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Analysis of the impact of a pandemic on the control of the process safety risk in major hazards industries using a Fault Tree Analysis approach

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ABSTRACT

The control of the risks associated with major hazard events is critical to the safe and continuous operation of the process industry. Over the last decades, the process industry has been successful at establishing and implementing robust Process Safety Management (PSM) systems to prevent and mitigate the consequences of such major hazard events. While there exist some industry guidelines developed relatively recently for events initiated by natural disasters and security-related threats, for initiating events like outbreaks of pathogens and pandemics, there is currently a lack of understanding of the impact of the restrictions and disruption caused by a pandemic on the ability of companies operating major hazard facilities to keep controlling the risks associated to their hazardous operations. Moreover, there is no industry guideline on how to account for such an impact in PSM systems for process safety hazards. The recent COVID-19 outbreak caused serious disruptions to normal operations that have challenged industry in their ability to control risks.

The objective of this paper is to perform an analysis of the impact of a pandemic situation on the implementation of selected elements of PSM systems related to the identification and evaluation of the risks of a major hazard and their control. The approach chosen involves the analysis of the root causes of the failure of the selected PSM elements using a Fault Tree Analysis method. The findings provide the first steps in the establishment of recommendations for the upgrade of PSM systems to face events such as pandemics.

1. Introduction

In end of August 2021, the coronavirus disease 2019 (COVID-19) pandemic caused by the severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2), has led to over 210 million confirmed cases, 4.4 million fatalities, and massive global economic slowdown (World Health Organisation, n.d.). COVID-19 pandemic is not the first outbreak of pathogens the world has faced in recent years. The past four decades have indeed seen the number of disease outbreaks per year more than tripled (Walsh, 2020). However, what sets the COVID-19 pandemic apart is its sheer scale and magnitude of its global impact on human life and the world economy that has not been seen since the 1918 influenza pandemic (Spanish Flu) (Blanc, 2020). Measures such as major lockdown at country level, closure of facilities, closure of country borders and travel restrictions with quarantine measures, limitation of personnel movements and gatherings, and social distancing measures have been implemented worldwide. These necessary measures have led to serious disruptions to normal operations, creating a challenging environment for the process industry to keep controlling the risks associated with major hazard events.

On such example of the impact of pandemic related measures on process safety risk is the LG polymer plant incident on May 7, 2020, in Visakhapatnam, Andhra Pradesh, India (known as the Vizag gas leak). This incident resulted in a major release of 800 tons of toxic styrene gas from a tank that was left unattended since March 24, 2020, due to the lockdown measures. Fifteen people died, and more than 1000 people suffered from toxic exposure. The release is believed to have been caused by the pressurization of the tank resulting from the exothermic polymerization of styrene. Among other safety deficiencies, the investigation revealed that the styrene tank was inadequately designed to detect and prevent the temperature increase. Tertiary Butyl Catechol (TBC), a chemical inhibitor, was not added to the tank since April 1 and the TBC concentration was not measured. Thus, the styrene polymerization was not prevented, and the tank pressurized by the exothermic polymerization of styrene to the pressure of the tank, leading to the release.

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are a result of the pandemic situation. While incidents are always resulting from multiple causes, it is of crucial importance to specifically identify how operating during a pandemic can impact the industry’s ability to implement its PSM systems and control the risks associated with Loss of Primary Containment (LOPC) of hazardous material or uncontrolled release of energy with a potential for major fires, explosions, and toxic exposure. For natural disasters (Baucher et al., 2018; World health Organization, n.d.) and security related threats (Bajpai and Gupta, 2005), there exist some industry guidelines developed relatively recently. However, for events like pathogen outbreaks and pandemics, there appears to be a current lack of understanding of the impact of the restrictions and disruption on the ability of process industries to control the risks associated to their hazardous operations. There is still a need for guidelines on how to account for such an impact in PSM systems for process safety hazards. The COVID-19 pandemic has led the industry, professional and academic institutions to take a step in this direction (Center for Chemical Process Safety (CCPS), 2020b; Center for Chemical Process Safety, 2020).

