RISK ASSESSMENT FOR COVID-19 TRANSMISSION IN A HEALTH CARE CENTRE BASED ON FAULT TREE AND EVENT TREE

by

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Submitted in partial fulfillment of the requirements
for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
December 2022

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

Healthcare systems face significant challenges in containing the spread of infectious diseases. This work applies risk assessment and risk management, to evaluate COVID-19 transmission in the healthcare system. The starting point of this research is a Bow-Tie analysis that identified virus threats and consequences of the COVID-19 pandemic for various receptor groups. The study was motivated by the need to assess barriers to transmission in a quantitative manner. This work proposed a quantitative framework for stakeholders to analyze transmission risk and barrier criticality based on Fault Trees and Event Trees. Using the framework, this study collected data on failure probabilities relevant to COVID-19 from journals and expert opinions for a case study. This work also conducted a qualitative assessment and sensitivity analysis of the data. The outputs of calculations based on the Fault Tree and the Event Tree provided numeric results for the probability of each threat and consequence, indicating that the highest risk of infection came from asymptomatic patients. Finally, the work evaluated the overall risk of pandemic transmission at the partner hospital using the As Low As Reasonable Practical approach. The framework is shown to be effective at quantitatively assessing the risk of COVID-19 transmission in the healthcare system.

Chapter 1 Introduction

1.1 COVID-19 pandemic

The SARS-CoV-2 virus has been a global pandemic since the end of 2019, bringing the world an unprecedentedly significant challenge. Despite having mutiple vaccines, the viruses continually change through mutation. Even though the US and Canada have dropped restrictions on the pandemic, it is still highly recommended that people be cautious about COVID-19 to avoid another contagion outbreak. According to Mayo (2022), most infected people may develop mild to moderate illnesses. The most common symptoms are fever, cough, tiredness, and loss of taste or smell. Some infected people may experience severe symptoms such as shortness of breath, chest pains, or even problems speaking or moving. Another proportion of infected people is asymptomatic. They have been considered a potential source for the virus spread to healthy people, potentially resulting in an increased risk of transmission. Complications of the infected people include pneumonia and kidney failure. Severe cases may result in death. As of early October 2022, there have been 6.56 million deaths worldwide caused by COVID-19, including 45,640 in Canada. Public health is not the only challenge presented by the pandemic; economic and social disruption is also devastating.

The SARS-CoV-2 virus can be transmitted from human to human by direct and indirect contact. Direct transmission occurs via the emission of large droplets through coughing or sneezing from an infected person, and indirect transmission occurs through the deposition of large droplets on surfaces such as plastic, disposable gowns, masks, glass, paper, steel. The virus can survive on those surfaces for 2 to 9 days (Kampf et al., 2020). People can be infected after touching surfaces contaminated with the virus, then touching the eyes or mouth with contaminated hands (Science Brief: SARS-CoV-2 and Surface (Fomite) Transmission for Indoor Community Environments | CDC, n.d.). Risk controls are crucial due to the virus' rapid spread and persistence.

In the Canadian healthcare system, there have already been issues such as insufficient healthcare practitioners and hospital capacity, and long wait times. The infectious disease inevitably caused a major crisis in the shortage of healthcare workers and hospital capacities due to the overwhelming numbers of patients (WHO, 2022) . The transmission in hospitals undoubtedly worsened the problems. Due to limited resources, the institute's administrators must determine how to manage the risk associated with the disease.

1.2 Quantitative Risk Assessment

Risk assessment is a process of looking for scenarios that could lead to unwanted outcomes as part of the risk management process. It includes identification of all possible scenarios, calculation of their likelihoods, and description of the consequences. It is an important way for an organization to assess the risk level of the current system.

To control the spread of infectious diseases, different communities, workplaces, and organizations must perform a risk assessment to stratify safety threats and monitor responses (Ostrom & Wilhelmsen, 2019). Organizations should use the basic principles of risk management to prevent transmission. Risks should be removed wherever possible by choosing control measures and dealing with bio-agents. Whenever it is not possible to eliminate risk, physical controls or safe work practices are needed to mitigate it.

Different types of risk assessment can be performed in different kinds, as support for design decisions or continuous improvement when implementing measures. There are numerous qualitative or/and quantitative tools and techniques for risk assessment, such as Failure Mode and Effects Analysis (FMEA), What-if Analysis, Markov chain analysis, and decision trees.

1.3 Research motivation

This research was motivated by the need to implement a scientific approach to managing the risk of individuals acquiring SARS-CoV-2. None of the measures for COVID-19 are 100% effective (Haug et al., 2020), and they might influence people's life and health as well as the operations of an organization. Thus, making risk-based decisions is crucial for the government and organizations. This requires a scientific framework of risk management dealing with different hazards the pandemic might cause.

The COVID-19 pandemic has proven challenging for healthcare systems. There has been a shortage of staffing, supplies, and space in almost all health systems worldwide (Yang & Mason, 2022). With the high risk of virus exposure and limitations of resources, it is necessary to implement the approach to risk management. As not all measures are equally effective, quantitative analysis that provides numeric probabilities for risk mitigation barriers and consequence can support evidence-based decision-making and strategic planning. It thus mitigates the occurrence and the consequences of COVID-19 spread.

The foundation of this research is a project conducted in 2020 when a sophisticated Bow-Tie diagram, which worked as a tool for qualitative risk analysis and communication risks, was produced to identify the risks and controls of the transmission of COVID-19. It is an integrated diagram with hundreds of events and barriers from qualitative risk analysis theories, such as Layers of Protection and the Swiss Cheese Model. To prevent the most critical risks from occurring, stakeholders identify and manage them with the most effective controls based on a quantitative approach.

This work seeks to use the well-established and classic Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) as the cardinal techniques considering their close connection with the Bow-Tie diagram and their application for quantitative risk analysis. By using an algorithm, assessors can map the Bow-Tie diagram to FTA and ETA, from qualitative analysis to quantitative analysis.

1.4 Objectives

The objectives of this study can be summarized in the following points:

1. Present existing literature on the management of COVID-19 risks and qualitative and quantitative risk assessment methods.
2. Identify the main risk groups that affect transmission of the virus to investigate the causes of transmission.
3. Develop a risk assessment framework using FTA and ETA that can be used for assessing the overall risk of a system and prioritizing risk controls based on available data and Bow-Tie diagram.
4. Apply the FTA and ETA model using data from literature to a case study at the IWK healthcare centre.
5. Make recommendations for assessing the current risk levels and prioritizing risk controls.
6. Collect quantitative information about COVID-19 through a review of published papers. Taking the uncertainty of the data into consideration, the work aims to assess the quality of data with a Strength of Evidence (SoE) assessment to help the stakeholders understand the data when reviewing the outputs and planning for risk management.

1.5 Organization of Thesis Document

The organization of the thesis is as follows. Chapter 2 reviews literature related to risk management for the pandemic, studies using Fault Tree or Event Tree, and studies based on quantitative risk analysis. Chapter 3 introduces the methods used in this work, including the Fault Tree, the Event Tree, and the Bow-Tie diagrams. Their applications in risk analysis are reviewed. Chapter 4 presents the data collection and uncertainty assessment.

Chapter 5 illustrates a case study with the proposed method. Chapter 6 presents the results and discussion. Finally, Chapter 7 describes the conclusions and future studies.

Chapter 2 Literature Review

This section presents the literature in three areas related to quantitative assessment for the risk of transmission of COVID-19 based on Fault Tree and Event Tree. The first section reviews the framework of risk management for COVID-19. The second section focuses on research studies about risk analysis incorporating Fault Trees and Event Trees for the pandemic. Finally, the third section reviews research incorporating these two techniques to analyze process safety quantitatively in various industries.

2.1 Risk management for pandemic

The risk management framework illustrates the phases of risk identification, risk classification, risk assessment, risk analysis, risk evaluation, risk treatment, and risk communication, with different emphases (Klucka et al., 2021, p. 2). For example, Kartoglu et al. (2020) developed control strategies for COVID-19 with the ICH-Q9 model which is an approach for Quality Risk Management (QRM), to holistically manage the risk of COVID-19 in four key process groups - Risk Assessment, Risk Control, Risk Communication, and Risk Review. Issa et al. (2021) focused on risk assessment, to determine the critical risk factors for decision-making. Alauddin et al. (2021) emphasized the importance of risk assessment as it guides decision-making in determining risk controls.

When assessing the risk controls of COVID-19, authors usually cluster the risk events and risk controls according to their common themes. Issa et al. (2021) identified 46 risk factors for the transmission of COVID-19 by their probabilities of occurrence and impacts on virus spreading and categorized them into nine groups according to their function. Klucka et al. (2021) classified risks into Known risks, Specific Risks, and Novel risks characterized by volatility, uncertainty, complexity, and ambiguity (VUCA). Brown et al. (2021) identified the barriers with a Bow-Tie diagram and categorized them with the four types of Hierarchy Of Controls (HOC) (from most to least effective): inherently safer design (ISD), passive engineered, active engineered and administrative (Kletz & Amyotte, 2010). Similarly, Alauddin et al. (2021) categorized risk-mitigation strategies for COVID-19 into four main types based on the engineering risk reduction classifications. The four types are defined as follows:

- Inherent - Social distancing, wearing PPE, and hygiene practices;
- Administrative - Contact tracking, increasing universal testing, and quarantine of the exposed cases;
- Passive - Immunity;
- Procedural - Treatment.

The lack of precise data and its uncertainty are central concerns in risk management, especially during the COVID-19 pandemic. Both Klucka et al. (2021) and Alauddin et al. (2021) point out that the uncertainty of data is due to a lack of knowledge and variability in data in the novel situation. Data collection on the pandemic is based primarily on literature reviews, newspaper articles, academic papers, and interviews with COVID-19 experts (Klucka et al., 2021). Issa et al. (2021) use fuzzy logic to handle the uncertainty of data collected from brainstorming sessions. Fuzzy logic is a powerful tool for analyzing linguistic variables from surveys. The authors then rank the risk factors of the COVID-19 spread using the fuzzy logic model and found that social distancing and personal hygiene practices are the most critical risk factors. It can be regarded as a semi-quantitative risk assessment but cannot present the quantitative probabilities of these risk factors on the transmission of COVID-19.

The framework for risk management includes various scientific approaches that identify, assess, analyze, and communicate risks effectively. For example, Kartoglu et al. (2020) used a Swiss Cheese Model approach to analyze the effectiveness of multiple layers of risk controls to reduce the transmission danger of COVID-19. A hole in each layer represents the risk. The work of Brown et al. (2021) uses a similar methodology. The tool is a Bow-Tie analysis embedded with the hierarchy of controls to identify barriers in different priorities. FTA and ETA are probabilistic methods for assessing risks and consequences in various scenarios. ETA can examine all the possible outcomes when considering the scenarios of controls that work or fail. According to Kartoglu et al. (2020), if one knows the probabilities of the barriers, one can estimate the likelihood of the desired outcomes and determine if the controls are adequate. To analyze the risk of the pandemic, Alauddin et al. (2021) created Event Tree diagrams for organizations and individuals based on groups of preventive or mitigating measures, respectively. A detailed description of ETA and FTA can be found in Park & Lee (2009), (Krechowicz (née Gierczak), 2021), and (Bolbot et al., 2018).

