Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Assessment of COVID-19 barrier effectiveness using process safety techniques

Lauren Turner a, *, Kayleigh Rayner Brown b, Peter Vanberkel c, Faisal Khan d, Jeannette Comeau e, Jane Palmer e, Ibimina Koko e, Paul Amyotte a

a Department of Process Engineering & Applied Science, Dalhousie University, PO Box 15000, Halifax, NS B3H 4R2, Canada
b Obex Risk Ltd., Suite 208 – 620 Nine Mile Drive, Bedford, NS B4A 0H4, Canada
c Department of Industrial Engineering, Dalhousie University, PO Box 15000, Halifax, NS B3H 4R2, Canada
d Mary Kay O’Connor Process Safety Center, Texas A&M University, Jack E. Brown Chemical Engineering Building, 3122, 100 Spence St, College Station, TX 77843, USA
e IWK Health Centre, 5850/5980 University Avenue, PO Box 9700, Halifax, NS B3K 6R8, Canada

ARTICLE INFO

Keywords:
Risk management
Inherently safer design
Process hazard analysis
Bow tie analysis

ABSTRACT

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) causes a respiratory illness called the novel coronavirus 2019 (COVID-19). COVID-19 was declared a pandemic on March 11, 2020. Bow tie analysis (BTA) was applied to analyze the hazard of SARS-CoV-2 for three receptor groups: patient or family member at the IWK Health Centre in acute care, staff member at a British Columbia Forest Safety Council (BCFSC) wood pellet facility, and staff member at the Suncor refinery in Sarnia, Ontario. An inherently safer design (ISD) protocol for BTA was used as a guide for evaluating COVID-19 barriers, and additional COVID-19 controls were recommended. Two communication tools were developed from the IWK bow tie diagram to disseminate the research findings. This research provides lessons learned about the barriers implemented to protect people from contracting COVID-19, and about the use of bow tie diagrams as communication tools. This research has also developed additional example-based guidance that can be used for the COVID-19 pandemic or future respiratory illness pandemics. Recommended future work is the application of BTA to additional industries, the consideration of ISD principles in other control types in the hierarchy of controls (HOC), and further consideration of human and organizational factors (HOF) in BTA.

1. Introduction

The novel coronavirus 2019 (COVID-19) is a respiratory illness caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Burak et al., 2021). SARS-CoV-2 was identified in December 2019. Common symptoms of COVID-19 include cough, congestion or runny nose, fever or chills, headache, muscle or body aches, nausea or vomiting, new fatigue, new loss of taste or smell, shortness of breath or difficulty breathing, and sore throat. While some people with COVID-19 experience no symptoms or have mild illness, severe cases can lead to respiratory failure, long-lasting damage to the lungs and heart, nervous system problems, kidney failure, and death (Sauer, n.d.).

The first case of COVID-19 in Canada was confirmed on January 25, 2020 (Burak et al., 2021). On March 11, 2020, the World Health Organization (WHO) declared COVID-19 a pandemic; at this time, there were over 118,000 cases in over 110 countries and territories, and sustained risk of continued global spread (Ducharme, 2020). SARS-CoV-2 is the hazard of global concern with respect to this pandemic (Rayner Brown et al., 2021a).

In regards to COVID-19, WHO Director-General Dr. Tedros Adhanom Ghebreyesus said, “This is not just a public health crisis, it is a crisis that will touch every sector” (Ducharme, 2020). The pandemic has disrupted supply chains and business operations across all industrial sectors. In the spring 2021 months, more than twenty outbreaks occurred at oilsands worksites and camps in Alberta, Canada, and the two largest outbreaks resulted in nearly 3000 cases of COVID-19 (Yourex-West, 2021).

The risk of acquiring COVID-19 continues to drive unprecedented measures worldwide to prevent contact with SARS-CoV-2, and to protect against the potentially severe consequences of illness. To design an effective pandemic risk reduction strategy, the risk posed by SARS-CoV-
must be identified and analyzed. Additionally, effective communication of public health measures from decision-makers and public experts is a critical component of a pandemic response (Rayner Brown et al., 2021a).

The scope of this research is the COVID-19 pandemic, with an emphasis on the province of Nova Scotia (NS), Canada from a healthcare perspective, and the risk of individuals in various receptor groups of interest acquiring the SARS-CoV-2 virus.

This research was motivated by the need for comprehensive hazard analysis of the unique threat of COVID-19 and effective communication of risk reduction measures during a pandemic.

The first objectives of this research were to identify virus threats and likelihood of infection, and to evaluate current prevention and mitigation measures using a process hazard analysis (PHA) technique known as bow tie analysis (BTA). Another research objective was to explore additional measures based on inherently safer design (ISD) and the hierarchy of controls (HOC). The final research objectives were to efficiently communicate the project findings and to provide guidance for making risk-based decisions regarding the selection of the most effective COVID-19 safety measures.