The objective of this paper is to perform an analysis of the impact of a pandemic situation on the implementation of selected elements of PSM systems related to the assessment and control of the risks of major hazards. The approach chosen involves the analysis of the root causes of the failure to implement the selected PSM elements using a Fault Tree Analysis (FTA) method.

2. Methodology

The Center for Chemical Process Safety (CCPS) provides a structured approach to process safety management through twenty specific elements, categorized into four pillars following pillars (Fig. 1) (CCPS, 2007): Commit to Process Safety, Understand Hazards and Risks, Manage Risk and Learn from Experience. The CCPS has recently made available to industry the CCPS Monographs (Risk Based Process Safety During Disruptive Times. Insights for Managing Process Safety During and Following the COVID-19 Pandemic and Similar Crises) (Center for Chemical Process Safety, 2020) and the Reflections from Global Process Safety Leaders During and Following Pandemics which presents the best practices for managing process safety according to a selected panel of worldwide industry leaders (Center for Chemical Process Safety (CCPS), 2020b). These publications provide a general sense of vulnerable elements within each pillar of a RBPS based PSM system during a pandemic. In order to further investigate the deficiencies of the current PSM systems in a pandemic situation, we chose to identify the root causes of the failure to implement PSM elements using Fault Tree Analysis (FTA) method as a Root Cause Analysis (RCA) tool. Although other RCA tools such as 5-Whys and Fishbone Diagram exist, they were deemed not applicable in the context of our analysis. Indeed, the 5-Whys method is a relatively simple tool that follows a linear progression of logical reasoning for the identification of a single root cause for a given failure and is therefore not fit for the identification of multiple root causes of failures. The Fishbone Diagram is a category-based RCA tool in which a number of cause categories, which are the potential contributors to the events, have to be carefully pre-identified. The success of the resulting analysis depends on the correct selection of the category of failure and therefore an incorrect choice of category may lead to overlooking some root causes (Latino et al., 2020). In comparison, the FTA method is a top-down deductive failure analysis tool using logic diagrams to combine (directly or indirectly) a series of basic and intermediate events that lead to a top event (usually the unwanted failure). It is widely used in safety and reliability engineering as a powerful tool to highlight the logical relationships between a potential failure or incident and its corresponding underlying causes as a tree diagram and to proposes countermeasures or barriers to prevent the failure or incident (Wang, 2018). The FTA method is suited for a thorough and extensive analysis of a wide range of causes for a failure of different nature (equipment, organizational, human, etc) and was chosen as the most adapted tool to identify the root causes of the failure to implement PSM elements.

Even though all four pillars of RBPS are important and necessary for the successful implementation of a PSM system, we narrowed our scope to two pillars: Understand Hazards and Risks (2 elements) and Manage Risk (9 elements). The restriction of the scope of analysis was based on the assumption that the two above-mentioned pillars have an immediate impact on the capability of an organization to identify and evaluate their risk exposure as well as their practical ability to manage these risks from an operational standpoint during a pandemic. Additionally, a recent study which reviewed over 50 incidents in the literature that were caused due to abnormal or transient operations during startups and shutdowns attributed nearly 74% of the incidents to the two pillars that were selected for this study (Vaughen, 2020). However, it needs to be noted that the decision to restrict our analysis to only two pillars is not meant to underplay the importance of the other two pillars. An in-depth analysis of the impact of pandemic of the two other pillars, namely Commit to Process Safety and Learn from Experience shall be considered for future work.

When used in the context of Quantitative Risk Analysis (QRA) or reliability analysis, fully developed FTAs can be further reduced to the minimum cut sets (unique combinations of events that can cause the top event) to calculate the likelihood of occurrence of these top events. In this paper, the FTAs are not intended for likelihood analysis and it is desired to present the complete and complex fault trees to visualize the direct and indirect failure paths for the investigated top events. A comprehensive qualitative minimum cut set analysis of the FTAs was however performed for each of the FTAs to highlight the root causes involved in the failure of each PSM elements.

