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Application of bow tie analysis and inherently safer design to the novel coronavirus hazard

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A B S T R A C T

This work involves the application of process safety concepts to other fields, specifically bow tie analysis and inherently safer design (ISD) to COVID-19. An analysis framework was designed for stakeholders to develop COVID-19 risk management plans for specific scenarios and receptor groups. This tool is based on the incorporation of the hierarchy of controls (HOC) within bow tie analysis to identify priority barriers. The analysis framework incorporates inherently safer design (ISD) principles allowing stakeholders to assess the adequacy of controls along with the consideration of degradation factors and controls. A checklist has also been developed to help stakeholders identify opportunities to apply the ISD principles of minimization, substitution, moderation, and simplification. This work also considers barrier effectiveness with respect to human and organization factors (HOF) in degradation factors and controls. This paper includes a collection of bow tie elements to develop bow tie diagrams for specific receptor groups and scenarios in Nova Scotia, Canada. The pandemic stage (At-Peak or Post-Peak) and its influence on different scenarios or settings is also considered in this work. Bow tie diagrams were developed for numerous receptor groups; bow tie diagrams modelling a generally healthy individual, a paramedic and a hair salon patron contracting COVID-19 are presented in this work.

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1. Introduction

SARS-CoV-2, the novel coronavirus discovered in 2019, is the hazard of global concern with respect to the current pandemic. The risk of acquiring COVID-19 caused by the virus is driving unprecedented measures worldwide to prevent contact with the virus and to protect against the potentially severe consequences of infection. The risk posed by this hazard must be thoroughly identified and analyzed in order to design an effective risk reduction approach. This approach includes both prevention measures to limit the likelihood of coming in contact with the hazard as well as mitigation measures to reduce the severity of the consequences. Measures, or barriers, that have been well-socialized throughout the course of the pandemic response, include social distancing, working remotely, wearing face coverings and performing good hand hygiene. They have been critical for curbing the spread of COVID-19. However, these barriers are not 100% effective; for example, the barrier of social distancing can be degraded if individuals inadvertently come within 6 feet (2 m) of each other. Identifying how barriers may fail or be degraded is a critical component of an effective risk reduction approach. Additionally, because not all prevention and mitigation techniques are equally effective, the preferred order of implementation should be considered. Lastly, communication of public health measures is a critical component of the pandemic response. Decision-makers and public health experts must educate and inform the public so they can understand their role in risk reduction and the significance of barriers. This highlights the need for effective risk assessment and communication. The complex nature of communicating risk is highlighted by the recent publication by the World Health Organization (WHO), which highlights the need for effective risk communication and community engagement (RCCE) in order to improve the public's willingness to follow COVID-19 public health measures. Identified challenges with communicating with different groups include complacency, lowered risk perceptions and reduced trust in government responses caused by growing pandemic fatigue and socio-economic and psychological stress caused by uncertainty, the crisis and restrictions (World Health Organization (WHO), 2021). To address this, WHO recommends...
four pillars for an RCCE strategy: be community-led, be data-driven, reinforce capacity and local solutions and be collaborative.

These concepts of risk assessment and communication are not isolated to the COVID-19 pandemic, but rather are fundamentals of process safety. A foundational pillar of the Canadian Standards Association (CSA) (2017) process safety management standard is Understanding hazards and risks, which includes the Process risk assessment and risk reduction element. “Stakeholder participation/risk communication” is a feature of the risk management framework and communication is also a component of the Process safety culture and Conduct of operations — senior management responsibility elements. Bow tie analysis as a tool for performing process hazard analysis (captured within the Process risk assessment and risk reduction element) and communicating risk is discussed next.

1.1. Bow tie analysis

Bow tie analysis (BTA) is a barrier-based risk management tool that uses diagrams to graphically demonstrate and communicate how various factors can cause loss of control of a hazard and lead to undesirable consequences (CCPS/EI (Center for Chemical Process Safety/Energy Institute). 2018). One of the greatest strengths of bow tie diagrams is that they are a visual tool able to communicate hazardous scenarios to a wide range of audiences. CCPS/EI (Center for Chemical Process Safety/Energy Institute) (2018) highlights that the visual nature of bow tie analysis allows it to be tailored to the communication needs of different audiences, including regulators, workforce and local community. In March 2020, EI/CCPS (Energy Institute/Center for Chemical Process Safety) produced a fundamental document that demonstrates how bow tie analysis can be used to model and communicate hazardous scenarios involving contracting COVID-19. Energy Institute/Center for Chemical Process Safety (EI/CCPS) (2020) provided a starting point for the research.

1.2. Hierarchy of controls (HOC) and inherently safer design (ISD)

As mentioned above, not all prevention and mitigation controls are of equal effectiveness for a given situation. Therefore, prioritization of interventions is advisable. The hierarchy of controls (HOC) is the order of preferred consideration of risk reduction measures (Kletz and Amyotte, 2010). The HOC – in order of increasing preference – is administrative, active engineered, passive engineered and inherently safer design (ISD). Each of these types of controls should be considered when designing a risk reduction approach.

1.3. Research motivation, scope and objectives

The scope of this work includes modeling the risk of individuals acquiring COVID-19 and the associated consequences. This work is motivated by the need for a comprehensive hazard analysis of the novel coronavirus, and the need for an effective means of communicating hazard and risk reduction measures. The objective of this research is to use bow tie analysis and the HOC to assess which barriers are the most effective at preventing the spread of COVID-19 and how to effectively communicate prevention and mitigation measures. This also included the consideration of degradation factors and degradation controls, specific pandemic stages and different receptor groups. An outcome of this work is an analysis framework, suitable for broad audiences and stakeholders that can be used to create specific bow tie diagrams for COVID-19 risk for their applications. This work was completed in Nova Scotia and includes bow tie adaptation requirements for Nova Scotia-scenarios and stakeholders. The next section describes how this work expands on the bow tie analysis described in Energy Institute/Center for Chemical Process Safety (EI/CCPS) (2020).