This research is part of a collaborative Natural Sciences and Engineering Research Council of Canada (NSERC) COVID-19 Alliance grant. Official research partnership involves Dalhousie University and Memorial University of Newfoundland, and official industry partnership includes the Nova Scotia Health Authority. Additional partnerships with the IWK Health Centre and the BC Forest Safety Council (BCFSC) have been developed, and online COVID-19 resources for a Bluewater Association for Safety, Environment, and Sustainability (BASES) member facility have been used.

It must be noted that this project was proactive and did not arise in response to any specific outbreak occurrences. Rather, it was developed from the perspective of quality improvement through the preventative analysis of a hazard.

2. Background

2.1. Hierarchy of controls

The hierarchy of controls (HOC) describes the preferred order of consideration for risk reduction measures. From most to least effective, this order is: inherently safer design (ISD), passive engineered safety, active engineered safety, and administrative safety (Kletz and Amyotte, 2010).

ISD controls aim to eliminate or reduce the hazards associated with a set of conditions using four main principles: minimization, substitution, moderation, and simplification (CCPS, 2020). Add-on safety devices are categorized as engineered controls (Kletz and Amyotte, 2010). Passive engineered safety controls do not require initiation beyond the undesired event itself, and active engineered safety controls depend on hazard detection, initiation, and support systems. Procedural safeguards are categorized as administrative controls (CCPS, 2020).

It must be noted that ISD, engineered safety, and administrative safety work in cooperation to reduce risk; ISD is not a stand-alone concept. Also, the importance of engineered and administrative safety is not invalidated by the HOC; the risk assessment process must incorporate consideration of all control measures (Kletz and Amyotte, 2010).

According to Rayner Brown et al. (2021a), incorporating the ISD principles with an ISD mindset may improve other types of controls in the HOC. In the context of this research, in addition to the controls as described by the HOC, administrative barriers and controls with characteristics of ISD principles are considered and they are categorized as “administrative (with aspects of ISD)”. This distinction aims to highlight the incorporation of the ISD principles while clearly stating that the controls are administrative safety.

Within the context of the COVID-19 pandemic, the HOC has been referred to in several resources. In May 2020, a “hierarchy of controls... for reducing transmission hazards” was presented by health officials in British Columbia (BC), Canada. (McElroy, 2020). Similarly, Johns Hopkins University in Baltimore, MD used a “modified hierarchy of controls” to represent their COVID-19 mitigation measures (Johns Hopkins University, 2020). The HOC was also used by the Canadian Centre for Occupational Health and Safety (CCOHS) to categorize COVID-19 safety measures for workplaces (Canadian Centre for Occupational Health and Safety CCOHS 2020).

2.2. Bow tie diagrams

Bow tie analysis (BTA), or the bow tie methodology, is a barrier-based risk management tool (Rayner Brown et al., 2021b). It is becoming more prevalent as a PHA tool (Anderson et al., 2016), and demonstrates how threats can lead to the loss of control of a hazard and how this unsafe condition can develop into undesired consequences (Rayner Brown et al., 2021b). Bow tie diagrams are excellent visualization and communication tools (Anderson et al., 2016) that can support the analysis, management, and communication of both process and non-process industry risks (CCPS/EL, 2018). A standard bow tie diagram is illustrated in Fig. 1.

2.3. Human behaviour and human and organization factors

The International Association of Oil & Gas Producers (IOGP) defines human factors as “the term used to describe the interaction of individuals with each other, with facilities and equipment, and with management systems” (CCPS/EL, 2018). Bow tie diagrams typically address human error and violations and organizational factors in degradation factors (CCPS/EL, 2018). In the context of the COVID-19 pandemic, many degradation factors are related to human behaviour and HOF (Rayner Brown et al., 2021a).

The common HOF categories of degradation factors are slips and lapses, mistakes, unintended violations, situational violations, organizational optimizing, personal optimizing, and recklessness (CCPS/EL, 2018; Rayner Brown et al., 2021a). Categorizing degradation factors with respect to the common HOF categories can help identify degradation factor controls (Rayner Brown et al., 2021a).

2.4. Bow tie ISD protocol

PHA provides an opportunity to explicitly consider ISD within the framework of PSM. A protocol was previously developed by Dalhousie University researchers to integrate ISD into BTA (as a PHA tool). This protocol includes the use of a collection of specific, practical applications of ISD, referred to as example-based guidance, to identify ISD opportunities within the bow tie (Rayner Brown et al., 2021b).

2.5. Application of bow ties in healthcare

The bow tie methodology is an increasingly popular PHA tool and is often employed in high-hazard industries. However, BTA has also been successfully used in medical safety applications (Ward et al., 2016).