The FTA was performed by the research team composed of 9 members from academia (Mary Kay O’Connor Process Safety Center, Texas A&M University at Qatar) who are currently active in research and education in process safety (2 senior members, 1 Research Associate and 2 PhD Students and 3 Masters students). The research team was split into 5 groups each in charge of the development of initial versions of two fault trees. Bi-weekly meetings were held over 2 months to allow each group to present its analysis to the entire research group, discuss, modify and improve until a consensus was reached for all the FTAs developed. A series of 1-2 h long interviews of representatives of six major operating companies in the Middle East (composed of process safety engineers, head of process safety divisions, higher management, etc) was conducted by the research team. The interviews covered main discussion themes that emerged from the FTAs and additional opened discussion themes brought up by the interviewed companies. These interviews provided valuable insight on the issues and challenges faced by industry during the COVID-19 pandemic regarding the control of the process safety risk. The information was used to confront the developed

Fig. 1. AIChE CCPS risk based process safety (RBPS) program elements (Center for Chemical Process Safety (CCPS), 2010).
FTAs to subject matter experts and practitioner’s opinion and validate, modify, improve and optimize the FTA when necessary.

In addition, these interviews provided information on the measures taken by the industry to ensure the continuous practice of process safety under a pandemic situation and overcome the challenges. The research team is currently working with industry to gather this information in the form of a guideline.

3. Results of the Fault Tree Analysis (FTA)

Fig. 2 presents the basic fault tree with the top event: Failure to manage process safety risks during a pandemic. The underlying causes of this top event are the failure to implement the selected PSM elements presented in Table 1 which are further developed in additional FTAs (using the transfer gates represented by triangles) in Fig. 3 to Fig. 12. It is important to note that the intermediate and basic events for building the fault trees were solely related and restricted to the pandemic situation. Fig. 13 and Fig. 14 show the additional transfer gates that are used in most of the fault trees developed for the selected PSM elements.

Table 2 provides a summary of the root causes identified in the FTAs organized in categories:

- Hazard Identification: root causes linked to the non-recognition of pandemics in hazard and risk analysis;
- Pandemic related: root causes linked to the pandemic situation and the associated restrictions and consequences;
- Remote working related: root causes linked to the remote working infrastructures and methodologies.

A comprehensive minimum cut set analysis was performed for each of the FTAs to produce reduced FTAs and highlight the root causes involved in the failure of each PSM element.

The following provides a discussion of the identified root causes supported with the observations and feedback received from the interviews of the representatives of six major operating companies as described above.

4. Discussion

The inability of PSM systems to manage process safety risks when a pandemic occurs is primarily associated with the lack of preparedness for pandemic situations. Pandemics should be recognized as triggers to process safety events similarly to Natech events (natural-hazard-triggered technological; e.g. climatic events like tsunamis, floods, hurricanes; geological events: earthquakes) (Mesa-Gómez et al., 2020). Unlike Natech events, pandemics do not have a direct impact on the equipment and facilities (i.e. no direct physical impact on the assets, no directly induced equipment failures leading to LOPC, etc.). But pandemics can be indirect triggers to process safety incidents in a way that they generate new hazards (see 4.1) and challenge the implementation of PSM systems as highlighted in our FTA. It is therefore of central importance to identify the process safety hazards generated by pandemics, understand the impact of pandemics on the implementation of PSM and take the necessary measures to develop or upgrade PSM systems and business continuity plans to cope with pandemic situations.

4.1. Impact of a pandemic on the risk profile

The failure to identify process safety hazards associated to pandemics may be due to the fact that a pandemic may not be considered as a credible scenario during hazard identification activities and the associated process safety hazards simply ignored. The COVID-19 situation has most certainly settled any arguments on the credibility of pandemic scenarios.