2. Expansion on center for energy institute/chemical process safety bow tie for COVID-19 guidance

A review of the Energy Institute/Center for Chemical Process Safety (EI/CCPS) (2020) bow ties was completed, and the following sub section describes and delineates how this research expands on this seminal document. Specifically, this project expands on Energy Institute/Center for Chemical Process Safety (EI/CCPS) (2020) with respect to the following components:

- bow tie elements extending to include other examples of top events, threats, consequences, barriers, degradation factors and degradation controls,
- human and organizational factors (HOF),
- pandemic stage, and
- hierarchy of controls (HOC).

2.1. Bow tie elements

The hazard and top event terminology used in this paper are aligned with the accepted distinction between coronavirus, COVID-19 and SARS-CoV-2 (as described in Time (2020) and Health Canada (2020)). Specifically, COVID-19 is the disease caused by SARS-CoV-2, the virus also known has novel coronavirus discovered in 2019. The bow tie hazard is therefore “Novel coronavirus in human population” with the top event specific to each receptor group, i.e., “COVID-19 [within a receptor group].” Receptor groups modelled in this work are:

- Immunocompromised individual
- Long term care facility resident
- Primary care giver
- Nurse
- Paramedic
- Grocery store employee
- Elementary school student
- Fitness studio patron
- Hair salon patron

Table 1 outlines the additional analysis of the bow tie elements to expand on the Energy Institute/Center for Chemical Process Safety (EI/CCPS) (2020) bow ties.

2.2. Human and organizational factors (HOF)

Many barriers rely on human behaviour, and hence, this project identifies the importance of HOF when developing and implementing risk reduction plans. Gurses et al. (2020) and PS Net (2020) discuss the influence of HOF on managing COVID-19 (e.g. staff fatigue and burnout, workflow adaptation and redesign, training, team restructuring, etc.). CCPS/EI (Center for Chemical Process Safety/Energy Institute) (2018) also discusses addressing HOF in bow ties. In this project, HOF is considered and incorporated by identifying common HOF degradation factors, categorizing these degradation factors with respect to HOF degradation type (according to CCPS/EI (Center for Chemical Process Safety/Energy Institute (2018))) and identifying common respective degradation controls.

2.3. Life cycle stage

The WHO developed pandemic phases to assist with planning and response. World Health Organization (WHO) (2010) describes the six pandemic stages, as well as post-peak and post-pandemic stages, based on influenza (it is assumed this framework is also applied to the current COVID-19 pandemic). Phases 1–3 consist of primarily animal infections and few human infections. Phase
4 is characterized by sustained human-to-human transmission. In Phases 5 and 6, a pandemic is underway. Phase 5 consists of widespread human infection in a few countries in one geographical region. In Phase 6, there is community-level spread in more than one geographical region. The post-peak phase is a decrease in disease activity below peak levels; however, the possibility of waves (increased cases) is still present. Lastly, the post-pandemic stage is a decrease in disease activity to normal levels.

The pandemic life cycle stage is considered because the protocols, practices, government regulations and directives vary with respect to the stage. Within this research, Phase 6 (At Peak) and Post-Peak are the stages of interest and are considered within this project scope.

2.4. Hierarchy of controls

In the context of COVID-19, the HOC has been referred to in a number of resources (CBC, 2020a; Dalhousie University, 2020; Johns Hopkins University, 2020; WorkSafeBC, 2020). The HOC is incorporated within this research, including inherently safer design (ISD). This paper describes an analysis framework for incorporating the HOC in bow tie analysis for COVID-19 risk reduction. This analysis framework expands on the protocol presented by Rayner Brown et al. (2020).

3. Literature review

The literature review is organized into the following three areas:

- Bow tie analysis in healthcare applications,
- Bow tie analysis in pandemic scenarios and,
- Lessons learned from previous pandemic scenarios.

The purpose of this literature review was to understand how bow tie analysis has been used previously in healthcare applications, to understand if bow tie analysis has been used previously in pandemic scenarios, and to understand lessons learned from other pandemics. The scope of the literature review included general internet searches, as well as archival journal articles in Science Direct.

3.1. Bow tie analysis in healthcare applications

Literature discussing the application of bow ties in healthcare as a proactive risk management planning tool to improve patient safety include Abdì et al. (2016); Kerckhoffs et al. (2013); McLeod and Bowie (2018, 2020), Moore et al. (2019); Mullins et al. (2019) and Wierenga et al. (2009).

Abdì et al. (2016) describes the use of bow tie analysis to manage patient safety in Intensive Care Units (ICU). The hazards of focus in the study were different factors that could negatively impact patient safety, including drug incidents, pneumonia, and infections. The bow ties were proactive tools for identifying deficiencies in barriers and developing controls to address them. The diagrams helped stakeholders understand and convey hazard prevention measures. Wierenga et al. (2009) also describes similar findings with respect to managing medication risk. The authors identified that when a large number of risks are identified, it is important to prioritize the risks and the drawing of bow tie diagrams. When the scope of the study is more clearly defined and realistic, the bow tie methodology was easier to understand and more beneficial to those involved in the analysis.

Kerckhoffs et al. (2013) describes the use of bow tie diagrams to manage the safety of patients in the ICU. This work focussed on the identification of missing barriers to manage risk associated with intra-hospital transportation, extubation, and communication. The practicality and feasibility of implementing new barriers was emphasized in this work. The authors also reported that bow tie analysis was fairly easy to complete, which helped to improve adoption by ICU staff.