2.5.1. Patient safety in intensive care unit (ICU)

A study published in 2016 (Abdi et al., 2016) used the bow tie methodology to analyze risks threatening patient safety in an ICU. The study was conducted for a 12-bed semi-closed medical ICU in a teaching hospital between late 2011 and early 2014. The researchers found that the bow tie methodology is a feasible tool for proactive risk management in an ICU. The bow tie diagrams allowed team members to generate practical solutions to address deficiencies and promoted the clinicians’ awareness regarding errors and conditions that might create undesired issues within their practice. The visualization of the diagrams also facilitated comprehension of the required barriers for safer operations in the ICU. However, the study noted the following challenges: BTA was...
time-consuming, and the reliability of the outputs depended on the reliability of the inputs. In general, the study found BTA to be capable of being a useful tool in ICU safety improvement programs (Abdi et al., 2016).

2.5.2. Surgical instrument retention

Research presented in 2016 applied the bow tie methodology to analyze the risk of surgical instrument retention following central venous catheterization (CVC). The team found the links between the bow tie diagram elements to be helpful, and the diagram itself to be useful in identifying further opportunities for safety improvements. This research concluded that BTA is an effective tool to systematically display and examine the threats, consequences, and prevention and mitigation barriers associated with an incident of guidewire retention. The work also expresses that perhaps bow tie diagrams can be an effective communication tool. Bow ties were thus determined to be useful as a proactive tool to examine where gaps exist in broader issues with guidewire use in CVC procedures (Ward et al., 2016).

2.5.3. Anaesthesia

Another study published in 2016 applied the bow tie methodology to the analysis of risks associated with anaesthesia. The work identified several potential uses for bow tie diagrams in anaesthesia risk management including understanding risks, teaching risk management, demonstrating risk management strategies, proactively identifying weaknesses in risk management, and investigating clinical incidents. Clinical risk management in anaesthesia currently includes predominantly retrospective and reactive tools; BTA is a useful tool to proactively identify and understand risks as well as investigate incidents. Additionally, bow tie diagrams facilitate teaching and multidisciplinary discussions regarding risk analysis, helping healthcare professionals to understand and respond to challenges (Culwick et al., 2016).

2.5.4. Primary healthcare

A 2016 research paper reported an informal evaluation that explored the potential benefits of the application of the bow tie methodology to primary healthcare. The evaluation determined that BTA has the potential to be applied to the risk management of serious events in primary healthcare; however, it also reported challenges regarding the practicality and logistics of implementing the bow tie methodology in healthcare. Although the methodology seems relatively easy to implement, some of the terminology and concepts may not be intuitive to healthcare professionals. To be capable of developing bow tie diagrams to an adequate quality standard without relying on supports from external sources like external facilitators, training, supports, and resources would be required for the primary healthcare community (McLeod and Bowie, 2018).

2.5.5. Medication

A study published in 2009 applied the bow tie methodology to prospective analysis of medication risks. The study was performed between January and December 2005 in a large teaching hospital and a large general hospital. The study found BTA to be an appropriate tool for prospective analysis of medication safety risks in a hospital. It gave team members insight into medication-related risks, increased safety awareness, and motivated team members to prioritize potential safety improvements. However, team members reported the following challenges: the large amount of information collected in the bow tie diagrams was difficult to interpret, and the bow tie methodology was time consuming (Wierenga et al., 2009).

2.5.6. COVID-19 pandemic

In April 2020, the Energy Institute/Center for Chemical Process Safety (EI/CCPS) published a white paper demonstrating the utility of bow tie analysis to model and communicate hazardous scenarios regarding contracting COVID-19. This fundamental document provided validation for the work being undertaken at that time by a joint Dalhousie/Memorial research team (Rayner Brown et al., 2021a). Since early 2020, bow tie diagrams concerned with the prevention and control of COVID-19 have been developed from different perspectives (CGE Risk, 2021). Rayner Brown et al. (2021a) developed bow tie diagrams to model a scenario associated with contracting COVID-19 for several receptor groups in Nova Scotia, Canada.

2.6. Application of bow ties as communication tools

As a visual tool, bow tie diagrams can communicate hazardous scenarios to a range of audiences at all levels of an organization (Rayner Brown et al., 2021a). They are suitable to be displayed on posters to highlight key risk control concerns (Lewis and Smith, 2010), and they have been found to enhance communication about risk awareness and management in stakeholder groups (Gerkensmeier and Ratter, 2018).

Regarding the COVID-19 pandemic, bow tie diagrams are an excellent communication tool to disseminate key safety information to a workforce. Risktec has proposed that information for each barrier on a COVID-19 bow tie diagram could be easily communicated to workers in a one-page summary (Risktec, n.d.).