It may also be that the impact of a pandemic situation on incident scenarios, and therefore the risk profile, is not properly evaluated. Indeed, while pandemics do not directly impact equipment nor generate failures (or process deviation), they can impact the availability and reliability of layers of protection or equipment related to major hazard scenarios. Indeed, some layers of protection require human intervention through the execution of critical tasks or critical procedures. The unavailability of critical personnel due to the pandemic (see 4.2.1 and Fig. 13) may seriously compromise such layer of protection. Critical layers of protection or equipment need to be maintained through asset integrity programs which can be severely affected by a pandemic (Fig. 7). The identification of process safety hazards associated to pandemics is also central to the design of ERPs adapted to pandemic times (Fig. 12).

4.2. Impact of a pandemic on the implementation of PSM

4.2.1. Unavailability of critical personnel

Pandemics are by definition associated with people being exposed to the pathogens, getting contaminated and develop the diseases that leads to potential illnesses and in the worst-case death. Illness may lead to the incapacitation of the employee for a given amount of time, that may extend to months in severe cases. People who are developing symptoms or test positive to the pathogens are also placed in quarantine for a one or two weeks. Even if one can still perform some work in quarantine, this is only possible if the employee is in the right physical condition to work, if the nature of the work can be performed remotely and the employee has access remote working infrastructure at the location of the quarantine.

Pandemics are associated with financial losses for a company. It is not surprising that the company decides to perform some budget cuts which may result in the termination of employment. Travel bans prevent the return of staff located overseas (or other regions/states of the same country) at the time of the ban. The socio-economic climate imposed by pandemic may lead employee resign from their employment (e.g. relocations for family reasons related to the pandemic).

It is highly expected that the employee incapacitation will happen during pandemic time and it is imperative that the organization has some redundancy measures in place to ensure the continuity of the PSM related tasks or procedures to maintain safe operations. This should particularly be the case of PSM related tasks or procedures associated with major hazards scenarios.
The issue of the non-availability of required staff (Fig. 13) to perform a given task is a recurring issue in all the developed FTAs. The required personnel are involved in the following:

- The execution of a given task which directly impacts the safety/reliability of the facility, unit or equipment; e.g. ITPM (Fig. 7), collection of information in the plant (Fig. 3), task under PTW (Fig. 6).
- The development, authorization, and validation of a step of a safety procedure; e.g. PTW (Fig. 6), ITPM (Fig. 7), MoC (Fig. 10), OP (Fig. 5)
- The supervision and verification of a task; e.g. tasks under PTW (Fig. 6) and/or done by a contractor (Fig. 8).
- The participation in a PSM related activity requiring a particular expertise, e.g. expertise needed for HIRA activity like HAZOP (Fig. 4), selection of contractor based on safety criteria (Fig. 8), expertise needed for trainings (Fig. 9).
- The participation to the preparation to emergency response or the response to an emergency or crisis as a member of an emergency response team (Fig. 12).

Regarding those tasks that involve the intervention of a personnel because of their particular knowledge and skills for the implementation of a PSM element, it is important that the company identifies such tasks and related personnel and makes sure that personnel of equal competence is available when needed. The industry has made significant
progress over the last decade in the field of asset integrity management and in particular, the identification of safety-critical equipment (e.g. API 580/581 standards). This is to ensure the prioritization and management of ITPM activities on equipment, which upon failure can lead to a major hazard or on equipment that contributes in the control of the risks of a major hazard (e.g. protection layers). Similarly, there should be a focused effort to identify safety-critical tasks and safety-critical personnel/functions to ensure continuity in the control of risks for major hazards scenarios in a time of pandemics.

4.2.2. Operations with reduced workforce

Operations with a reduced workforce during a pandemic may result from measures (often decided and executed by authorities) to limit the spread of the pathogen, safeguard employees from a potential exposure and cope with the restrictions related to social distancing and limitations of the number of authorized personnel on-site.

All the operating companies interviewed in this work had to operate with a reduced workforce.

One example of a PSM element particularly impacted is asset
Fig. 9. Transfer gate for G: Failure to provide training.