Moore et al. (2019) discusses the use of bow tie analysis for the purpose of quality improvement in healthcare and for reducing medical errors. The procedure of interest was venous thromboembolism prophylaxis. This study also reported that bow tie analysis helped identify problems with current safeguards for managing this hazard. Mullins et al. (2019) explored bow tie analysis to improve radiation treatment (RT) safety, with an emphasis on human factors. As with the previous studies highlighted in this sub section, the use of bow ties also allowed the effectiveness and robustness of the barriers to be better understood.

Workshops have been identified as a valuable tool for educating personnel about hazard analysis, as well as conducting hazard analysis (CCPS/EI (Center for Chemical Process Safety/Energy Institute, 2018; Edwards et al., 2015). McLeod and Bowie (2018, 2020) provide guidance for conducting workshops to incorporate bow tie analysis in primary care. This includes a staged process involving initiation of the analysis, development of the bow tie and creating a barrier management plan to ensure that the safeguards are implemented and effective.

3.2. Bow tie analysis in pandemic scenarios

The use of bow ties for previous pandemics or seasonal influenza was not found in literature. With respect to COVID-19, Lindhout and Reniers (2020) describes the use of bow tie analysis to develop an integrated pandemics control model that emphasizes the prevention of pandemics altogether; this is aligned with the concept of ISD.

Other efforts have been undertaken to apply bow tie analysis to help address the current COVID-19 pandemic. ASSP (American Society of Safety Professionals) (2020) provides a tool with aspects of bow tie analysis and layers of protection analysis (LOPA) to help assess and manage COVID-19 risk. Various workshops and workbooks have also been offered to help different stakeholders use bow tie analysis in their specific application or workplace to help reduce risk (CGE, 2020a, 2020b; Protecht, 2020).
3.3. Lessons learned from previous pandemic scenarios

There have been two other specific coronaviruses that have spread from animals to humans and which have caused severe illness in humans. These are severe acute respiratory syndrome coronavirus (SARS CoV) and Middle East respiratory syndrome coronavirus (MERS CoV) (Health Canada, 2020). Literature that describes lessons learned from previous pandemics includes Efian et al. (2017); Finberg (2014); National Health Service (NHS) (2009) and World Health Organization (WHO) (2016, 2017, 2019).

Efian et al. (2017) and World Health Organization (WHO) (2019) describe measures to prevent infection (e.g. good hand hygiene, droplet precautions) in the context of MERS-CoV. The importance of monitoring cases, traceability procedures to reduce transmission rate and tracking of infections to understand viral transmissibility pattern are also highlighted as important measures.

Finberg (2014) examines lessons learned from the H1N1 influenza pandemic of 2009, primarily with respect to the 2005 International Health Regulations. Recommendations include reinforcement of evidence-based decisions on international travel and trade, enhancement of the WHO Event Information Site and revise pandemic-preparedness guidance.

World Health Organization (WHO) (2016, 2017) also include lessons learned from the H1N1 influenza pandemic of 2009, including risk management tools and guides for addressing future influenza pandemics. This includes the role of risk assessment in preparedness, response and recovery actions.

The Government of Canada (2018) includes lessons learned from the H1N1 influenza pandemic of 2009 and describes preparedness planning for an influenza pandemic. These lessons include strategies to communicate risk, uncertainty and changing information.

The Government of Canada (2010) also describes lessons learned (areas for action), as well as aspects of the response that went well, including systems that facilitated quick exchange and sharing of information and communicating with Canadians. Within the COVID-19 pandemic, systems like CanCOVID have been a tool for researchers to share information and connect with other specialists working in the field. With respect to communications, many different media types have been used to connect with Canadians and share accurate and timely information, including television advertisements from PHAC (Public Health Agency of Canada), briefs with the federal and provincial governments, social media graphics and website resources.

National Health Service (NHS) (2009) provides general guidance for workplaces and organizations to assess risk and apply measures in their specific settings to reduce the spread of viruses (in this case, of influenza within workplaces). These measures broadly include environmental, organization and individual behaviour. One of the tools described is a workplace checklist of measures to apply in the workplace to reduce the spread of the virus. This forms part of the COVID-19 workplace protocols, used by Dalhousie University (2020) and Nova Scotia College of Physiotherapists (2020). Checklists are also recommended as a tool with respect to HOF in PS Net (2020) to help ensure safety protocols and steps are followed.

4. Inherently safer design (ISD) and hierarchy of controls (HOC)

This section describes how ISD principles can be used for COVID-19 risk reduction. The following sub section describes how the ISD principles are observed in other controls in the hierarchy.

4.1. ISD mindset and the hierarchy of controls

Other types of controls in the hierarchy, like procedural safety measures, may be improved through incorporating ISD principles and concepts with an ISD mindset. For example, in the field of dust explosions, the ISD principle of minimization is applied in cleaning and good housekeeping to remove dust and minimize the inventory of dust that poses a hazard. This minimization is achieved through the procedural safeguard of housekeeping programs (Amyotte et al., 2018). With respect to COVID-19 controls, social distancing in the form of stay at home orders contains elements of the ISD principle of minimization. Minimization is applied to eliminate contact at workplace or public spaces – while it is achieved through procedural means, it has aspects of minimization. Clearly, this barrier can be easily degraded or defeated by individuals leaving their homes, whether it is for necessity or recreation.

Social distancing in the form of maintaining a 6 foot/2 m space when outside of the home has characteristics of the ISD principle of moderation in the form of limitation of effects. The hazard still exists since the individual is outside of the home, but the likelihood of transmitting the virus to someone else or coming into contact with the virus from an infected individual is reduced. This barrier is also implemented using administrative means and this safe distance can be easily defeated in public, shared spaces if individuals are not compliant.

The ISD principle of substitution is observed with respect to the use of recommended cleaning products and disinfectants. It is recommended to substitute “natural” or “green” cleaners with bleach or alcohol-based solutions that are known to be effective at destroying the virus. While this may also be thought of using the appropriate product for the application, considering the ISD principle of substitution may lend itself to identifying more effective tools and barriers.