Considering the urgency and the lack of robust data, most risk management frameworks for the COVID-19 pandemic have been qualitative. When there is more data available and a demand for more accuracy in the later phases of the pandemic, researchers can develop a risk management framework based on a combination of qualitative and quantitative analysis.

2.2 Risk assessment for pandemic based on FTA, ETA or Bow-Tie diagram

FTA and ETA are risk assessment methods frequently used for analysis to identify and assess threats and consequences in process safety. Bow-Tie diagrams provide a comprehensive illustration of risks and consequences and are used to communicate risks among various stakeholders. From the structure of Bow-Tie diagrams, Fault Trees and Event Trees can be derived. A key objective of the analysis is to facilitate decision-making in response to the pandemic.

A few studies analyze the critical risk factors for the pandemic with FTA to determine critical risk controls in response to the pandemic. For example, Ashraf et al. (2022) developed Fault Trees for qualitative risk analysis to manage process safety risks in process industries. Instead of focusing on the risk of virus transmission, Ashraf et al. (2022) focused on the effects of the pandemic-induced restrictions and disruptions. Interviews with experts were conducted to develop Fault Trees, from which the authors made a variety of recommendations for industrial organizations to prevent safety risks during the pandemic. Fault Trees are used to illustrate the logical relationship between the failures. Liu et al. (2014) applied Fault Tree Analysis for risk assessment for a pandemic at a deeper level. The authors developed a model for risk decision-making based on a Fault Tree to select the most desirable emergency responses to treat a pandemic. The authors did not only illustrate logical relationships, but also quantitatively ranked all risk responses using the FTA. Probabilities of occurrence, costs, and damage results are all quantified for the analysis. Also, Portarapillo & Di Benedetto (2021) proposed a methodology to assess the risk of the pandemic propagation on the purpose of policy containment design. The study starts with simulating the paths of particles when a person sneezes to learn the transmission routes. Then the authors developed a Fault Tree to illustrate the two main transmission routes, droplet and airborne. The respective causes of each transmission route are identified from top down. Both the above two papers use Fault Tree for quantitative analysis, which is further discussed in the next section.

Whereas FTA analyzes the initiating causes, ETA analyzes the consequences. Alauddin et al. (2021) developed several Event Tree diagrams to analyze the severity of consequences of the pandemic for different risk controls from various aspects. An example is the qualitative analysis of the severity of the consequences, whether they are negligible, low, moderate, high, very high, or exceedingly high. The four categories of risk controls are immunity, government interventions, corporate responsibilities, and individual responsibilities. In addition to illustrating the impact on individuals, the ETA also illustrated the impact on communities. Based on the results, an ALARP analysis was conducted to determine whether or not to implement the measures. The authors also developed an Event Tree for quantitative analysis, to be discussed in the next section.

For the studies analyzing both causes and consequences, Fault Tree and Event Tree, or Bow-Tie Analysis are widely used. For example, Sun et al. (2020) analyzed the impact of the pandemic on process safety with FTA and ETA. The authors proposed a comprehensive qualitative and quantitative risk analysis model for hazardous material leakage accidents in the chemical industry to identify and assess the critical risk factors due to the COVID-19 pandemic. To demonstrate the logical relationship between risk factors and potential accident development paths, the authors combined an Event Tree with a Fault Tree. There are 28 basic events identified as risk factors through FTA in the hazardous event of ammonia leakage accidents. Safety barriers are identified and divided into three categories, dispersion prevention, ignition prevention and emergency response barriers. ETA identifies five possible outcomes based on the effectiveness of the barriers: safe, near miss, poisoning accident, explosion accident, and catastrophe. As described in the Methods section, Bow-Tie analysis simplifies and combines a Fault Tree and an Event Tree to show logical relationships. Brown et al. (2021) illustrated the causes, consequences, and barriers to Coronavirus transmission by using Bow-Tie Analysis. The authors developed multiple Bow-Tie diagrams for various receptor groups based on their knowledge of Bow-Tie diagrams' effectiveness for communicating risk. The authors incorporate the hierarchy of controls to identify critical barriers. A barrier analysis is conducted using an inherently safer design (ISD), which has four primary principles (minimization, substitution, moderation, and simplification) (Amyotte & Khan, 2021). These principles are a way to remove or reduce hazards at their source.

2.3 Quantitative FTA, ETA and Bow-Tie analysis in all fields

Various industries use FTA and ETA for quantitative risk analysis (de Ruijter & Guldenmund, 2016a). A Bow-Tie diagram, as a combination tool of Fault Tree and Event Tree, can also be used for quantitative risk analysis based on the methodology of FTA and ETA. In this section, papers using FTA and ETA quantitatively are reviewed.

As reviewed in Section 2.1, Liu et al. (2014) and Portarapillo & Di Benedetto (2021) developed similar frameworks of quantitative FTA by propagating the probabilities of basic events to calculate the overall reliability. They first studied the transmission routes to construct the Fault Tree. Portarapillo & Di Benedetto (2021) reported COVID-19 transmission routes as airborne, droplet direct, and droplet indirect transmissions. Liu et al. (2014) analyzed the routes of H1N1 transmission as detected or unclear. Their methods for determining the probability of each basic event differ slightly. Portarapillo & Di Benedetto (2021) set failure rates for each basic event based on analysis of the situation and expert opinions. And by setting the maximum tolerable risk threshold value, they derived the acceptable probability of failure of each basic event to help policymakers make decisions for operation during the pandemic. Liu et al. (2014) employed indirect elicitation techniques, the Delphi method, and Nominal Group Techinique to collect expert judgments on the probabilities of historic similar events to create a probability matrix. They both performed sensitivity analyses to quantify the effect of a single basic event on the top event, which could be helpful in decision-making.

The numeric output of the FTA and ETA can be analyzed further with As Low As Reasonably Practicable (ALARP) or as low as reasonably achievable (ALARA) principles to determine whether the risk is tolerable. According to HSE UK (The Health and Safety Executive), ALARP is a principle in the management of safety-involved systems. It is usually decided by referring to existing ‘good practice’ or building on good practice for high, complex, or novel situations. Also, if a risk can be reduced but the money, time, or trouble it would take would be disproportionately high, it would not be considered reasonably practicable. In the work of Alauddin et al. (2021), the authors created a simplified Event Tree diagram to compute the fatality rate based on the probability of failure of the barriers - natural recovery, acute care, and intensive care. The outcome is reviewed with ALARP to determine whether the possibility of risk still needs to be reduced.

In terms of data collection, the failure rate for each barrier is mainly computed based on assumptions and literature review. For example, when calculating the fatality rate for acute care, the authors assumed a 90% recovery rate. They argued that many factors might cause a difference in reporting, such as the rate of ICU admissions, which was reported differently among papers, from 5% to 20% of all hospitalized patients. The data would also change over time, so the authors have made assumptions in the calculations. These uncertainties make it essential to provide a solid argument or subjective assessment of the data and assumptions. Likewise, Kumar & Ghosh (2017) studied the results from an integrated ET and FT with ALARA principles to analyze and improve the reliability of the design for mine safety systems. As for the data, the authors assume the failure of each basic event is exponentially distributed. Therefore, failure probability can be calculated using estimated failure rates.

In Section 3.1., the Bow-Tie diagram is introduced as a method predominant for qualitative analysis and risk communication. To implement a Bow-Tie diagram for quantitative analysis, Sheehan et al. (2021) developed a framework for cyber risk classification and assessment combining a quantitative Bow-Tie diagram with a risk matrix. The calculation of threats and consequences is still based on FTAs and ETAs. As for the data, the number of received claims determines the occurrence probabilities for each type of threat. Expert ratings with risk matrices determine the probabilities of each barrier failing based on the median, minimum, and maximum scores. This method is feasible as there are no duplicate and dependent barriers or threats in different branches. To account for the uncertainty of the data, the authors assumed a 20% residual risk and a three-fold improvement in the efficiency of the barriers compared to degradation controls. In quantitative risk assessments, reasonable assumptions can assist in assessing risks considering uncertainty, scarcity, and limitations.

Chapter 3 Methods

3.1 Bow-Tie diagram

Bow-Tie Analysis (BTA) is a risk management tool that connects the causes and consequences of risks. It graphically illustrates how various threats can cause the occurrence of a hazard and what undesired consequences the hazard can lead to (American Institute of Chemical Engineers, 2018). A Bow-Tie diagram is a great visual tool to communicate risks to different audiences. A Bow-Tie diagram consists of a hazardous event under examination in the center, a tree diagram identifying the causes of the hazardous event on the left-hand side, and another tree diagram analyzing the consequences of the hazardous event on the right-hand side. Another key element is barriers on the left side to prevent failure events and on the right-hand side to mitigate the consequences of the hazard. A barrier is a means of preventing unwanted events from occurring. They are designed to mitigate a hazard's impacts or prevent it from manifesting. The failure of the barriers is further analyzed as a degradation factor. All possible controls, called degradation factors, are also identified in order to prevent degradation factors.

In a comprehensive review of the Bow-Tie method (de Ruijter & Guldenmund, 2016b), the authors state that Bow-Ties can be qualitative and quantitative. Researchers and professionals construct qualitative Bow-Ties to illustrate the cause-effect scenarios to communicate the risk to an audience. The Bow-Tie analysis is similar to a combination of Fault Tree Analysis (on the left-hand side) and Event Tree Analysis (on the right-hand side) (Zurheide et al., 2021). The two trees are connected via a top event. In the Event Tree, it is called the initiating event.

A generic Bow-Tie diagram is shown in Figure 3-1. In the center is the undesired event, or the hazard, such as acid spilling from a container in the chemical lab, a car accident, or an infectious disease transmission. The blue rectangles on the left side represent threats of a hazardous event, such as a lack of personal protection equipment or distractions within the lab that may cause the accident of spilling acid. On the right side of the diagram, the mitigation barriers branch out toward the red rectangles, representing the possible consequences of the hazard, such as the burning of a student's face or the destruction of lab equipment. A breakdown of degradation factors and controls is added to each barrier to further analyze its failure.

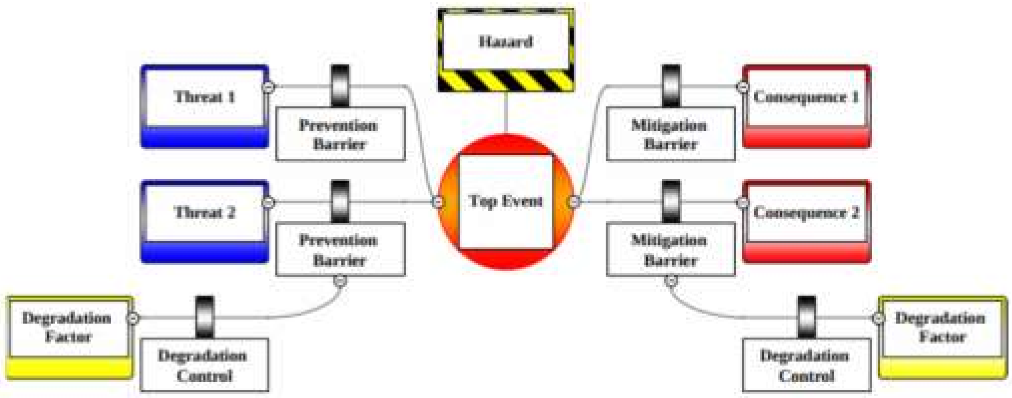


Figure 3-1. A standard Bow-Tie diagram (American Institute of Chemical Engineers, 2018)

3.2. Fault Tree Analysis

3.2.1. Construction of Fault Tree

Fault Tree Analysis (FTA) is a deductive method (usually drawn vertically) that visually models logical interrelationships and investigates potential faults. There can be events associated with component hardware failures, human errors, or other pertinent incidents that can lead to a hazardous event. A Fault Tree consists of three main components: the top event, intermediate and basic failure events, and logic gates. The top event is a potentially undesirable event. Failure events are all possible causes of the top event. An intermediate event, symbolized in rectangular form in the Fault Tree, is a fault event that occurs because of one or more antecedent causes acting through logic gates. A primary event, symbolized in a circle, is a basic initiating fault requiring no further development. Then Boolean gates or logic gates are used to connect and represent the interrelationships between failure events.