3. Barrier evaluation methodology

As previously discussed, the objectives of this research include evaluating prevention and mitigation measures currently in place, and exploring additional measures based on ISD and the HOC. As this barrier evaluation methodology is based on the ISD protocol for BTA developed by Rayner Brown et al. (2021b), the first step is to examine and categorize the barriers with respect to the HOC. The next step is to evaluate...
the degradation factors and degradation controls. The final step is to use example-based guidance and supporting literature to identify additional barriers and degradation factor controls based on ISD and the HOC.

4. IWK bow tie

As stated earlier in this paper, a partnership with the IWK Health Centre was developed to produce a bow tie diagram for proactive, preventative analysis of the hazard of COVID-19.

4.1. Bow tie scope

The scope of the bow tie diagram was defined by the hazard and top event. Using terminology that follows the accepted distinction between COVID-19 and SARS-CoV-2, the hazard was “Novel coronavirus in human population”, with the top event specific to a receptor group at the IWK Health Centre contracting COVID-19 (Rayner Brown et al., 2021a).

The IWK Health Centre, located in Halifax, Nova Scotia, is a tertiary health centre.

Input from the IWK Infection Prevention and Control (IPAC) team helped further define the top event. Based on team roles and responsibilities, and the organization of the facility, the top event was “Patient and family in IWK Health Centre in acute care contracts COVID-19”.

4.2. Bow tie development

The bow tie diagram was developed through collaborative workshops with the IPAC team. Two workshops took place on-site at the IWK Health Centre in April 2021 and July 2021. Workshop personnel consisted of the IPAC team (four registered nurses, two specialists in performance improvement, a director, and a physician director), a scribe assistant (corresponding author), and an experienced facilitator/scribe.

Fig. 2 shows an excerpt of the bow tie diagram, including the hazard, top event, threats, and consequences. The full bow tie diagram is very complex and requires several pages for clear interpretation (see Turner, 2022, for the full bow tie diagram).

4.3. Barrier evaluation

4.3.1. Barrier categorization with respect to the hierarchy of controls

To begin the barrier evaluation for the IWK bow tie diagram, the identified barriers were categorized with respect to the HOC. Table 1 provides a selection of the COVID-19 prevention and mitigation barriers currently in place at the IWK Health Centre in acute care (see Turner, 2022, for more details).

4.3.2. Evaluation of degradation factors

Next, the degradation factors were categorized with respect to the common HOF categories. Table 2 provides a selection of the COVID-19 barriers currently in place at the IWK Health Centre in acute care and the corresponding degradation factors (see Turner, 2022, for more details).

4.3.3. Evaluation of degradation factor controls

Next, the degradation factor controls were categorized with respect to the HOC. Table 3 provides a selection of the COVID-19 barrier degradation factors currently in place at the IWK Health Centre in acute care and the corresponding degradation factor controls (see Turner, 2022, for more details).

4.4. Results and discussion

Almost all the COVID-19 barriers identified in the IWK bow tie diagram were administrative, and many of these administrative barriers were identified to have aspects of ISD. For the barriers that were administrative (with aspects of ISD), most were rooted in the strategy of minimization and the rest were rooted in the strategy of moderation (limitation of effects). There was one passive engineered barrier, and none of the identified barriers were active engineered or ISD. Due to the research team’s understanding that many COVID-19 barriers rely on human behaviour (Rayner Brown et al., 2021a), it was expected that most of the barriers identified in this bow tie diagram would be categorized as administrative or administrative (with aspects of ISD).

Of the identified degradation factors that were related to human behaviour and HOF, the most common categories were situational violation and personal optimizing. With these two categories as the most common, it could be understood that many degradation factors in this bow tie diagram are the result of the COVID-19 barriers being inconvenient or less attractive than the way things were done before the COVID-19 pandemic. Additionally, IWK team members, patients, and family/support persons may be unaware that their actions are degrading the effectiveness of the barriers.

All the degradation factor controls identified in the IWK bow tie were categorized as administrative or administrative (with aspects of ISD). As with the barriers, it had been anticipated that this would be the case.

This seems reasonable given that many of the degradation factors were related to human behaviour and HOF.

4.5. Recommendations

Several resources from the CDC (CDC, 2020a, 2020b, 2021a, 2021b, 2021c, 2021d, 2021e) and the Public Health Agency of Canada (Government of Canada, 2020), as recommended by the IPAC team, other resources considered for this research (British Columbia Centre, Disease Control BCCDC (2020), and the lived experiences of the researchers, were reviewed and compared to the barriers and degradation factor controls identified in the bow tie diagram. Table 4 lists additional barriers or degradation factor controls that could be considered to prevent and mitigate the spread of COVID-19. These barriers and degradation factor controls were also categorized with respect to the HOC. It should be noted that although these controls do exist at the IWK Health Centre, they were not identified for the specific receptor group investigated.