The ISD principle of simplification is observed in the guidance that long term care facility (LTCF) staff from outbreak facilities must not work in non-outbreak facilities. This guidance helps reduce hazards by reducing the complexity of the staffing process.

With all of the barriers mentioned above, degradation factors exist. For example, the barrier “LTCF (long term care facility) staff from outbreak facilities must not work in non-outbreak facilities” may be defeated in the case of staff shortage. These degradation factors need to be identified, along with corresponding degradation controls. After implementation, follow-up should be completed and barriers audited for effectiveness and compliance.

The following sub section describes how ISD guidewords, checklist questions and example-based guidance can be used to apply the principles of ISD to COVID-19 risk reduction.

4.2. Incorporating ISD using checklist questions and example-based guidance

To incorporate the principles of ISD, the use of checklist questions and example-based guidance is recommended. ISD checklist questions are a demonstrated tool to incorporate the principles of ISD (CCPS (Center for Chemical Process Safety), 2009; Kletz and Amyotte, 2010). Table 2 lists ISD checklist questions that have been developed for using ISD principles to reduce risk associated with COVID-19. The checklist questions in Table 2 were developed using the guidewords minimize, substitute, moderate and simplify. These guidewords are the general principles of ISD. Guidewords can be used as mind-triggers in the formulation of recommendations (Goraya et al., 2004).

Example-based guidance allows users to find specific applications of ISD that may be applicable to their scenario or use as the basis for mind triggers to help them identify opportunities (Rayner Brown et al., 2020). In this paper, the best-practices recommended by public health and sector-specific guidance have been collected and can be referred to for implementation or be used to develop measures for their specific applications.
Table 2
Checklist questions to consider for incorporating the principles of ISD for COVID-19 risk reduction.

| ISD Guideword | Checklist Question |
|---------------|-------------------|
| Minimize      | Can the time that individuals are in contact with each other be minimized to prevent prolonged periods of exposure? |
|               | Can the activity or work be completed remotely? |
|               | Can the number of personnel present in a location be minimized? |
|               | Can equipment sharing be kept to a minimum? |
|               | Can the number of hours per day or days per week be minimized? |
| Substitute    | Are there alternative processes available for eliminating the exposure to the hazard? |
| Moderate      | Can alternate, more effective cleaning products or safety equipment be used? |
|               | Can personnel be segregated from the hazard (e.g., through social distancing) to reduce the risk to other personnel and minimize disruption to business operations in the event of an infection? |
| Simplify      | Can processes and workflows in organizations be designed to limit the magnitude or severity of disruption due to an infection? |
|               | Have human factors been considered in the design of the workplace? |
|               | Can equipment be designed such that it is difficult or impossible to create a potential hazardous situation due to an error? |
|               | Can workflows and schedules be planned and optimized to facilitate simple turnover and minimize cross-over between individuals? |
|               | Are there any other alternatives for simplifying operations? |
|               | Is there additional equipment or resources that can be provided that would make working remotely easier? |

5. Collection of bow tie adaptation requirements for NS scenarios and example-based guidance

A literature review was completed to collect Nova Scotia (NS) specific bow tie elements and receptor groups. This included a review and summary of the controls, and barriers, used by public health to prevent infection and transmission of the COVID-19 virus, as well as sector-specific best-practices. This information about barriers forms the basis of example-based guidance; different stakeholders and organizations can use example-based guidance to identify barriers and reduce risk within their specific applications. A Glossary of Terms is presented in Table 3 to provide definitions of terminology for clarity and consistency, primarily with respect to the terms “social distancing”, “isolation” and “quarantine.”

Table 4 overviews the general building blocks of bow ties, including a set of common barriers (example-based guidance). Table 4 contains barriers from both At-Peak and Post-Peak stages. Many of barriers that prevent a receptor group from contracting COVID-19 are the same as those mitigating the transmission of COVID-19 to another individual as a consequence. A full listing of bow tie elements captured during the course of this work is found in Supplementary Material A. Note that vaccination has not been included as a barrier/control in this paper because during the timeframe of the project it had not yet been developed and was not an available barrier. Discussion on incorporating vaccination within the bow tie diagrams is included in Section 11.

6. Degradation factors and controls and operational discipline

Identifying degradation factors associated with barriers is an important component of bow tie analysis. Table 5 provides a listing of degradation factors and controls for common barriers.

With respect to bow tie analysis, operational discipline can be thought of as a degradation factor control. Work in this area is currently underway at Dalhousie University. Murphy (2020) describes how performing and complying with the primary safeguards (practicing social distancing, wearing PPE and enhanced personal hygiene) are analogous to operational discipline in process safety. Halim and Mannan (2018) describes the different aspects of achieving and maintaining excellence in process safety, one of which includes operational excellence. Forest (2012) developed a conduct of operations framework based on the Plan-Do-Check-Act cycle (Fig. 1), which also lends itself to implementing COVID-19 risk reduction plans. This conduct of operations model can encompass the use of data-driven systems and digitalization to monitor the effectiveness of barriers and restrictions, as evident through the numerous publicized resources used throughout the course of the pandemic (e.g., epidemiologic modelling, projections, situational awareness maps) (Government of Nova Scotia, 2021b; Institute for Health Metrics and Evaluation (IHME), 2021; Nova Scotia Health – IWK, 2021).

7. Human and organizational factors (HOF)

As discussed in Section 6, many degradation factors relate to human behaviour and HOF. Common HOF degradation factors categories are (CCPS/El (Center for Chemical Process Safety/Energy Institute, 2018):

- slips and lapses,
- mistakes,
- unintended violation,
- situational violation,
- organizational optimizing,
- personal optimizing

- and reckless.

Categorizing these degradation factors with respect to the HOF degradation categories helps identify effective, common degradation controls (shown below in Table 6).

