators. This makes planning for future pandemics more relevant than ever. All policies offered are intended to build healthcare resiliency and promote emergency preparedness in the event of future pandemics.

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