The first step of Fault Tree Analysis is to define the system, the scope and boundaries of the analysis, and the assumptions. The top event should be defined precisely. The next step in the construction process is to break down all intermediate events into basic events, starting with the top event. In the Fault Tree Analysis, the negative logic is applied. Therefore, all the events should be stated as malfunctions or failures. After that, logical gates are added to link intermediate events to their basic events based on their logical relationships. The final steps are to analyze the Fault Tree and present recommendations for risk management as the critical output.

The failure of a vehicle to start, for example, is considered a top event in the Fault Tree analysis. By using deductive reasoning, analysts can determine the intermediate causes - a control failure or a fault in the electrical system - either or both of which eventually leads to the top event. Hence, one should use an OR gate to connect them. Below each intermediate event, the causes are decomposed further and connected with appropriate logic gates. The lowest level consists of basic events, which can no longer be decomposed. The Fault Tree Analysis for this example is shown in Figure 3-2.

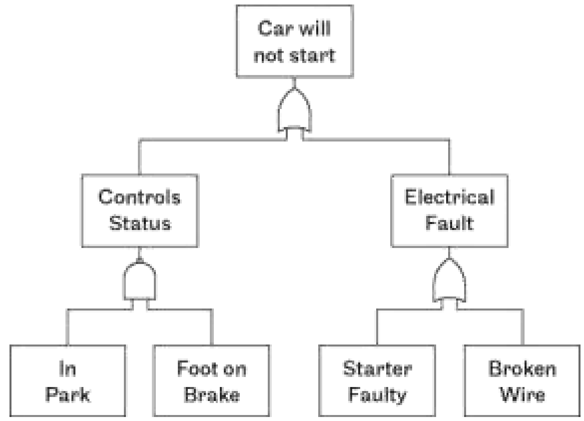


Figure 3-2. A Fault Tree Analysis example of car not starting up (Fred et al., 2015)

3.2.2 Minimal Cut Sets Analysis

An FTA diagram is used to identify a critical concern and its contributing factors. After researchers construct the Fault Tree diagram from the top event to intermediate events and primary events in a logical diagram with Boolean gates, the minimal cut set analysis can be conducted.

The first step is to define the cut sets. A cut set is a set of basic events whose occurrence ensures that the top event occurs. A minimal cut set is the smallest combination of basic events whose simultaneous occurrence leads to the occurrence of the top event (Lambert, 1975). The Top Event occurs if one or more of the minimal cut sets occur. The minimal cut sets can be determined through inspections but larger and more complex Fault Trees rely on algorithms for identifying minimal cut sets. Take the Fault Tree shown in Figure 3-2 as an example; 'In Park' and 'Foot on Brake' (basic events) are connected with the 'AND' gate, so they must both occur to result in the occurrence of the top event. On the right-hand side, 'Starter Faulty' and 'Broken Wire' are connected with the 'OR' gate, so either of these two events can lead to the top event. As a result, the minimal cut sets are ['In Park'] and ['Foot on Brake'] and ['Starter Faulty'] and ['Broken Wire'].

3.2.3 Structural Importance Analysis

An additional quantitative analysis used in this thesis is the Structural Importance Analysis. Structural Importance Analysis was introduced by Birnbaum to assess the influence of each basic event on the Top Event (Lambert, 1975). Events are evaluated based on their position, not on their probability of occurring. When the probability of the basic event is unknown or less certain, Structural Importance Analysis is a good alternative (Wang et al., 2019). The equation used for the Structural Importance Analysis is shown as follows:

$$I^{S_t}(X_i) = \sum_{X_i \in B_r} \frac{1}{2^{n_i - 1}} \qquad (1)$$

where $I^{St}(X_i)$ represents the structural importance of Event X_i, and $i = 1, 2, \ldots$; Br represents the minimal cut sets that include X_i , and $r = 1, 2, \ldots$; and n_i represents the number of all the basic events contained in each minimal cut sets, which includes X_i. For example, if Event X_1 is in three minimal cut sets and each minimal cut set contains three basic events, then the structural importance of X_1 is calculated with the Equation (1), $I^{St} = \frac{1}{2^{3-1}} + \frac{1}{2^{3-1}} + \frac{1}{2^{3-1}} = \frac{3}{4}$. When the structural importances of all basic events are computed, they are compared to determine the most critical ones.

3.2.4 Probability Analysis

The third quantitative analysis requires assessing the probability of each primary fault event, computing the probability of intermediate events, and finally, obtaining the probability of the top event. If the lower events are connected with an AND gate, then the probability of the upper event should be:

$$P = \prod_{i=1}^{n} P_i \qquad (2)$$

Where P_i represents the probability of occurrence of i^{th} input event;

In case of OR logical gate:

$$P = 1 - \prod_{i=1}^{n} (1 - P_i) \quad (3)$$

So using the equations for the example of Fault Tree in Figure 3-3:

$P_1 = P_{11} + P_{12} - P_{11} P_{12}$

$P_2 = P_{21} P_{22}$

$P_{TE} = (P_{111}P_{112} + P_{12} - P_{111}P_{112}P_{12}) (P_{21} (P_{221} + P_{222} - P_{221}P_{222}))$

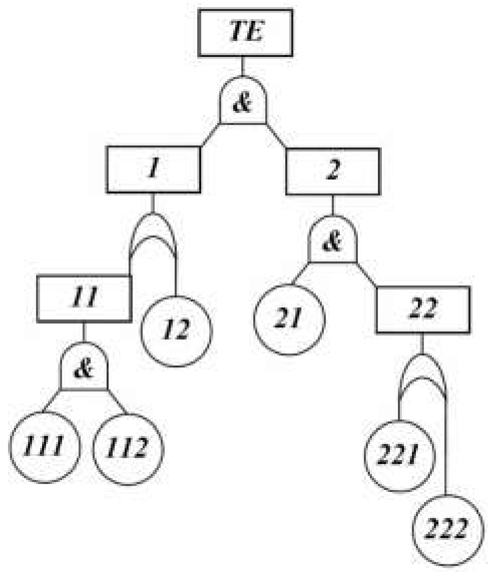


Figure 3-3. Example of the Fault Tree (Pokoradi, 2011a)

By rotating the left side of a Bow-Tie diagram counterclockwise, researchers can get a diagram that resembles a Fault Tree with several differences (American Institute of Chemical Engineers, 2018, p. 12). The top event in FTA is the hazardous event of the Bow-Tie diagram. As the main purpose of a Bow-Tie diagram is to express all threats and barriers graphically, there is no need to connect the barriers and threats with Boolean logic gates, which are imperative in the Fault Tree diagram. An event of failure in a Fault Tree diagram is equivalent to a failure of a barrier in the Bow-Tie diagram.

3.3 Event Tree analysis

Event Tree Analysis (ETA) is a graphical representation (usually drawn horizontally) of the logic model that identifies and quantifies the possible outcomes flowing from an initiating event. It is a technique that uses decision trees and logically develops visual models of all the possible outcomes. It starts from the initiating event and a series of barriers in the sequence of the intervention. Each barrier leads to two branches, success or failure until reaching the final outcomes. Success ends the failure sequence and the outcome is either the risk is removed successfully or is mitigated.

An Event Tree mainly consists of a hazardous event, barriers/controls to mitigate the consequences, and all possible outcomes resulting from whether each installed barrier is functioning or not in chronological order. The initiating event uses dichotomy and progresses to the right, branching progressively.

ETA is widely used both qualitatively and quantitatively. Qualitative ETA can obtain all possible outcomes of each path. For example as shown in Figure 3-4, when examining the consequences of ‘Fire’, ‘Fire’ is the initiating event. Two barriers are identified: the first one is fuel feed to engine stops, and the second one is fire suppression system actuates. Next, consider the two possibilities of each barrier, success or failure. There is minimal damage if the first barrier stops the fire. If it fails, the fire continues. If the second barrier works effectively, the system actuates, and the fire is controlled. Moderate damage might occur. But if it still fails, the fire might cause severe damage. Figure 3-5 shows this accident via an Event Tree.

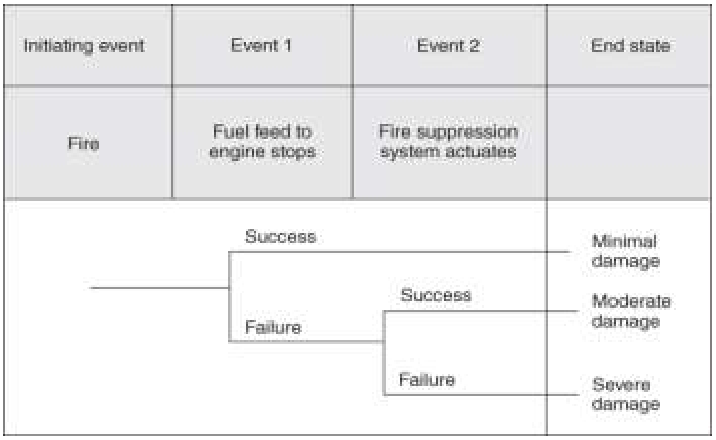


Figure 3-4. An Event Tree diagram for analyzing fire hazard (Event Tree and Fault Tree Analysis - Risk Assessment: Tools, Techniques, and Their Applications, 2012)

In a quantitative ETA, researchers can further formulate the Probabilities of Failure Demand (PFD) of each barrier so the probability of its success equals (1-PFD). Proceeding forward, one is able to figure out the probabilities of each outcome and the probability of the system failing. In the example of 'Fire ignition', probabilities can be assigned to the barriers to derive the probabilities of the end state- minimal, moderate, and severe damage.