8. Framework for developing bow ties based on the HOC

An analysis framework has been developed and is discussed within this section. As outlined by National Health Service (NHS) (2009), it is challenging to describe detailed infection control guidance for every occupation or workplace, or every scenario/situation where receptor groups may be at risk of exposure to the virus. This analysis framework is a tool for developing application-specific risk reduction plans based on the HOC to reduce the risk of COVID-
Table 3
Glossary of terms.

| Term                                      | Definition                                                                                                                                                                                                 | References                                                                 |
|-------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Social distancing                         | Keep physical distance between each other. Maintain a space of 6 ft/2 m from others. Avoid crowded places and gatherings and stay at home as much as possible. Other name: physical distancing. You must isolate if any of the following apply: | (Government of Nova Scotia, 2020c; Government of Canada, 2020a, b)         |
| Isolate                                   | • you have been diagnosed with COVID-19, or are waiting to hear the results of a lab test for COVID-19  
   • you have symptoms of COVID-19, even if mild  
   • you have been in contact with a suspected, probable or confirmed case of COVID-19  
   • you have been told by public health that you may have been exposed to COVID-19  
   • you have returned from travel outside Canada with symptoms of COVID-19 (mandatory)  
   • Other name: Self-isolate                                                                                                                            | (Government of Canada, 2020a)                                               |
| Quarantine                                | Quarantine for 14 days if you have no symptoms and any of the following apply:  
   • you are returning from travel outside of Canada (mandatory quarantine)  
   • you had close contact with someone who has or is suspected to have COVID-19  
   • you have been told by the public health authority that you may have been exposed and need to quarantine.  
   • Other name: Self-isolate                                                                                                                            | (Government of Canada, 2020a)                                               |
| Example-based guidance                    | Best practices recommended by public health and sector-specific guidance that can be implemented by others or be used to develop measures for their specific applications. | Rayner Brown et al. (2020)                                                 |
| Hierarchy of controls (HOC)               | The preferred order of consideration of risk-reduction measures (from most to least effective): inherently safer design (ISD), passive engineered, active engineered and administrative | (Kletz and Amyotte, 2010; National Institute for Occupational Safety and Health (NIOSH), 2020) |
| Inherently safer design (ISD)             | Avoiding hazards or reducing their likelihood or severity by changing the inseparable characteristics of the process, rather than through the use of add-on safety equipment and human action. Based on four principles: minimization, substitution, moderation and simplification. | (Kletz and Amyotte, 2010)                                                 |
| Passive engineering control              | Add-on safety device that does not require event detection and actuation of moving parts (e.g., plastic partition/barrier) | (Kletz and Amyotte, 2010)                                                 |
| Active engineering control                | Add-on safety device that requires event detection and actuation of moving parts (e.g., alarm)                                                                                                           | (Kletz and Amyotte, 2010)                                                 |
| Administrative control                   | Procedures and programs with human input (e.g., safe work procedures)                                                                                                                                 | (Kletz and Amyotte, 2010)                                                 |
| Human and organizational factors (HOF)    | Interaction of individuals with each other, with facilities and equipment, and with management systems. This interaction is influenced by both the working environment and the culture of people involved | CCPS/EI (Center for Chemical Process Safety/Energy Institute) (2018)        |

19 transmission and contraction. The analysis framework shown in Fig. 2, which has been developed for incorporating the HOC in bow tie analysis, is an adaption of the protocol described by Rayner Brown et al., 2020.

9. Example of analysis framework application

This section describes the application of the analysis framework to develop a bow tie based on the HOC. The bow tie elements captured in this example are drawn from publicly available literature and focuses on activities and scenarios highlighted as having more associated risk; additional bow elements (i.e., threats, barriers, degradation factors and controls) may be identifiable by subject matter experts in a collaborative bow tie workshop approach, as described by CCPS/EI (Center for Chemical Process Safety/Energy Institute (2018). The bow tie diagrams are drawn using the BowTieXP software program. Note the “+” and “−” symbols on the bow tie elements appear as a function of the software for collapsing different features for space considerations and viewing. Red boxes have also been added to the bow tie diagrams to highlight the barriers identified and added during each stage of the protocol.

9.1. Stage 1 – determine the life cycle stage being modelled

The following bow tie is completed assuming the pandemic is “At Peak” with respect to the number of cases within the jurisdiction (e.g. province) of interest.

9.2. Stage 2 – identify the hazard

As previously stated in Section 2, the terminology for the hazard that is used in this research is “Novel coronavirus in human population” (shown in Fig. 3).

9.3. Stage 3 – identify the top event

As previously stated in Section 2, the terminology for the top event that is used in this research is with the top event.
Table 4
Common barriers (categorized with respect to the HOC) and corresponding degradation factors and controls.