5. BCSC bow tie

As stated earlier in this paper, a partnership with the British Columbia Forest Safety Council was developed to produce a bow tie diagram for proactive, preventative analysis of the hazard of COVID-19.

5.1. Bow tie scope

As with the IWK bow tie diagram, the scope of this bow tie diagram was defined by the hazard and top event; the hazard was “Novel coronavirus in human population” (Rayner Brown et al., 2021a). The British Columbia Forest Safety Council (BCFSC) is the Health and Safety Association (HSA) for the forest sector in British Columbia, Canada. Based on the Dalhousie research team’s previous research collaboration with BCFSC and the Wood Pellet Association of Canada (WPAC) (WPAC, n. d.), wood pellet manufacturing facilities were identified as an area of interest and the top event was defined as “Staff member at wood pellet facility contracts COVID-19”.

5.2. Bow tie development

The bow tie diagram was developed through a “single-analyst” approach by two Dalhousie researchers. In this context, a “single-analyst” approach describes developing the bow tie without the direct input of the industry partner as in a collaborative workshop. The researchers collected COVID-19 resources available online from the BCFSC, British Columbia Centre for Disease Control (BCCDC), and WorkSafeBC (BCCDC, 2020, BCFSC, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g, 2020h, 2020i, 2020j, 2021; WorkSafeBC, 2020) and reviewed
Fig. 2. Excerpt of bow tie diagram representing a patient or family member at the IWK Health Centre in acute care contracting COVID-19.
them prior to developing the bow tie.

The researchers met virtually in June 2021 over Microsoft Teams. The bow tie diagram was developed primarily using the resources from the BCFSC, degradation factors and controls for common barriers (Rayner Brown et al., 2021a), and recommended barriers and degradation factor controls from the provinces of Nova Scotia and British Columbia.

The bow tie diagram was reviewed by a BCFSC representative in October 2021, who provided expert input and clarification on the implementation of COVID-19 barriers in BCFSC wood pellet facilities. Fig. 3 shows an excerpt of the bow tie diagram, including the hazard, top event, threats, and consequences. The full bow tie diagram is very complex and requires several pages for clear interpretation (see Turner, 2022, for the full bow tie diagram).

5.3. Barrier evaluation

5.3.1. Barrier categorization with respect to the hierarchy of controls

To begin the barrier evaluation for the BCFSC bow tie diagram, the barriers were categorized with respect to the HOC. Table 5 provides a selection of the COVID-19 prevention and mitigation barriers identified for the BCFSC wood pellet facility bow tie diagram (see Turner, 2022, for more details).

5.3.2. Evaluation of degradation factors

Next, the degradation factors were categorized with respect to the common human and organizational (HOF) categories. Table 6 provides a selection of the COVID-19 barriers identified for the wood pellet facility and the corresponding degradation factors that are related to HOF (see Turner, 2022, for more details).

5.3.3. Evaluation of degradation factor controls

Next, the degradation factor controls were categorized with respect to the HOC. Table 7 provides a selection of the COVID-19 barrier degradation factors and the corresponding degradation factor controls (see Turner, 2022, for more details).

5.4. Results and discussion

Almost all the COVID-19 barriers identified in the BCFSC bow tie diagram were administrative, and many of these administrative barriers were identified to have aspects of ISD. For the barriers that were administrative (with aspects of ISD), most were rooted in the strategy of minimization, and some were rooted in the strategies of simplification, moderation (limitation of effects), and substitution. There were two passive engineered barriers, and none of the identified barriers were active engineered or ISD. As before, due to the research team’s understanding that many COVID-19 barriers rely on human behaviour (Rayner Brown et al., 2021a), it was expected that most of the barriers identified in this bow tie diagram would be categorized as administrative.

Of the identified degradation factors that were related to human behaviour and HOF, the most common category was situational...
violation. With this category as the most common, it could be understood that many degradation factors in this bow tie diagram are the result of the COVID-19 barriers being inconvenient, or the result of situations that are out of the staff members’ control. Additionally, wood pellet facility staff members may be unaware that their actions are degrading the effectiveness of the barriers.

Most of the degradation factor controls identified in this bow tie were categorized as administrative, and many of these administrative controls were identified to have aspects of ISD. As with the barriers, it was expected that most of the degradation factor controls would be categorized as administrative or administrative (with aspects of ISD). This also seems reasonable given that many of the degradation factors were related to human behaviour and HOF. Two of the degradation factor controls were identified as passive engineered and three of the degradation factor controls were identified as ISD, adhering to the strategy of simplification. These ISD degradation factor controls demonstrate overcoming the degradation factors by helping to make the barriers more robust.
5.5. Recommendations

As described in Section 5.2, the development of this bow tie diagram included recommended barriers and degradation factor controls from the provincial governments of Nova Scotia and British Columbia. These recommendations are given in Table 8. It should be noted that these measures may be in place in the BCFSC wood pellet facilities, but they were not identified in the BCFSC COVID-19 resources available at the time of the initial analysis.