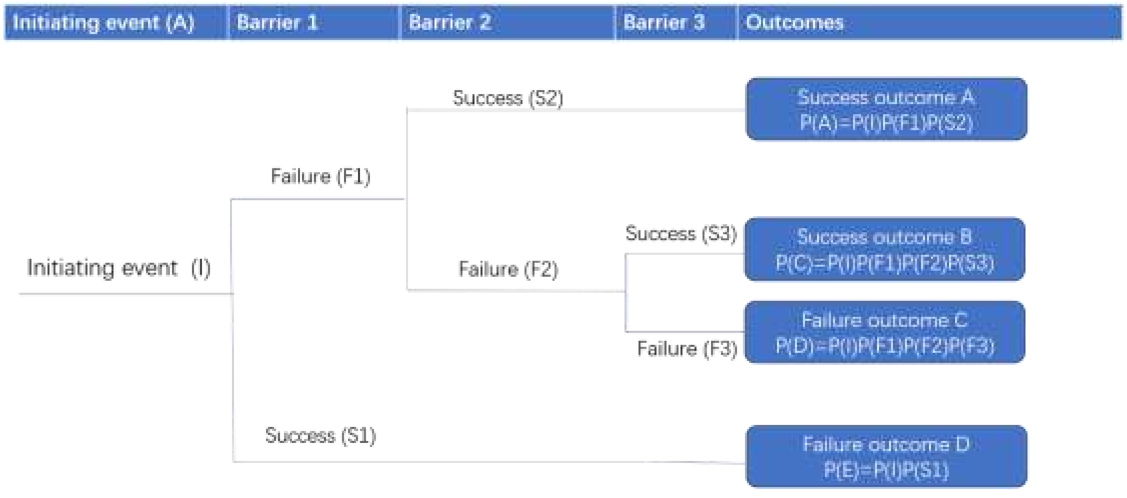


Figure 3-5. An Event Tree example

The Event Tree is similar to the right side of the Bow-Tie diagram which identifies the consequences and mitigation barriers. The major difference between them is that the Bow-Tie does not display the outcome that terminates when a certain barrier prevents the occurrence of a consequence while the Event Tree display all the outcomes whether it leads to a consequence or not.

Chapter 4 Data Collection and Assessment

4.1 Introduction

Data are crucial to support quantitative risk analysis. According to Ipekci et al. (2021), there have been 21,990 publications about SARS-CoV-3 as of May 2020, and it keeps increasing. This vast amount of research has enabled the use of a secondary data collection method by utilizing facts and statistics that have already been published in journals or newspapers.

Understanding of the disease and our data on the pandemic are changing constantly with the evolution and spread of the pandemic. To account for this, data collected for this thesis assumes probabilities based on previous scientific investigations. It is used to predict the impact of each risk control for decision-making. Recent years have seen a rise in concern and discussion about uncertainty treatment in risk analysis, especially in quantitative analyses. Goerlandt et al. (2017) pointed out that limited evidence showed that quantitative risk analysis could provide accurate risk estimates for large-scale systems. It is necessary to make some assumptions about the data underlying complex and uncertain systems to produce results. Risk indexes can be calculated with confidence if enough knowledge is available to support them (Flage & Aven, 2009). Aven (2013) argues that the strength of knowledge should also be evaluated when making decisions based on risk assessments. Lu et al. (2020) stated that sensitivity analysis and strength of evidence are the main methods for identifying critical risk factors in quantitative FT and ET models.

In this chapter, the data sources for the model are introduced, and then assessed. Considering the uncertainties of data in risk assessment, authors use the scientific approach of Strength of Evidence (SoE), which is a qualitative assessment of the data, and sensitivity analysis to analyze the data of COVID-19 transmission in quantitative risk assessment based on the FT and the ET.

4.2 Data Collection

To calculate the probability of the top event in the FT, it is necessary to determine the probability of each basic event. Failure probabilities can be obtained from historical databases, when available, or provided by relevant organizations. However, when there is a lack of historical data in some novel situations, such as the COVID-19 pandemic, other approaches must be used. In this work, the quantitative probabilities of each event are based on the best available information from either journal papers, or from gray literature sources such as office agency white papers. Similarly in the ET, it is necessary to determine the probabilities of each barrier to calculate the probabilities of each consequence. Most of the data are from general surveys or investigations from research papers. The data on vaccination rates is specific to Nova Scotia.

The data are collected as shown in Table 4-1. The failure of immunization includes two subfactors. One is the unvaccinated rate of the population. The data is dependent on the study region. The other is the ineffectiveness of vaccines, which also means the infection rate among the vaccinated population. The failure of universal testing includes false positives and false negatives. False negatives are collected since only false negatives result in virus transmission. Failures of wearing masks, hand-hygiene and physical distancing are hard to determine with their high variabilities for people during different periods. However, specific data have been found for healthcare workers as reported in Table 4-1. The mortality rate of infected patients is another critical piece of data for risk assessment. It also evolves with different stages of the pandemic. With the development of vaccines, a continuously lower mortality rate can be expected. Symptom concealment is another data element that is highly variable. Different researchers are investigating this mainly through surveys. There are statistics on the proportion of symptomatic and asymptomatic patients among all infected people.

Table 4-1. List of risk events

No	Description	Probability	Source
1	Immunization for patients that are vaccine-eligible	Second dose: 36%, 24-45% Third dose: 61%, 56-65% (against severe outcomes: 95%, 87-98%)	(Andrews et al., 2022) (Buchan et al., 2022)
2	Rate of population vaccinated	Population fully vaccinated in NS: two doses:84.93%; three doses: 50.72%	(COVID-19 Tracker Canada -Nova Scotia Vaccination Tracker, n.d.-b)
3	Universal testing failure	False Negative Rate: 9.3%, 1.5-17%;	(Kanji et al., 2021)
4	Missed Masks/ Cleaning/ Handwashing/Physical distancing	Missed hand washing: 5% PPE absence: 5% Physical distancing: 17%	(Portarapillo & Di Benedetto, 2021, p. 10) Handwashing: (Makhni et al., 2021)
5	Mortality for general patients admitted to the hospital (excluding critical care-only studies)	11.5%	(Macedo et al., 2021)
6	Mortality of critical illness treated in ICU, therapeutics and supportive management (e.g. ventilators)	40.5%	(Macedo et al., 2021)
7	Patients not honest about symptoms or travel histories	34%	(O'Connor & Evans, 2022a)
8	Asymptomatic rate of COVID patients	35.1% (95% CI: 30.7 to 39.9%)	(Sah et al., 2022)

No	Description	Probability	Source
9	Symptomatic rate of COVID patients	64.9% (95% CI: 60.1 to 69.3%)	(Sah et al., 2022)
10	Infected person of IWK staff	7%	(COVID-19 Infections among People Working in Healthcare Settings - Canada.Ca, 2022)

4.3 Data Assessment

The risk events are defined through quantitative probabilities shown in the last section. It is also necessary to consider issues about how to analyze, describe, and communicate uncertainty in risk analysis to find critical risk factors for decision-making (Goerlandt & Montewka, 2015). In this subsection, the method of assessing data qualitatively and sensitivity analysis are introduced to deepen our understanding of the data used in risk assessment.

Probabilities assigned to each event in Table 4-1 are knowledge-based, which means they depend on the best available evidence. This probability reflects the degree of belief of the assigner. However, the values assigned can be judgemental and subjective. Assessing the knowledge's strength with an analytic framework reflects the probability's 'quality' or 'goodness' and overall uncertainties.

4.3.1 Strength of Evidence (SoE)

The strength of evidence has been widely assessed in health care to evaluate different designs of medical interventions. Evans (2003) stated that the aim of grading the strength of the evidence was to use the best available evidence and indicate the confidence the stakeholders could have in the research. To assess the strength of evidence in risk analysis, Goerlandt & Reniers (2016) suggested the approach of strength-of-evidence assessment.

This method is used in this thesis to describe and communicate uncertainty and key aspects of evidence since it is more understandable in an application (Lu et al., 2020). The four main aspects of assessing the evidence of risk events are data, model, judgment, and assumptions (Goerlandt & Reniers, 2016). Figure 4-1 outlines the criteria of assessment.

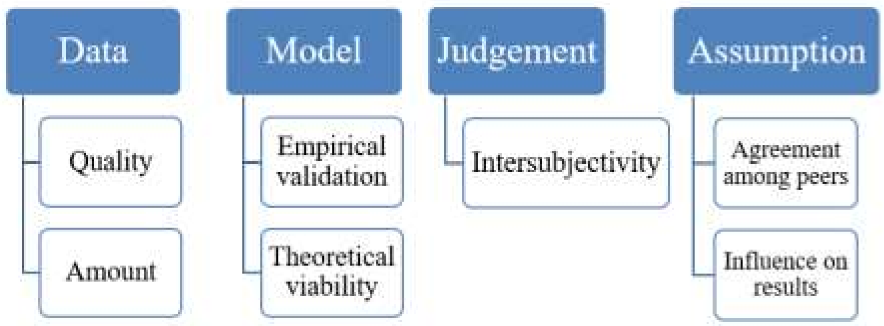


Figure 4-1 SoE Assessment criteria (Goerlandt & Reniers, 2016)

According to the framework proposed by Goerlandt & Reniers (2016), data are firstly assessed based on their quality and amount. Data that meets the criteria for strong evidence should have few errors, high accuracy, reliability, and many relevant data available. Models are then assessed based on their degree of empirical validation and theoretical viability. Besides, when the evidence consists of judgments, it is assessed based on peer support. If it consists of assumptions, it is assessed based on agreement and impact on results. Strong evidence should have limited influence on results, based on sensitivity analysis, and widely agreed upon by peers.

To assess the four aspects of each risk event, assessors can categorize them into five levels: low, low-medium, medium, medium-high, and high. For the overall strength, as suggested (Goerlandt & Reniers, 2016), the decision-makers rather than the analysts should make the judgment. This is because certain decision-makers weigh data and models more than judgments and assumptions, and vice versa (Glendon et al., 2006).

Tables 4-2 and 4-3 present evidence ratings for data and model evidence types, and judgments and assumptions evidence types, respectively. In assessing data, quality and amount are taken into account. High-quality data have the following characteristics: few errors, high accuracy, and reliable data source, whereas models are assessed based on their empirical validation and theoretical variability.

Table 4-2 Criteria for SoE rating for data and model evidence types (Goerlandt & Reniers, 2016)

Evidence type	Strong evidential characteristics	Weak evidential characteristic
Data		
Quality	Low number of errors	High number of errors
	High accuracy of recording	Low accuracy of recording
	High reliability of data source	Low reliability of data source
Amount	Much relevant data available	Little data available
Models		
Empirical validation	Many different experimental tests performed	No or little experimental confirmation available
	Existing experimental tests agree well with model output	Existing experimental tests show large discrepancy with model output
Theoretical viability	Model expected to lead to good predictions	Model expected to lead to poor predictions

Table 4-3 Criteria for SoE rating for judgement and assumption evidence types (Goerlandt & Reniers, 2016)

Evidence type	Strong	Medium	Weak
Judgments	Broad intersubjectivity: more than 75% of peers support the judgment	Moderate intersubjectivity: between 25% and 75% of peers support the judgment	Predominantly subjective: less than 25% of peers support the judgment
Assumptions			
Agreement among peers	Many (more than 75%) would have made the same assumption	Several (between 25% and 75%) would have made the same assumption	Few (less than 25%) would have made the same assumption
Influence on results	The assumption has only local influence	The assumption has wider influence in the analysis	The assumption greatly determines the results of the analysis

Detailed information about the evidence and qualitative SoE assessment for this study is listed in Table 4-4. To visualize the levels of SoE, they are illustrated in five colors: Low in red, Low-medium in orange, Medium in yellow, Medium-high in light green, and High in dark green. Different features of the events are rated, and the minimum value of all categories is considered the overall SoE. In other words, the weakest feature determines the final SoE rate (Lu et al., 2020). When making the ratings, a single analyst approach was used in which the author took the best evidence support for each aspect of the model and took the minimum as the overall SoE.