| Barrier | Barrier Type | Degradation Factor | Degradation Control | References |
|---------|--------------|---------------------|---------------------|------------|
| Social distancing of 6 feet | Administrative (with aspects of ISD) | Distance unclear (unintended violation) Policy unclear (unintended violation) Lack of enforcement within a retail location (organizational optimizing violation) | 6 feet markers on ground Verbal directions/instructions | Government of Nova Scotia (2020c); Chu et al. (2020) |
| Self-isolation following travel | Administrative (with aspects of ISD) | Not followed | Follow ups from public health Others encouraged to contact public health if individuals are known to not be adhering Fines | Government of Nova Scotia (2020c) |
| Hand-sanitizer to kill virus on hands when washing not possible. | Administrative | Low-supplies Poor-quality/not high enough alcohol content Price-gouging makes inaccessible to people Incorrect application method used | Expedited approval and production of hand sanitizer | Government of Canada (2020d); Government of Nova Scotia (2020c); CBC (2020b) |
| Plastic barriers at cash registers | Engineering (Passive) | | Cashier goes around plastic barrier to scan item because they cannot complete their job otherwise | Energy Institute/Center for Chemical Process Safety (EICPS) (2020) |
| Good hand-hygiene using frequent washing and proper method | Administrative | Low supplies of soap Proper procedure not followed because unaware of proper method (unintended violation) Proper procedure not followed because not enough time/production pressures (situational violation) Proper procedure not followed because resources unavailable in workplace (out of soap or no access to hot water) | Expedited approval and production of disinfecting products Education, posters | Government of Canada (2020d); Government of Nova Scotia (2020c); Pan et al. (2020). |
| Wearing gloves | Administrative | May create false sense of security and reduce adherence to good hand hygiene practices | | CBC (2020c) |
| Stay at home | Administrative (with aspects of ISD) | Domestic violence Unwillingness to stay home (personal optimising violation) | Support programs (e.g. NS 211) and transition homes (with protocols) Connect with friends and family in other ways (social media, video calls, virtual messaging) Education | CBC (2020d); e; Government of Nova Scotia (2020c) |
| High frequency cleaning of high-touch surfaces | Administrative | Low quality cleaner that is not effective against virus Increased cleaning-product related poisonings due to: - more cleaning products in homes as people stock up in isolation - more exposure to those products as people clean and disinfect their homes more often - more time spend at home - including for children Supply chain | Store chemicals away from children | CBC (2020f); Government of Nova Scotia (2020c) |
| Face covering | Administrative | Can be difficult to breathe with or uncomfortable to wear Must be worn and removed correctly Mis-information through social media or less reputable news sources | Education Daily briefings by federal and provincial governments Advertisements (TV, social media) | Kreps and Kriner (2020); CNBC (2020) |
| Long term care facility (LTCF) staff from outbreak facilities must not work in non-outbreak facilities | Administrative (with aspects of ISD) | In event of critical staff shortages, staff from non-outbreak facilities may work in outbreak facilities | | Government of Nova Scotia (2020d) |
| Cohorting symptomatic and asymptomatic lab-confirmed cases and close contacts | Administrative (with aspects of ISD) | | | Government of Nova Scotia (2020d) |
| Contact tracing by NSH Public Health | Administrative | Individuals are not honest with contract tracers | | Nova Scotia Health (2020) |
Table 4 (Continued)

| Barrier                                                                 | Barrier Type                                      | Degradation Factor                                                                 | Degradation Control                                                                 | References                        |
|------------------------------------------------------------------------|--------------------------------------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------|
| Mobile assessment units in areas with increased disease activity and/or limited resources | Administrative                                   | Poor weather conditions or need for equipment and utilities may make it difficult to do business outdoors or keeping doors and windows open | Clear space of people regularly to reduce potential build up of infectious respiratory droplets over time. Consult with an HVAC professional to ensure the system is optimized. Limit or avoid situations where there is an increased production of aerosols and droplets, including from singing, speaking loudly or yelling, and heavy breathing from exercising. Ensure occupancy is reduced to minimum levels and when rooms are in use, maintain maximum ventilation rates. | CBC (2020g)                     |
| Mental health and addictions services (NSH, IWK Health Centre, 811)    | Administrative                                   |                                                                                     |                                                                                    | CBC (2020h); Government of Nova Scotia (2020e)                                       |
| Financial support by government (provincial, federal)                  | Administrative                                   |                                                                                     |                                                                                    | Government of Nova Scotia (2020e)                                                    |
| Testing if referred by 811 assessment nurse                            | Administrative                                   |                                                                                     |                                                                                    | Government of Nova Scotia (2020f)                                                    |
| Improve indoor air quality through increased ventilation.              | Administrative, Passive Engineering              | Poor weather conditions or need for equipment and utilities may make it difficult to do business outdoors or keeping doors and windows open | Clear space of people regularly to reduce potential build up of infectious respiratory droplets over time. Consult with an HVAC professional to ensure the system is optimized. Limit or avoid situations where there is an increased production of aerosols and droplets, including from singing, speaking loudly or yelling, and heavy breathing from exercising. Ensure occupancy is reduced to minimum levels and when rooms are in use, maintain maximum ventilation rates. | Government of Canada (2021f); Government of Nova Scotia (2021a)                           |

Table 5
Common barriers and respective degradation factors and controls.

| Common Barrier                                                                 | Degradation Factor               | Degradation Factor Control                                                                 |
|-------------------------------------------------------------------------------|----------------------------------|-------------------------------------------------------------------------------------------|
| Social distancing                                                            | Not followed                     | Visual cues on floor and signage                                                           |
| Face mask or covering worn by other individuals to prevent transmission       | Worn improperly                  | Education about proper donning and doffing                                                 |
| Practice good hand hygiene and sneeze/cough etiquette                        | Proper method not followed       | Education, training                                                                        |
| Plastic partition at cash register                                            | Individuals go around barrier    | Consider ergonomics to optimize space                                                      |
| Prohibit individuals who have symptoms of/or have had exposure (in last 14 days) to COVID-19 from entering facilities | Not followed                     | Signage                                                                                   |
| Improve indoor air quality through increased ventilation.                    | Poor weather conditions or need for equipment and utilities may make it difficult to do business outdoors or keeping doors and windows open | Communication strategies are strengthened to include messaging about staying home            |
|                                                                               |                                  | Active or passive screening                                                                |
|                                                                               |                                  | Clear space of people regularly to reduce potential build up of infectious respiratory droplets over time. Consult with an HVAC professional to ensure the system is optimized. Limit or avoid situations where there is an increased production of aerosols and droplets, including from singing, speaking loudly or yelling, and heavy breathing from exercising. Ensure occupancy is reduced to minimum levels and when rooms are in use, maintain maximum ventilation rates. |

“COVID-19 [within a receptor group].” When users are applying the analysis framework to their specific application/scenario of interest, the identification of the receptor within the top event helps define the scope of the bow tie analysis (e.g., what is the person or receptor group of concern for reducing the risk of COVID-19).