6. Chemical process industry barriers

As stated earlier in this paper, online resources from the Bluewater Association for Safety, Environment, and Sustainability were used to identify and evaluate COVID-19 barriers, degradation factors, and degradation factor controls implemented in the chemical process industry.

6.1. Scope

Even though a bow tie diagram was not prepared, the scope of this analysis was similarly defined by the hazard and top event. As with the bow tie diagrams, the hazard was “Novel coronavirus in human population” (Rayner Brown et al., 2021a). Identified through the Dalhousie research team’s chemical process industry (CPI) network, the Bluewater Association for Safety, Environment, and Sustainability (BASES) facilitates the exchange of information in the Sarnia-Lambton area of Ontario to protect workers, the public, and the environment (BASES, n.d.). A search into the publicly available online COVID-19 resources of BASES member facilities in the Sarnia-Lambton Petrochemical and Refining Complex (Sarnia-Lambton Economic Partnership, n.d.) revealed many Suncor COVID-19 guidelines and protocols. Therefore, the top event was “Staff member at Suncor refinery in Sarnia, Ontario contracts COVID-19”.

6.2. Barrier identification and evaluation

The COVID-19 barriers in place at the Suncor refinery in Sarnia, Ontario, were identified through the publicly available online Suncor COVID-19 resources, including guidelines and protocols. The corresponding degradation factors and degradation factor controls were identified using the same online resources, degradation factors and controls for common barriers (Rayner Brown et al., 2021a), and knowledge previously accumulated during this research.

6.2.1. Barrier categorization with respect to the hierarchy of controls

To begin the barrier evaluation for the identified COVID-19 barriers, the barriers were categorized with respect to the HOC. Table 9 provides a selection of the COVID-19 barriers identified for the Suncor refinery in Sarnia (see Turner, 2022, for more details). Many of the barriers, if presented in a bow tie diagram, would be both prevention and mitigation barriers and would, therefore, appear on both sides of the bow tie diagram.

Table 8

| Control | Control Type | Reference |
|---------|--------------|-----------|
| Waive ambulance fee for COVID-19 patients | Administrative (with aspects of ISD) | (Gorman, 2021) |
| Pop-up testing centres like in Nova Scotia | Administrative (with aspects of ISD) | |
| Point-of-care diagnostic testing for remote, rural, and Indigenous communities | Administrative (with aspects of ISD) | (GORM, 2021) |
cannot be eliminated, these administrative barriers incorporate mini-

cation by aiming to minimize the number of people on-site, and they

6.2.2. Evaluation of degradation factors
Next, the degradation factors were categorized with respect to the com-

6.2.3. Evaluation of degradation factor controls
The next step in the barrier evaluation was to evaluate the degra-

6.3. Results and discussion
Almost all the COVID-19 barriers identified in this bow tie analysis

Table 9
Sarnia refinery COVID-19 barriers (categorized with respect to the HOC).

Table 10
Sarnia refinery COVID-19 barriers and corresponding degradation factors (categorized with respect to the HOF categories).

Table 11
Sarnia refinery COVID-19 barrier degradation factors and corresponding degradation factor controls (categorized with respect to the HOC).

of COVID-19). There was one ISD barrier, adhering to the principle of
substitution, and none of the identified barriers were passive engineered
or active engineered. It should be noted that, when employing the
principle of substitution, the risks associated with the substitution must
be identified and assessed. For example, substituting in-person meetings
for teleconferencing and allowing staff introduces new challenges
related to remote access. As previously discussed, it was expected that
most of the barriers identified would be categorized as administrative
(Rayner Brown et al., 2021a).

Of the identified degradation factors that were related to human
behaviour and HOF, the most common category was situational viola-

tion. With this category as the most common, it could be understood that
many degradation factors identified are the result of the COVID-19
barriers being inconvenient, or the result of situations that are out of
the refinery staff members’ control.

Most of the degradation factor controls identified in this bow tie
analysis were categorized as administrative, and many of these admin-
istrative controls were identified to have aspects of ISD. As with the
barriers, it was expected that most of the degradation factor controls
would be categorized as administrative or administrative (with aspects
of ISD). This also makes sense given that many of the degradation factors
were related to human behaviour and HOF. One of the degradation
factor controls was identified as passive engineered, and none were
identified as ISD or active engineered.