Table 4-4 SoE rating for the data

No	Description	Data		Model		Judge-ment	Assump-tion	SoE
		Quality	Amount	Empirical validation	Theoretical viability			
1	Immunization for patients that are vaccine-eligible							
2	Rate of population vaccinated							
3	Universal testing failure							
4	Missed masks/cleaning/physical distancing							
5	Mortality for general patients admitted to hospital (excluding critical care-only studies)							
6	Mortality of critical illness treated in ICU							
7	Patients not honest about travel history or symptoms							
8	Asymptomatic rate of COVID-19 patients							
9	Symptomatic rate of COVID-19 patients							

No	Description	Data		Model		Judge-ment	Assump-tion	SoE
		Quality	Amount	Empirical validation	Theoretical viability			
10	Infection rate of healthcare workers							

Low	Low-Medium	Medium	Medium- High	High

Using the method of SoE assessment, the data shown in Table 4-4 are assessed. Two are rated as low-medium strength of evidence. A crucial problem is the lack of data which is because the fact that since COVID-19 only appeared about two years ago, and it was hard to track data in the early phase without much knowledge, and research still took time to complete. Also, some events, like hand hygiene and concealing symptoms, are difficult to track. Surveys are a common way to investigate them, and the results may vary by region.

With the tracking system established and numerous researchers exploring facts and numbers of COVID-19, data such as the total mortality rate and vaccination rate are well-tracked daily. Other important parameters like the rate of false negatives of testing have also been studied thoroughly since such cases were discovered. Therefore, those are rated as strong evidence. Overall, the data are valuable for the case study because they are mostly collected from peer-reviewed academic papers in scientific journals, and the amount is reasonable. However, given the dynamic nature of the pandemic, the data should still be updated regularly, especially when new vaccines or virus variants emerge.

4.3.2 Sensitivity Analysis

As data can be uncertain, sensitivity analysis of FTA and ETA are necessary tasks. Sensitivity analysis involves determining the variability or inaccuracy of results as an outcome of the collective variation of the parameters and assumptions used to define the results (Pokoradi, 2011b). Sensitivity analysis investigates the effect of changes in numerical parameters (i.e., probabilities) on the output parameters (Lu et al., 2020). High-sensitivity parameters affect reasoning results more significantly, as expected. Identifying them can support decision-making on an effective and efficient allocation of effort and resources on particular parameters for further risk controls.

For FTA, sensitivity analysis should come after Minimal Cut Sets (MSC). By performing a sensitivity analysis, how the uncertainty in the events identified by MSC impacts the Fault Tree's top event and the consequences in the Event Tree can be determined. For example, if rough estimates are used to calculate reliability, the calculated reliability may be of limited value if small changes in basic event probabilities can significantly change system reliability (Ruijters & Stoelinga, 2015). If the overall reliability is sensitive to the failure rate of an event, this event could be a good candidate for improvement. Typically, sensitivity analysis involves analyzing the variables at different value ranges (Ruijters & Stoelinga, 2015). Thus, the sensitivity of the basic events in the Fault Tree and Event Tree to the probability of the top event can be computed by increasing and reducing their failure rates.

In this thesis, sensitivity analysis is completed for all fault events in the case study. The results combined with SoE are presented in Chapter 6 to determine the most uncertain fault events.

Chapter 5 Case study

In this section, by using the risk management framework, the risks of COVID-19 transmission in the acute care center of IWK Health Centre are assessed to illustrate the feasibility of the FTA and ETA-based quantitative risk assessment method. First the case is introduced. Following that, the author uses the aforementioned methods to assess the risk and prioritize measures to control the transmission. This section also analyzes the data to provide a supplement for decision-making based on sensitivity and strength of evidence.

5.1 Introduction of the case

IWK Health Centre is the largest pediatrics hospital and trauma center in Atlantic Canada that provides care to maritime youth, children, and women from Nova Scotia, New Brunswick, and Prince Edward Island. As a key piece of data for this paper, Turner (2022) has developed a series of Bow-Tie diagrams with experts of IWK illustrating all the threats, consequences, and barriers identified for the hazard of COVID-19 transmission for various receptor groups at the IWK Health Centre. This study builds on the work of Turner (2022) by adding quantitative aspects.

5.2 Risk Identification - Construction of FT and ET

5.2.1 Fault Tree Construction

Firstly, it is necessary to define the system or scope of the analysis. The authors study the Bow-Tie diagram of a patient or family member at the IWK Health Centre in acute care contracting COVID-19 (Turner, 2022) to understand the functional interconnections and measures of the system (see Figure 5-1). The flowchart displays the steps taken when a patient visits the acute care centre of IWK during the pandemic, which helps to identify the risk and controls. Before arrival, patients should make an appointment if possible, and there is a pre-screening to check whether the patient has had exposure to the virus or traveled to any high-risk places. There is door screening to check whether the patient has symptoms upon arrival, and masks are required on site. If admission is needed, testing for COVID is required.

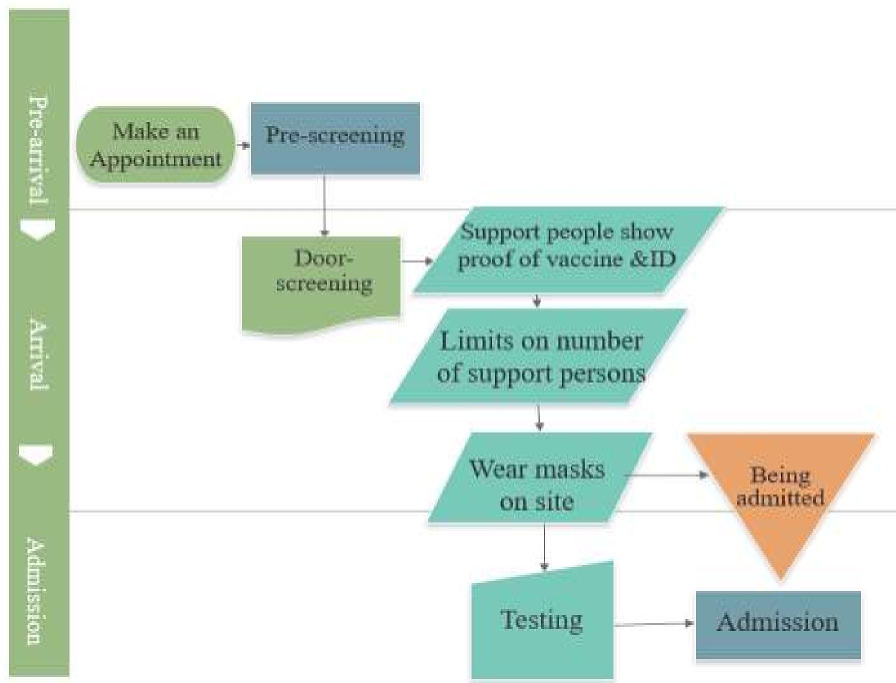


Figure 5-1 Highlevel Swimlane Flowchart of IWK patient flow during the pandemic

In the framework of risk assessment, risk identification is a core step. The authors construct the Fault Tree and Event Tree by identifying fault events and consequences converted from the Bow-Tie diagram. As introduced in Section 3, the top event in FTA is the hazardous event of the Bow-Tie diagram. A fault event in the Fault Tree is equivalent to the failure of a barrier in the Bow-Tie diagram. With the top event on the top of the Fault Tree, assessors understand the system thoroughly to identify the causes of transmission from the top down and their logical interrelationships.

Referring to the Bow-Tie diagram for the crucial threats, barriers, degradation factors, and consequences, the authors convert them to corresponding elements in the Fault Tree and Event Tree to quantify. See Figure 5-2 for a Bow-Tie diagram showing six threats and twelve consequences identified by (Turner, 2022). Asymptomatic and symptomatic patients, support people, IWK team members, contractors, and the public are identified as potential sources of transmission. (Turner, 2022) also categorized and assessed the barriers for each group in acute care at the IWK Health Centre concerning the Hierarchy of Controls: Inherent, passive-engineered, active-engineered, and administrative. In this study, the author sought to quantify the common barriers of most threats and consequences to assess the overall risk level and prioritize risk controls for the groups- asymptomatic, symptomatic patients, and the staff. Risk assessors then classify all events into middle/intermediate events and basic events. It is an intermediate event when further investigation is required to identify its causes. For example, in the event of 'Failure of Immunization', assessors can further identify its causes as 'Failure of taking the vaccine' or 'Ineffectiveness of the vaccine'. Consequently, 'Failure of Immunization' is an intermediate event, while 'Failure of taking vaccine' and 'Ineffectiveness of vaccine' are basic events. The final step is to connect the events with appropriate logical gates. Either of the lower events causes the intermediate event of 'Failure of Immunization' to occur. Therefore, the events should be linked with the 'OR' gate. If the intermediate event or the top event occurs only if all its lower event occurs, then the events should be linked with the 'AND' gate.

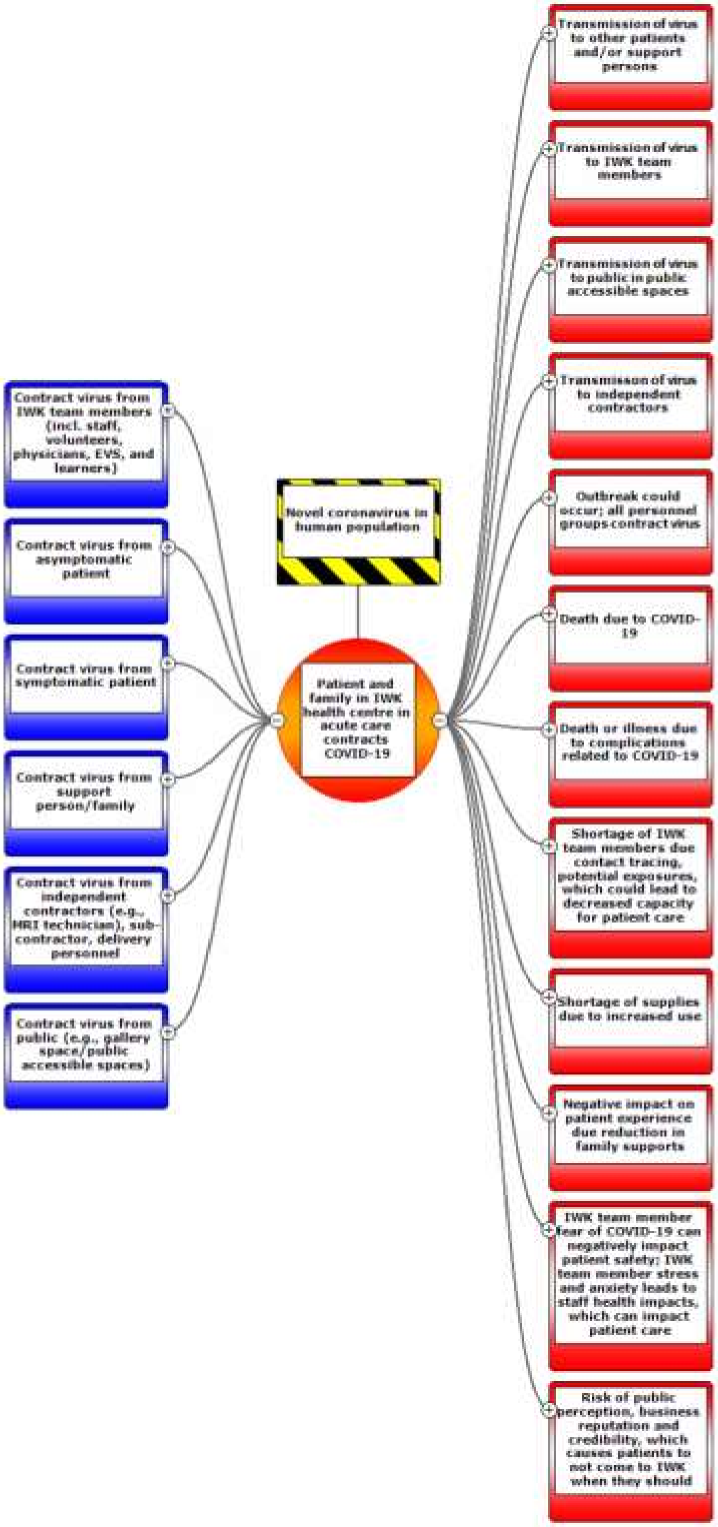


Figure 5-2. Excerpt of Bow-Tie diagram representing a patient or family member at the IWK Health Centre in acute care contracting COVID-19 (Turner, 2022)