For the purposes of this example, the receptor group being modelled is a “generally healthy person” (shown in Fig. 4).

9.4. Stage 4 –Identify threats and consequences

Next consider how the top event could occur, i.e., how the generally healthy person could contract COVID-19. Consider the activities and settings where risk of coming into contact with the virus exists (shown in Fig. 5). COVID-19 spreads via respiratory particles, so transmission modes for COVID-19 include breathing, talking, shouting, coughing and sneezing (Government of Canada, 2021f; Zhang et al., 2020); the threats identified involve this aerosol transmission. This represents more risk in enclosed spaces and indoor settings. Additionally, the time of exposure also a relevant factor in threats and risk of contracting the virus. The threats that are identified include situations where the receptor group may be exposed for longer times.

Next identify the consequences; consider the effects or what could happen if the receptor group contracted COVID-19 (shown along with threats in Fig. 6). In Fig. 6, the abbreviation “EMA” in the consequence “Extended EMA/lockdown” refers to the Emergency Management Act, which is the legislation in Nova Scotia that is “An Act to provide for a prompt and co-ordinated response to a state of emergency”
Table 6
Examples of common HOF degradation factors with respect to degradation types and examples of common degradation controls.

| Barrier | HOF Degradation Factor Examples | HOF Degradation Type | Degradation Controls |
|---------|--------------------------------|----------------------|----------------------|
| Social distancing | Directional arrows not followed in retail store because visual cue not obvious | Slips and Lapses | Design of visual cues |
| Hand hygiene | Improper hand sanitizer application | Mistake | Training, Education |
| Face mask or covering worn by other individuals to prevent transmission | Improper donning and doffing of face mask | Unintended Violation | Education for curbside pickup customers |
| Social distancing | Not followed | Situational Violation | Workflow redesign |
| Plastic partition at register or desk | Cashier goes around plastic partition to scan item because they cannot complete their job otherwise | Organizational Optimizing | Safety culture program |
| Hand hygiene | Hand sanitizer not provided at entrances of buildings due to cost and maintenance/refilling |
| Social distancing | Social distancing not followed at retail store because individual wanted to pick up an item near another individual | Personal Optimizing | Education, Signage |
| Social distancing | Social distancing (i.e. large gathering of people) not followed because disregard public health directives | Reckless | Legal action/fines, Education |

Fig. 2. Analysis framework for applying the HOC to bow tie analysis for COVID-19 risk reduction.
9.5. Stages 5 and 6 – identify ISD-based controls using checklist questions and example-based guidance

The next stage is identification of barriers; as the barriers are identified and added to the bow tie, they are added left-to-right following the HOCs. Using the ISD checklist questions and example-based guidance, ISD-based barriers are identified (shown in Fig. 7).

9.6. Stage 7 – identify engineering controls

Using example-based guidance, identify engineering controls; as shown in Fig. 8, the engineering control commonly identified is an add-on barrier to separate and shield individuals from each other (highlighted in the red boxes). The engineering barriers are added to the right of the ISD-based barriers following the HOC.

9.7. Stage 8 – identify administrative controls

Using example-based guidance, administrative controls are identified (highlighted in red boxes). For space considerations, prevention and mitigation barriers are shown in Figs. 9 and 10, respectively.

9.8. Stage 9 – identify opportunities to use PPE

Lastly, using example-based guidance, effective and appropriate personal protective equipment (PPE) are identified (highlighted in red boxes). In contrast to medical masks, such as N95 respirators, which are referred to as PPE, equipment like non-medical face masks and face coverings may be referred to as community protective equipment (CPE) (University of Ottawa, 2020). This distinction is made because non-medical face masks and coverings do not necessarily protect the wearer, but rather reduce potential droplet propagation to minimize community spread (University of Ottawa, 2020). This feature of CPE is captured within this analysis by being included as both prevention and mitigation barriers. Non-medical facemasks and coverings worn by other individuals are included as a prevention barrier, since if they were worn by others, they would serve as a barrier for the receptor group (shown in Fig. 11). Non-medical facemasks and coverings are also included as a mitigation barrier to reduce COVID-19 transmission from the receptor group to others (shown in Fig. 12).
9.9. Stage 10 – identify degradation factors and degradation controls

The last bow tie element to be identified are degradation factors and controls. A selection of degradation factors and controls is shown due to space considerations in Fig. 13. As discussed previously in Section 2.2, many of the degradation factors and controls relate to human and organizational factors (e.g. education about proper donning and doffing of masks to prevent improper mask use).

The listing of common degradation factors and controls are provided in Table 5.

9.10. Stage 11 – implement barriers and follow up

The last stage of the analysis framework includes the implementation of barriers and follow up. This includes audits to determine barrier effectiveness and health of barriers; barriers, as well as degradation controls, must be auditable [CCPS/EI (Center for Chemical Process Safety/Energy Institute, 2018)].

10. Developed bow tie diagrams

The intent of the bow ties in this section are to show activity-based threats for coming in contact with the virus, the potential consequences of an infection, barriers/controls that may be in place or used and the respective degradation factors and controls. The bow ties may not be completely accurate or reflective of practices, and as with the Energy Institute/Center for Chemical Process Safety (EI/CCPS) (2020) bow ties, feedback and input from subject matter experts and authoritative stakeholders should be solicited. Work in this area is currently underway at Dalhousie University.

These diagrams are shown in Figs. 14–17 (some diagrams are shown as left and right sides due to space limitations).

10.1. At Peak

For the “At Peak” pandemic stage, bow tie diagrams have been completed to model the scenario associated with COVID-19 in the following specific receptor groups:
The example with the top event “Paramedic Contracts COVID-19” is presented here. The other examples can be found in Supplementary Material B. This example is illustrative, but not exhaustive; other bow tie elements, like threats, consequences, barriers, degradation factors and degradation controls, may be identifiable. Buick et al. (2020) describes information to help paramedics in their clinical practice during COVID-19 and was referred to for supporting information to develop this bow tie.