7. Bow tie communication tools
As there is a need for effective communication of risk reduction
measures during a pandemic, an objective of this research is to develop
ways to disseminate the results. The IWK Infection Prevention and
Control (IPAC) team expressed interest in producing communication
tools for different stakeholders from the bow tie diagram that was
developed.

One communication tool that was developed is a document for IWK
executives and leadership. The objectives of this document are to
introduce the bow tie methodology and its potential uses at the IWK
health centre and demonstrate the success of the COVID-19 barriers that
were implemented. This document may also be summarized by the IPAC
team in a presentation aimed at senior leaders responsible for IWK
policy decisions.

The other communication tool that was developed is a one-page
document or poster for IWK frontline team members, similar to the
Center for Chemical Process Safety (CCPS) Process Safety Beacon. The
Process Safety Beacon is a one-page monthly newsletter that aims to
deliver process safety messages to manufacturing personnel such as
plant operators (CCPS, n.d.). Frontline workers are the target audience
for the Beacon, and it focuses on suggested actions that frontline workers
can do within the scope of their jobs (Kletz and Amyotte, 2019). The
objective of this document, illustrated in Fig. 4, is to communicate to
IWK frontline team members the effectiveness of the health centre’s
COVID-19 barriers and why they were implemented.

Communication tools were first discussed as a potential product of
the IWK COVID-19 bow tie diagram during the first bow tie workshop in
Preventing the Spread of COVID-19 with Bow Ties

WHAT'S A BOW TIE?
A bow tie goes beyond just identifying the risk. It's a visual tool that shows how a hazard could lead to a dangerous event like a viral outbreak at a given location. It allows us to assess how dangerous situations may arise and determine what controls we need to have in place to manage the risk.

Not only will bow tie analysis help protect team members, patients, and visitors, it will provide additional assurance that the necessary steps and control measures are in place to ensure their safety.

PROMOTING A SAFE WORK ENVIRONMENT
Based on workshops with the IWK IPAC team, transmission of COVID-19 to IWK team members was identified as a potential consequence.

The IPAC team has implemented many barriers to protect IWK team members from contracting COVID-19 but there are steps we can all take. It is also important to understand that barriers can degrade, and control factors are needed to maintain their effectiveness.

Reducing the risk: a team effort
1. Get vaccinated against COVID-19 if you are vaccine-eligible
2. Maintain 2 m of physical distance in public areas and when possible during assessments
3. Use additional precautions based on risk assessment e.g., patient exposure history
4. Practice good hand hygiene
5. Have a buddy for PPE donning and doffing to prevent self-contamination
6. Perform contact tracing and testing in partnership with Public Health and IWK Occupational Health, Safety, & Wellness (OHSW)
7. Wear all required universal pandemic precautions when providing direct care
8. Consult with the IPAC team if you have any questions

Fig. 4. One-page document, or poster, for IWK frontline team members.
April 2021. Following this first bow tie workshop, researchers met with one of the IWK continuous improvement specialists to and the two previously discussed target audiences were identified: IWK leadership and executives, and IWK frontline team members.

The communication tools were developed in collaboration with a science communications specialist and graphic designer. The science communications specialist developed the content of the two documents. After review and revision by the Dalhousie research team, the documents were sent to the graphic designer, who drafted and revised the communication tools based on comments from the Dalhousie research team.

8. Conclusions and future work

Bow tie analysis (BTA) has been applied to conduct comprehensive hazard analysis of the threat of contracting COVID-19 for three receptor groups of interest: patient or family member at the IWK Health Centre in acute care, staff member at a British Columbia Forest Safety Council (BCFSC) wood pellet facility, and staff member at the Suncor refinery in Sarnia, Ontario. Likely threats that could lead to the receptor groups acute care, staff member at a British Columbia Forest Safety Council hazard analysis of the threat of contracting COVID-19 for three receptor groups were identified; they describe contracting the virus from other groups at these locations including team/staff members, patients, auditors, visitors, and external contractors.

An inherently safer design (ISD) protocol for process hazard analysis (Rayner Brown et al., 2021b) was used as a guide for evaluation of the identified COVID-19 barriers, and additional COVID-19 controls have been recommended.

The barrier evaluation provided the following lessons learned:

- Most of the COVID-19 barriers identified were administrative, and many of these administrative barriers were determined to have aspects of ISD. It is important to use an ISD mindset (Rayner Brown et al., 2021a) to incorporate the ISD principles into controls of other levels in the HOC (like administrative controls). It is also important to note that, although they have aspects of ISD, administrative controls such as physical distancing are easily defeated and are the least effective type of control.
- Most of the COVID-19 degradation factors identified were related to human behaviour and human and organization factors (HOF). It is important to consider HOF in BTA for COVID-19 scenarios. The most common HOF category was situational violation; it is important to communicate how the COVID-19 barriers fit into the routines of staff members and how these barriers can fail, and to make COVID-19 barriers as convenient as possible.
- Like the barriers, most of the COVID-19 degradation factor controls identified were administrative, and many of these administrative controls were determined to have aspects of ISD. It is important to note that, for degradation factors related to human behaviour and HOF, the corresponding degradation factor controls are usually administrative.