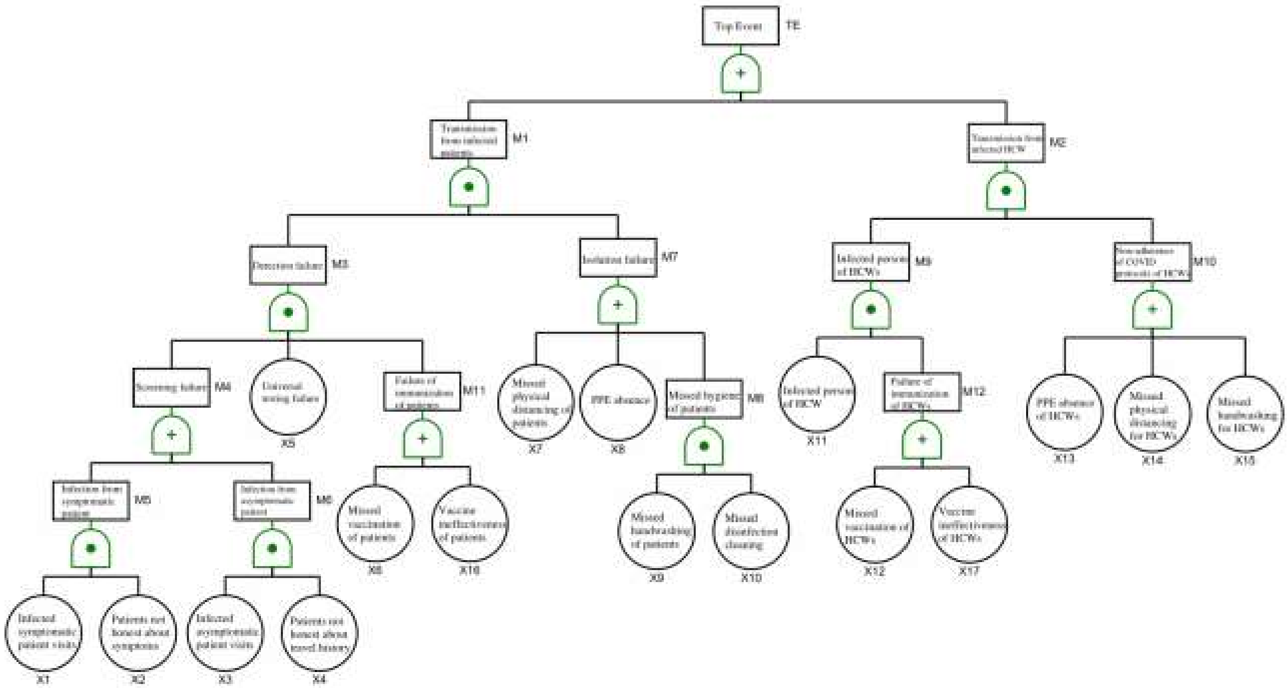


Figure 5-3, Fault Tree Diagram for the COVID-19 Infection in IWK acute care

The FT was developed as shown in Figure 5-3 with the top event 'COVID-19 infection among patients and staff in IWK acute care'. Two transmission routes were identified at the first level of intermediate events: newly infected persons from patients and newly infected IWK health care workers (HCW). As discussed in Section 2, barriers and degradation controls of the Bow-Tie diagram can be converted to failure events in the Fault Tree. Based on the Bow-Tie diagram, which contains all the existing measures, the universal ones are selected and clustered for the FTA. For example, the following barriers of the Bow-Tie were not very applicable for the quantitative study and therefore not included in the FT: 'Minimize the number of people caring for the patient at a given time', 'Limited public access to health centre', 'Encourage patients and family/support persons to use electronic modes of communications', etc. In the Bow-Tie, they were all included to communicate ways of preventing failure, but they were eliminated when constructing FT as they were unquantifiable. 'AND' gates and 'OR' gates are represented with '·' and

‘+’ respectively.

In the FT, the risk controls are classified into three categories. The first one is detection. Measures of detection include self-monitoring, screening, and universal testing. The other categories are isolation and immunization. The immunization barrier in the Bow-Tie diagram only applied to IWK HCW since proof of vaccination was not required originally. Vaccination of other groups was out of the control of the IWK. However, when developing the FT for the research, more than eighty percent of Canadian residents had taken at least one vaccination dose. Therefore, this event applied to both groups in the study.

The BT diagram (Figure 5-2) has three other threats which are contracting virus from support persons, contractors, and the public. They were not added to the FT as they were considered equivalent to patients or HCWs from a data point of view. However, if an assessor finds it necessary to perform quantitative analysis for these specific groups, they can be added to the FT.

Events of the FT diagram (Figure 5-3) are listed in Table 5-1. ‘ TE ’ refers to the Top Event. The events whose names start with ‘M’ are intermediate events. Basic events' names begin with ‘X’, and each is linked to an intermediate event by a logical gate. All events are stated as a failure since they are fault events.

Table 5-1, The meanings of symbols

Name	Event description
TE	A Patient or family member in IWK Health Centre in acute care contracts COVID-19
M1	Transmission from infected patients
M2	Transmission from infected HCW
M3	Detection failure
M4	Screening failure
M5	Infection from symptomatic patient

Name	Event description
M6	Infection from asymptomatic patient
M7	Isolation failure
M8	Missed hygiene of patients
M9	Infected person of HCW
M10	Non-adherence of COVID protocols of HCW
M11	Failure of immunization of patients
M12	Failure of immunization of HCW
X1	Infected symptomatic patient visits
X2	Patients not honest about symptoms
X3	Infected asymptomatic patient visits
X4	Patients not honest about travel history
X5	Universal testing failure
X6	Missed vaccination of patients
X7	Missed physical distancing of patients
X8	PPE absence
X9	Missed handwashing of patients
X10	Missed disinfection cleaning
X11	Infected person of HCW
X12	Missed vaccination of HCW
X13	PPE absence of HCW
X14	Missed physical distancing for HC workers
X15	Missed handwashing for HC workers
X16	Vaccine ineffectiveness of patients
X17	Vaccine ineffectiveness of HCW

5.2.2 Event Tree Construction

The right-hand side of the Bow-Tie diagram corresponds to an Event Tree. The initiating event of the Event Tree matches the hazardous event in the Bow-Tie diagram. To analyze the mitigation barriers and consequences quantitatively, the most common and effective barriers are selected and collected their probabilities as listed in Table 5-2. Using a Bow-Tie diagram, Turner (2022) analyzed the transmission in different receptors and other economic and reputational risks. This quantitative analysis, however, focuses on fatalities resulting from transmissions as the most critical consequence from the author's perspective. The focus can be adjusted according to the requirements of stakeholders. Figure 5-4 represents the Event Tree diagram for the top event.

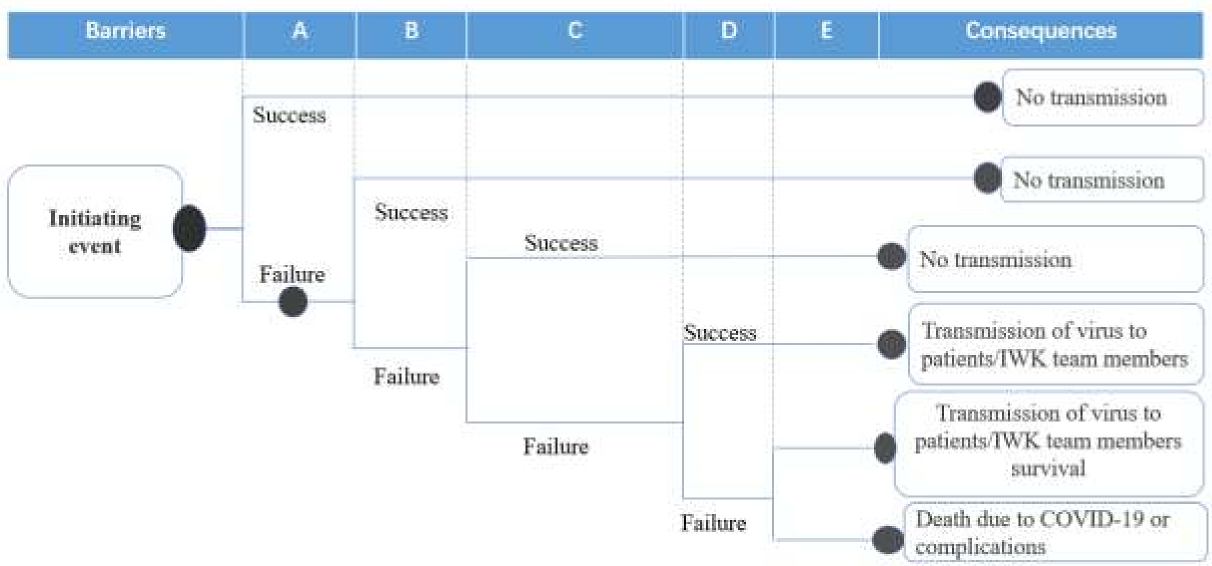


Figure 5-4. Event Tree diagram

Table 5-2 Mitigation barriers of the Event Tree

Label	Barrier
A	Immunization of patients that have taken vaccine
B	Universal Testing for identification and isolation
C	Masks/Handwashing (Individual responsilities)
D	Hospitalization
E	ICU, therapeutics and supportive management (e.g. ventilators)

5.3 Risk Analysis

The next phase in risk assessment is to analyze the risks identified. Based on the structure and logical relationships of the events in constructed FTA and ETA, the authors conduct a qualitative analysis first. Then, a quantitative analysis is conducted with the data collected to provide input on which risk controls are critical and require further treatment.

5.3.1 Fault Tree Analysis

To find the structural representation of the top event in terms of the total 17 basic events, the authors identify the minimal cut sets using Boolean algebra operations and analyze them with the equation of structural importance. After all minimal cut sets are identified, the occurrence probability of MSCs and the system failure probability $P_{top\ event}$ can both be calculated. The quantification allows for determining the reliability parameters of interest for the system improvement. They can also be used to compute the frequency of each transmission route exposure as the critical importance analysis.