10.2. Post-Peak/Return to Work

With respect to the Post-Peak phase and Return to Work protocols, scenarios and receptor groups modelled were:

- immunocompromised individual,
- resident in a long-term care facility (LTCF),
- primary care giver,
- grocery store employee,
- paramedic, and
- nurse.

These bow ties were developed using supporting information found in sector-specific reopening plans listed in Government of Nova Scotia (2020a). The example with the top event “Hair salon patron contracts COVID-19” is presented here. This example is illustrative, but not exhaustive; other bow tie elements, like threats, consequences, barriers, degradation factors and degradation controls, may be identifiable. The bow tie diagrams modelling the scenario involving elementary student and fitness studio patron are included in Supplementary Material B.
Fig. 10. Application of analysis framework - identification of administrative controls (mitigation).

Fig. 11. Application of analysis framework - identification of PPE controls (prevention barriers).

Fig. 12. Application of analysis framework - identification of PPE controls (mitigation barriers).
11. Future work and direction

Further research in this area is being completed in continued work under a Natural Sciences and Engineering Research Council of Canada (NSERC) Alliance partnership grant.

11.1. Communication for non-chemical process industry stakeholders

Additional guidance has been developed for communicating features of bow tie analysis with non-CPI stakeholders. For example,
for the bow tie diagram involving a paramedic contracting COVID-19 in Figs. 14 and 15, plain language for describing the objective of bow tie analysis has been developed as follows:

Objective: Use Bow Tie Analysis to:

– Show how paramedic could contract COVID-19
– Show how to prevent paramedic contracting COVID-19
– Show what would be the consequences
– Show how to mitigate the consequences
– Show how prevention and mitigation barriers degrade and fail

It has been found that adding labels for the hazard, top event, threats, and consequences, as well as the addition of legends for the bow tie elements, is beneficial when introducing bow tie diagrams to new audiences. The graphical nature of the bow tie improves the communication of hazardous scenarios to broad audiences through visualization, in comparison to other tabular-based approaches like a HAZOP (Hatch et al. (2019)). This paper has demonstrated how bow tie analysis is an effective tool for qualitatively communicating risk management. Quantitative analysis was out-of-scope of the current work, but it is recognized that bow tie analysis can be used for quantitative analysis and can be leveraged in cost-benefit analysis and decision-making. The use of quantitative data (e.g., probability of failure on demand, threat frequency, probability of consequences, demonstration of ALARP (As Low As Reasonably Practicable)) could be leveraged by decision-makers to weigh the cost-benefit of different risk management aspects. Work in this area is underway at Dalhousie University and Memorial University of Newfoundland.
11.2. Partner engagement

Further work is being completed with engagement of local healthcare partners in Nova Scotia under an NSERC Alliance partnership grant. This collaboration with subject matter experts in infection prevention and control and completing bow tie analysis in a workshop setting allows for a thorough consideration of bow tie elements, including initiating events and barrier degradation factors. The work completed to date, as well as proposed work, has been well-received by a number of groups. There has been great enthusiasm for addressing challenges associated with communication of risk reduction plans and systematically assessing barrier effectiveness. Healthcare partners have also identified potential uses of bow tie analysis for applications beyond COVID-19, which is consistent with literature review and is demonstrative of the value of this tool in applications beyond process safety.

11.3. Updating and expanding barriers and other bow tie elements

As the pandemic and ensuing response has evolved and progressed, there have been numerous learnings and new developments. This new information includes new bow tie elements, including threats, consequences, barriers and degradation factors and controls. New barriers include vaccine development (most notably) (Government of Canada, 2021a), along with Canada’s COVID Alert mobile app (Government of Canada, 2021b), additional recommendations on the use of three-layer masks (Government of Canada, 2021c) and pop-up rapid test clinics (Nova Scotia Health, 2021). Degradation factors include challenges associated with SARS-CoV-2 variants and human factors related to “pandemic fatigue” (Scientific American, 2021; Government of Canada, 2021d). When considering the vaccine as a barrier within a bow tie diagram, it would be both a prevention and a mitigation barrier. As a prevention barrier, vacation of others would reduce the likelihood that the individual/receptor group of interest in the top event would come in contact with the virus. As a mitigation barrier, vaccination of an individual would mitigate an infection (reducing severity of infection or likelihood of transmission) if the receptor group in the top event were to have COVID-19. Corresponding degradation factors of the vaccine barrier include the vaccine effectiveness rate less than 100 % (Center for Disease Control (CDC), 2012) and vaccine hesitancy or refusal (The Guardian, 2020). An example of a degradation control includes education. Further work incorporating this new information is currently underway at Dalhousie University. Additionally, while barriers should ideally be independent and there should not be a common mode failure, this is unfortunately practically impossible (CCPS/EI (Center for Chemical Process Safety/Energy Institute, 2018). The consideration of degradation factors and controls helps to identify the vulnerability of different barriers to common mode failure. Additional identification of degradation factors and controls is being completed in ongoing work with partners, as outlined above.

12. Conclusions

In closing, this project demonstrated how the process safety concepts of bow tie analysis and inherently safer design can be used in COVID-19 risk reduction. This work included the development of an analysis framework that incorporates the hierarchy of controls within bow tie analysis and encourages the consideration of ISD principles. This analysis framework can be used by a broad range of stakeholders to develop additional bow tie diagrams for their own specific applications and receptor groups of interest. This paper presented several bow tie diagrams that convey COVID-19 risk reduction measures for receptor groups including a generally healthy person, a paramedic and a hair salon patron. This project also emphasized the importance of identifying degradation factors and controls to ensure barrier reliability and effectiveness. Human and organizational factors (HOF) were also identified to play a significant role in barrier performance.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.psepp.2021.06.046.

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