Furthermore, two communication tools were developed from the IWK bow tie diagram to effectively disseminate the findings of this research to two target audiences: IWK leadership and executives, and IWK frontline team members. It is important to note that the information included in a communication tool, and the presentation of that information, must be adjusted to fit the communication needs of the intended audience.

By identifying and presenting COVID-19 barriers, degradation factors, and degradation factor controls, this research has developed additional example-based guidance that can be used for the COVID-19 pandemic or future respiratory illness pandemics. Furthermore, this research presents a methodology for evaluating the effectiveness of barriers; this provides guidance for making risk-based decisions regarding the selection of the most effective COVID-19 safety measures. Several challenges with implementing the use of BTA in healthcare were previously identified: BTA is time-consuming; the reliability of the outputs depends on the reliability of the inputs; the terminology and concepts may not be intuitive; external facilitators must be relied on, or training and resources are required; and the large amount of information in a bow tie diagram can be difficult to interpret. The example-based guidance developed in this research can be a useful resource when developing similar bow tie diagrams and can improve the reliability of the bow tie elements. Additionally, the presentation of selected bow tie elements in this paper demonstrates a strategy to facilitate the interpretation of the information in a bow tie diagram. Also, the communication tools developed from the IWK bow tie diagram demonstrate how BTA terminology and concepts can be communicated to healthcare professionals.

Research is currently being performed by Dalhousie researchers to quantify bow tie diagrams and/or the bow tie methodology. This ongoing research is using the bow tie diagram developed in collaboration with the IWK as a case study.

One recommendation for future work is the application of BTA to additional non-chemical process industry scenarios. BTA could be a valuable hazard analysis tool for a variety of industries; however, further research is needed to identify and understand the challenges related to introducing BTA in different industries, and to develop example-based guidance for these industry applications. Another recommendation for future work is the consideration and incorporation of ISD principles in other levels of the HOC. Further research could explore, and develop example-based guidance of, passive and active engineered safety controls with aspects of ISD. A final recommendation for future work is further consideration and incorporation of human behaviour and HOF in BTA. Further research could explore best practices for incorporating human behaviour and HOF in bow tie diagrams, explore the challenges related to treating HOF degradation factors in bow tie diagrams, and provide guidance for considering human behaviour and HOF in BTA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the research funding provided by NSERC through a collaborative COVID-19 Alliance grant with official research partnership with the Nova Scotia Health Authority.

References

Abdi, Z., Ravaghi, H., Abbasi, M., Delgoharbi, B., Esfandiari, S., 2016. Application of bow-tie methodology to improve patient safety. Int. J. Health Care Qual. Assur. 29 (4), 425–440. https://doi.org/10.1108/IJHCQA-10-2015-0121.
Anderson, D., Caufield, M., Ramsden, M., Penitt, G., Sarsred, M.G., 2016. The use of bow ties in process safety auditing. Inst. Chem. Eng. Hazards 26, 1–8.
CGE Risk, 2021. Application of the bowtie model in normalized epidemic prevention and control. https://www.cgerisk.com/2021/04/application-of-the-bowtie-model-in-normalized-epidemic-prevention-and-control/.
Bluewater Association for Safety, Environment, and S. (BASES). (n.d.). Bluewater Association for Safety, Environment, and Sustainability. Retrieved April 11, 2022, from https://ambrotnbasca.org/.
British Columbia Centre for Disease Control (BCCDC) (2020). Protecting Industrial Camp Workers, Contractors, and Employees Working in the Agricultural, Forestry, and Natural Resource Sectors During the COVID-19 Pandemic. http://www.bccdc.ca/Health-Info-Site/Documents/COVID_public_guidance/All-sector-work-camps-guidance.pdf.
British Columbia Centre for Disease Control (BCCDC) (2021). Interim Guidance on Point-of-Care Diagnostic Testing for Remote, Rural and Indigenous Communities. http://www.bccdc.ca/Health-Professionals-Site/Documents/Guidance_POC_Diagnostic_Testing_Remote_Rural_Indigenous.pdf.
Bural, K.W., Law, S., Rice, C., Hu, J., Fung, C.L., Woo, A.K.H., Fomeca, K., Lang, A.L.S., Kanji, J.N., Weatherall, B.L., 2021. COVID-19 outbreak among physicians at a Canadian curling bonspiel: a descriptive observational study. CMAJ Open 9 (1), E87–E95. https://doi.org/10.9778/cmajopen.20200115.