Based on logical relationships, logical equations (1) and (2) can be used to calculate the probability of multiple persons being transmitted from infected patients and multiple persons being transmitted from infected IWK staff. For example, the probability of M1 (contracting the virus from infected patients) is calculated by aggregating the probabilities of intermediate events below it, M_3 and M_7. M_3 further breaks down into M_4, M_{11}, and X_5 until it reaches the level of basic events. Events X_1 and X_2 are connected with an AND gate, so the probability formulation of their upper intermediate event is (X_1*X_2). In the case of events connected with OR gates as X_7 and X_8, the formulation is written as (X_7+X_8). The '*' and '+' do not mean multiplication and addition but refer to their logical relation where '*' represents AND and '+' represents OR.

$$X_5*(X_1*X_2+ X_3*X_4) *(X_6+X_{16}))*((X_7+X_8)+(X_9*X_{10})) \quad (4)$$

$$(X_{13}+X_{14}+X_{15})*X_{11}*(X_{12}+X_{17}) \quad (5)$$

Table 5-3 Basic events and their probabilities of failure

Name	Event description	Probability
X1	Infected symptomatic patient visits	34-55% (O'Connor & Evans, 2022b)
X2	Patients not honest about symptoms	35.1% (95% CI: 30.7 to 39.9%) (Sah et al., 2021)
X3	Infected asymptomatic patient visits	64.9% (95% CI: 60.1 to 69.3%) (Sah et al., 2021)
X4	Patients not honest about travel history	16% (Taylor & Asmundson, 2021)
X5	Universal testing failure	9.3% (95% CI 1.5–17.0%) (Kanji et al., 2021)
X6	Missed vaccination of patients	0.11 (COVID-19 Tracker Canada - Nova Scotia Vaccination Tracker, 2022)
X7	Missed physical distancing of patients	15.6-44.9% (Ga, 2021)

Name	Event description	Probability
X8	PPE absence	53%, 95% CI 25% to 68% (Downsides of Face Masks and Possible Mitigation Strategies: A Systematic Review and Meta-Analysis | BMJ Open, 2020)
X9	Missed handwashing of patients	10% (Scotia, 2021)
X10	Missed disinfection cleaning	5% (Portarapillo & Di Benedetto, 2021)
X11	Infected person of HCW	Second dose: 64%, 55-76% (Buchan et al., 2022)
X12	Missed vaccination of HCW	15% (Neuwirth et al., 2020)
X13	PPE absence of HCW	17% (Keller et al., 2022)
X14	Missed physical distancing for HC workers	91% per patient contact (Hand Hygiene - Government of Nova Scotia, Canada, 2022)
X15	Missed handwashing for HC workers	91% per patient contact (Hand Hygiene - Government of Nova Scotia, Canada, 2022)
X16	Vaccine ineffectiveness of patients	5.12% (Fourth Update on Vaccine Mandates - Government of Nova Scotia, Canada, 2021)
X17	Vaccine ineffectiveness of HCW	5.12% (Fourth Update on Vaccine Mandates - Government of Nova Scotia, Canada, 2021)

5.3.2 Event Tree Analysis

The procedure of Event Tree Analysis is similar. Instead of identifying causes, the consequences of the initiating event (the top event in the Fault Tree) under the failure of each barrier (Figure 5-4) are identified. The barriers are mapped from those on the right-hand side of the Bow-Tie diagram. The first barrier is the immunity from vaccines. The second barrier is mainly intervention of the health care centre, namely universal testing. The next barrier is individual responsibilities, including wearing masks and handwashing.

If these barriers work, there is no transmission among patients and staff. If these all fail, transmission occurs, and the next is mitigative barrier-hospitalization. And if it is severe, the last barrier is the treatment of the patients in the ICU. If the last one fails, the most severe consequence is death due to the virus or complications.

With the probability of the initiating event calculated through the FTA and the failure probabilities of each barrier (see Table 5-4), assessors can calculate the probability of each consequence using the equations shown in Figure 3-3. The probabilities of each consequence are evaluated with the ALARP principle for decision-making.

Table 5-4. PFD of barriers of the Event Tree

Label	Barrier	Probability	Source
A	Immunization of patients that have taken vaccine	Second dose: 36%, 24-45% Third dose: 61%, 56-65% (against severe outcomes: 95%, 87-98%) Population fully vaccinated in NS: two doses:84.935%; three doses: 50.729%	(Buchan et al., 2022) (COVID-19 Tracker Canada - Nova Scotia Vaccination Tracker, 2022)
B	Universal testing for identification and isolation	False Negative Rate: 9.3%, 1.5-17%; Physical distancing	(Kanji et al., 2021)
C	Masks/ Handwashing	Missed handwashing: 5% PPE absence: 47%	(Portarapillo & Di Benedetto, 2021, p. 10)
D	Hospitalization	Mortality for general patients admitted to the hospital (excluding critical care-only studies): 11.5%	(Macedo et al., 2021)

Label	Barrier	Probability	Source
E	ICU, therapeutics and supportive management (e.g. ventilators)	Mortality of critical illness: 40.5%	(Macedo et al., 2021)

5.3.3 Sensitivity Analysis

In this study, the author used most commonly used form of Sensitivity Analysis(SA) which is the one-way method (Qian & Mahdi, 2020). It works by changing one factor within a range, holding all other factors unchanged, and observing the change in the output. For some data collected, there is a range within the confidence interval, so their SA can be performed accordingly. Then assessors can find the percentage change in the output and the percentage change in the input written as follows:

Sensitivity = Percentage change in output / Percentage change in input.

The probability of the top event only provides one aspect of the risk of the system. Sensitivity analysis is a consolidated procedure of FTA and ETA to identify the weakest parts of the system. In other words, sensitivity analysis helps identify the basic events whose failure contributes most to the likelihood of occurrence of the top event. Strengthening the weakest link can improve system reliability. In this study, the author performs the sensitivity analysis by changing the probabilities of basic events within their possible ranges. This work analyzes how the uncertainty of the probabilities of basic events (input) would impact the top event (output).

5.4 Risk evaluation with ALARP

In risk assessment, the third phase is risk evaluation to determine whether the risk is acceptable or requires further controls. Based on the numeric outputs of the risk analysis, risk evaluation guides decision-making within the organization about which risks should be further controlled and identifies the priorities for implementing risk controls depending on the risk tolerance and objectives of the organization.

ALARP (As Low As Reasonably Practicable) is a widely used principle for determining criteria for acceptable risks. By comparing the results of the previous phases of Fault Tree and Event Tree Analysis and the thresholds, stakeholders can decide whether further action to reduce the current level of risk is needed. The ALARP principle recognizes that there are three broad categories of risks. First, there are negligible risks, which most people accept. As for tolerable risks, regulators would prefer to avoid them, but they are acceptable given the benefits obtained by accepting them. There are also unacceptable risks, which have such high-risk levels that they must be reduced. Determining criteria to evaluate risks is extremely important. By using these parameters, regulators or decision makers can further define how they approach assessing the risks and responding to them appropriately.

Figure 5-5. ALARP principles (Fiorentini, 2022)

Take the pipeline industry as an example, thresholds have been established about the annual probability of death for an individual:

The maximum threshold, between tolerable and unacceptable zones, is set at 10^{-3} for employees, 10^{-4} for the population in the vicinity of an existing site, and 10^{-5} for this population in the case of a new site; A site's lower threshold, between acceptable and tolerable zones, is set at 10^{-6} for the surrounding population. If the regulators of an organization or the industry have specific risk tolerance, then that should be reviewed and used (Cross-Country Pipeline Risk Assessments and Mitigation Strategies, 2018).

Chapter 6 Results and Discussion

6.1 Fault Tree Analysis

6.1.1. Minimal Cut Sets Analysis

From the minimal cut sets analysis on the Fault Tree, 18 minimal cut sets are found. They contain the minimum sets of events necessary to cause the top event. In some studies, researchers simplify the original Fault Tree to a new one with only MCS for quantitative analysis. The minimal cut sets of this Fault Tree were identified, as:

$B_1=\{X_1X_2X_5X_6X_7\}$; $B_2=\{X_1X_2X_5X_6X_8\}$; $B_3=\{X_1X_2X_5X_6X_9X_{10}\}$;

$B_4=\{X_1X_2X_5X_7X_{16}\}$; $B_5=\{X_1X_2X_5X_8X_{16}\}$;$B_6==\{X_1X_2X_5X_9X_{10}X_{16}\}$;

$B_7=\{X_3X_4X_5X_6X_7\}$; $B_8=\{X_3X_4X_5X_6X_8\}$; $B_9=\{X_3X_4X_5X_6X_9X_{10}\}$;

$B_{10}=\{X_3X_4X_5X_7X_{16}\}$; $B_{11}=\{X_3X_4X_5X_8X_{16}\}$; $B_{12}=\{X_3X_4X_5X_9X_{10}X_{16}\}$;

$B_{13}=\{X_{11}X_{12}X_{13}\}$; $B_{14}=\{X_{11}X_{12}X_{14}\}$; $B_{15}=\{X_{11}X_{12}X_{15}\}$;

$B_{16}=\{X_{11}X_{13}X_{17}\}$; $B_{17}=\{X_{11}X_{14}X_{17}\}$; $B_{18}=\{X_{11}X_{15}X_{17}\}$;

X_is represent the basic events listed in Table 5-3;

B_js represent the i^{th} Minimal Cut Set of the Fault Tree. B_1 to B_{12} are from the branch of contracting the virus from infected patients, and B_{13} to B_{18} are from the other branch, of contracting the virus from infected HCWs.

6.1.2 Structrual Importance Analysis

After solving Eq.(1), the structural importance of all the basic events was illustrated as follows:

$I^{St}(1) = I^{St}(2)= I^{St}(3) = I^{St}(4) = I^{St}(6) = I^{St}(16) =1/2^{5-1}*4+1/2^{6-1}*2=9/32$

$I^{St}(5) = 1/2^{5-1}*6+1/2^{6-1}*3=15/32$

$I^{St}(7) =I^{St}(8) = 1/2^{5-1}*4= 0.25$

$I^{St}(9) = I^{St}(10) = 1/2^{6-1}*4=1/8$;

$I^{St}(11) = 1/2^{3-1}*6=1.5$; $I^{St}(12) = I^{St}(17) =1/2^{3-1}*3=0.75$;

$I^{St}(13) = I^{St}(14) = I^{St}(15) = 1/2^{3-1}*2=0.5$;

Therefore, the structural importance of all the basic events was arranged in the following order:

$I^{St}(11) > I^{St}(12) = I^{St}(17) > I^{St}(5) > I^{St}(13) = I^{St}(14) = I^{St}(15) > I^{St}(1) = I^{St}(2) = I^{St}(3) = I^{St}(4) = I^{St}(6) = I^{St}(16) > I^{St}(7) = I^{St}(8) > I^{St}(9) = I^{St}(10)$

Based on the structural analysis, the study finds that the transmission route of IWK staff members has a higher probability of causing the top event. Infected persons among HCWs (X_{11}) are the most critical event. Second, the vaccination rate (X_{12}) and effectiveness of the vaccine among HCWs (X_{17}) are crucial. A key aspect of overall risk control is compliance with COVID-19 protocols among HCWs (X_{10}). The other transmission route, which is from visiting patients, is the false negative results of universal testing (X_5), and adherence to the hygiene protocols have the most impact on the transmission among patients. Conducting multiple tests on admitted patients helps reduce the risk of false negative results.

6.1.3 Probability of the top event

According to the logical expressions, the formulas for calculating probabilities of the two highest level of intermediate events and the top event are constructed as below.

$$P_1 = x_5*(x_1*x_2+x_3*x_4- x_1*x_2*x_3*x_4)*(x_6+x_{16}-x_6*x_{16})*((x_7+x_8-x_7*x_8+x_9*x_{10}- (x_7+x_8-x_7*x_8)*x_9*x_{10})) \quad (6)$$

$$P_2 = (x_{13}+x_{14}+x_{15}-x_{13}*x_{14}-x_{13}*x_{15}-x_{14}*x_{15}+x_{13}*x_{14}*x_{15})*x_{11}*(x_{12}+x_{17}-x_{12}*x_{17}) \quad (7)$$

$$P_{Top\ event} = P_1 + P_2 - P_1 * P_2 \quad (8)$$

Where;

- P_1 represents the probability of contracting the virus from infected patients;
- P_2 represents the probability of contracting the virus from infected HCWs;

- $P_{Top\ event}$ represents the probability of Top Event- Transmission in the acute care centre;
- x_is represent the probability of occurrence for the Basic Event X_i.

Each of the basic events has a probability collected in the previous section. The equation is used to calculate the probability of occurrence of the top event under the assumption that they are all interdependent. The probability of transmission route of patients is 6.779E-04, and that of transmission route of IWK staff is 2.69E-03. The probability of occurrence of the top event is 3.36E-03.

6.2 Event Tree Analysis

In the Event Tree Analysis, the probabilities of each identified consequence are computed. The potential fatality rate is of great importance to the institution. It occurs when all the matigation barriers fail. The probabilities of infections that require hospitalization or ICU can provide the stakeholders with the demands forecast, thus helping them make the decisions on allocating acute and critical care beds.

$$P_{Death} = P_{Initiating\ event} * P_A * P_B * P_C * P_D * P_E \quad (9)$$

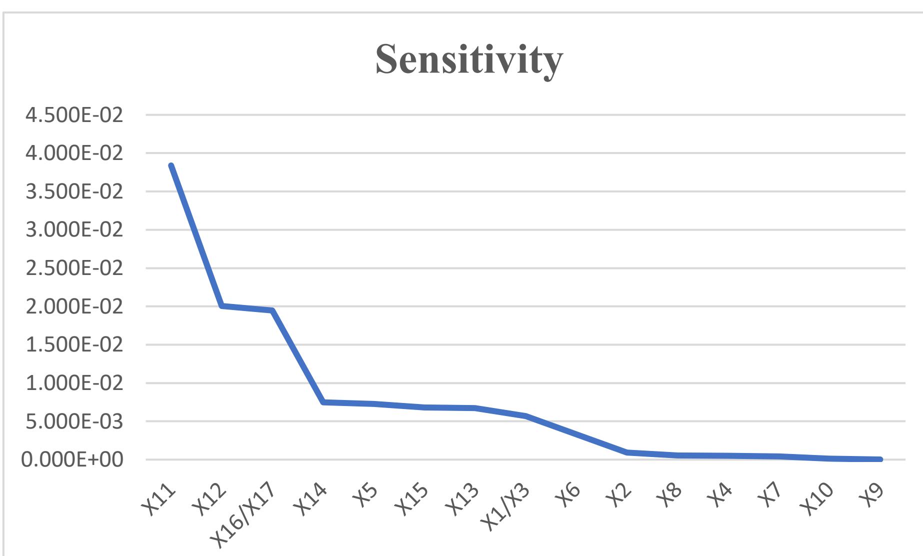
P_A , P_B, P_C, P_D, P_E represent the probabilities of failure for barriers A, B, C, D and E.

Using the probabilities listed in Table 5-4 and equation (4), the probability of fatalities is 7.22E-07. To assess whether further measures are required to reduce the risk, the ALARP principle discussed in Section 5.4 is used as the guideline to determine the risk level. The threshold between acceptable and tolerable zones is set at 10-6 for the surrounding population. Due to this, the case study's death risk is within an acceptable range of the ALARP. However, if the risk of death is greater than 10-6, the regulators might consider reducing it to a lower level. It is worth mentioning that as indicated by U.K.'s Health and Safety Executive, ALARP is not explicitly defined to give regulators more flexibility in how to apply and interpret it.

6.3 Sensitivity Analysis

By changing the value of a certain parameter (the probability of a basic event) one at a time, the assessor can have an overview of changes of which parameters have more impact on the occurrence of the top event in the FTA or the consequences in the ETA. When collecting the probabilities of occurrence of each basic event, studies often present statistical results with a range of 95% confidence interval. Therefore, the changes are made to the data of each basic event within its range as the input change. The output change is measured by the change in probability of the top event. The sensitivity is the ratio of percentage change in output and percentage change in input as discussed in Section 5.3.3. Table 6-1 illustrates the results. X_{11} (Infected persons among HCWs) has the highest sensitivity, and X_{12} (Missed vaccination among HCWs) ranks second. Compared with the results of structural analysis, the top two rankings are the same. X_{16} (Vaccine ineffectiveness of patients) ranks low in the structural analysis but ranks high in the sensitivity analysis. The events of the branch of contracting the virus from infected HCWs rank high in both analyses.

Figure 6-1. Sensitivity Analysis of the basic events



6.4 Determining critical factors

Determining the ranking of actions requires a criterion. In this case, the criteria are not a single one like a cost-benefit analysis. Instead, the risk controls are prioritized with the analyst'sp judgment based on the above qualitative and quantitative analysis combining the Strength of Evidence assessment of the data (Section 4.3.1.) and sensitivity analysis (Section 6.3.). The results of criticality are classified into three levels: high, medium, and low.

Firstly, the sensitivity analysis results show that infection among HCWs, the vaccine rate of healthcare workers, and the ineffectiveness of vaccines are the most sensitive ones. While false negative results of universal testing, missed physical distancing, PPE, and hand hygiene of HCW are in the medium sensitivity category. The results are presented in the form of a matrix to combine the results from the SoE assessment and the sensitivity analysis. By locating the basic events according to the results of sensitivity analysis and SoE, Table 6-2 is obtained.

Table 6-2 Basic events in combined SoE and sensitivity analysis

Sensitivity	High			X16	X1,X3,X11	X12,X17
	Medium			X13,X14,X15	X5	X6
	Low		X2,X4,X7,X8, X9,X10			
		Low	L-M	Medium	M-H	High
	SoE					

6.5 Discussion

The case study demonstrates the application of the proposed quantitative method for risk assessment of COVID-19 transmission in the acute care centre for safety improvement based on previous qualitative work. This example provides a novel application of quantitative risk assessment on the ongoing pandemic. This work presents a qualitative analysis of the structure and a quantitative analysis of the probabilities of failure of the Fault Tree and Event Tree.

From the qualitative and quantitative Fault Tree Analysis, it is found that the most critical risk controls are having the patients and healthcare workers take the vaccine and enhancing the effectiveness of the vaccine. Taking the vaccine is a great measure to mitigate the risk of infection. They are critical in structure analysis and also sensitive to the top event. Another critical control is universal testing. It would reduce the risk significantly to perform more tests and conduct multiple tests if possible in case of false negative results. The ALARP principles are used to assess fatality risk based on Event Tree analysis outputs. Since it falls in the region of acceptable risks, the existing measures are sufficient and should be maintained.

The qualitative Strength of Evidence Analysis and quantitative Sensitivity Analysis assist decision-makers in understanding the uncertainties in the data. In the model, the results indicate that events with low-medium SoE have low sensitivity to the occurrence of the top event, so the uncertainties are not critical. Otherwise, if events of low or low-medium SoE have medium or high sensitivity to the top event, they are regarded as critical events. From the research on the case study, several advantages of assessing risks with FTA and ETA are found as follows:

- FTA and ETA are well-established and broadly accepted techniques for risk assessment. Both are widely used to assess the safety of a system, such as in aerospace, oil, and gas transmission. Applications in various fields are abundant and have proven effective.

- FTA and ETA can be used for quantitative analysis and provide clear quantitative metrics and measurable outputs. Their ability to conduct comprehensive analyses and understand the issues thoroughly is a significant advantage.
- Although the underlying mathematics can be complex, the logically-developed diagrams are easy to explain to those who need to understand the risk assessment.

Meanwhile, there are limitations of this thesis which can be improved in future studies:

- Most data are collected from research papers due to the lack of data from the health care centre. A study that collects data from the organization itself will be more relevant. Besides, there is widespread support for data-driven decision-making. Therefore, it is valuable for an organization to track these data.
- As uncertainty analysis becomes more prevalent, fuzzy sets are being used to estimate data of high uncertainty. Indirect elicitation techniques, such as the Delphi method or Nominal Group Technique, can be used to determine the probabilities of basic events by involving several experts and professionals.
- Bow-Tie XP software has a quantitative function by linking the probabilities into an Excel spreadsheet. In this work, Microsoft Excel is used to compute the probabilities. In the case of large and complex Fault Trees and Event Trees, it is more feasible to facilitate software such as OpenFTA to construct, modify or analyze Fault Trees.
- Conventional Fault Trees have limitations, such as the inability to incorporate new knowledge, the difficulty of updating the probability of basic events, and the dependence between them. A Bayesian network is a probabilistic modeling technique representing a set of random variables and their conditional dependencies so that the events do not necessariliy need to be independent. Moreover, all events of Fault Tree and Event Tree can be linked in a Bayesian

Network. Assessors can potentially convert the model of FTA and ETA to a Bayesian Network to assess the uncertainties.

Chapter 7 Conclusions and future work

The work of this thesis presents data-based risk management for decision-making during the COVID-19 pandemic. It demonstrates the application of the proposed quantitative methods, Fault Tree and Event Tree for risk assessment of COVID-19 transmission in the acute care centre for safety improvement based on a Bow-Tie diagram. By constructing the FTA and ETA from a Bow-Tie diagram, this work presents methods to perform a quantitative risk analysis based on the results of the qualitative analysis. The constructed FTA and ETA present a logical relationship between the events. For the quantitative analysis, the probabilities of failure are derived from a review of scientific papers, and their uncertainties are assessed qualitatively. The course of searching data is also a way of understanding the research on the subject. The probabilities obtained can be used to analyze the system's overall risk. The finding can help prioritize the risk controls and understand which data are valuable for future studies on the pandemic.

Firstly, the construction of the Fault Tree and Event Tree requires a comprehensive understanding of the system. Identifying all threats and barriers was readily available from the Bow-Tie diagram, but determining their logical relations can be challenging for assessors. The assessors can resolve this issue by reviewing the system with practitioners and subject matter experts, thus facilitating communication among various stakeholder groups (Apostolakis, 2004). In addition, data collection can also be laborious if there is a limited amount of data available. However, it is of great value for the assessors to obtain more knowledge and information from studies and research on the subjects of interest. The uncertainty quantification creates a picture of what the experts know about the pandemic, thus providing valuable input to decision makers. In addition, it can inform practitioners about what data are worth tracking for risk assessment so that future studies can take advantage of them for prediction and planning.

This work also implements a qualitative assessment of the data to analyze the uncertainties which exist in the data. The qualitative uncertainty assessment is a subjective but realistic method to handle uncertain or imprecise data. However, the proposed approach may allow further improvement by completing a workshop with healthcare experts specialized in infection prevention and control. During an epidemic, the situation may evolve fast. Data tracking is essential for tracking flaws and adjusting risk management controls.

Quantitative analysis based on FTA and ETA quantify the occurrence of each risk factor and consequence, thus providing insights to improve decision-making in risk management. With numeric outputs of quantitative analysis, regulators are able to identify the dominant accident scenarios to avoid wasting resources on those insignificant risk factors.

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