Fig. 10. Transfer gate for H: Failure to conduct a successful Management of Change (MoC) process.

Fig. 11. Transfer gate for I: Failure to ensure operational readiness.

Fig. 12. Transfer gate for J: Poor emergency management.
integrity (Fig. 7). Indeed, the reduced workforce may lead to large backlog on ITPM activities, putting under pressure the completion of ITPM activities of critical equipment. It is also challenging to ensure emergency preparedness with a reduced workforce (Fig. 12).

From a purely operational standpoint, operation with a reduced workforce could require the minimization of the size of the operational team to operate the plant and perform PSM related activities. This raises the issue of how to define and decide on the minimum number of personnel to maintain operations. Here again, the idea of identification of safety-critical tasks and safety-critical personnel/functions may be of help (see 4.2.1). Three of the operating companies interviewed indicated that at the early stages of the Covid-19 pandemic they went through the exercise of identifying critical operations and critical personnel for safe operation with a reduced number of competent personnel.

Working with a reduced workforce also raises the need to ensure redundancy of teams of equivalent competency, particularly operational teams working in shift. This requires a thorough prior identification of the required competency for given functions (which should be addressed by the implementation of the competency element of a PSM program). All the operating companies interviewed went through a reorganization of the work around shifts composed of members of equivalent competency level.

However, if one of the team members tests positive to the pathogen, the entire shift may be made unavailable (e.g. contamination or quarantine), such putting more pressure on the other shift to cover the workload or exposing them to contamination and ultimately jeopardize the operations of the plant. Two of the interviewed companies reported this situation was faced and had to be managed. One company reported the cross-contamination of 3 out of 4 working shifts leaving only 1 shift to operate for 24 h which ultimately resulted in the plant shut down. It is therefore important to identify the way cross-contamination can occur (e.g. through shift handover or social interactions) in and outside the work environment.

4.2.3. Lower employee performances

Operation with a reduced workforce during a pandemic (see 4.2.2)
may lead to personnel working extended shifts which in turn could contribute to high levels of worker fatigue.

Working in during a pandemic with the associated socio-economic climate may put a strain on the moral, mental health and emotional status of the workforce. The COVID-19 pandemic has shown that social distancing measures, quarantine isolation, absence of social activities, an overwhelming amount of information including misinformation have contributed to fear, sadness, frustration, loneliness stress, anxiety, depression, etc. (Khan et al., 2020).

The shift towards remote working or working from home (see 4.3) also comes with its share of issues that can impact the personnel’s wellbeing and performances. For example, remote working may be associated with a lack of the ability to build social relationships behind a computer screen, lack of social connection (including relationships with line manager), increased employee workloads often with work outside regular working hours, lack of clear boundary between work and home (Graves and Karabayeva, 2020).

Employee fatigue or stress may result in the quality and safety of the safety-related tasks such as SWP (Fig. 6), ITPM (Fig. 7) being compromised. It may also affect the quality of work performed in a HIRA session (Fig. 4) or the ability to make informed decision to review and authorize safety-related activities. One of the companies interviewed also raised concerns about the ability of fatigued worker to respond to an emergency as reflected in the FTA (Fig. 12).

Such challenges would require the company to be proactive in managing the workload of both employees working onsite and the ones working remotely in order to minimize fatigue. The company should also develop strategies to manage the mental health issues associated with the pandemic socio-economic climate and the isolation associated with remote working. Graves et al. (2020) propose a set of measures to managing virtual workers that may counter these issues (Graves and Karabayeva, 2020).

### 4.2.4. Impact of pandemic restrictions on PSM

#### 4.2.4.1. Impact of travel and gathering bans

Pandemics are associated with radical measures limit the spread of the pathogen within populations and between countries. Travel bans and gathering bans are examples of such measures that can impact PSM.

Travel bans have an immediate effect on the supply chain (4.2.6) making difficult the intervention of contractors or subject matter experts based overseas (ITPM, training, etc) as they are not allowed to enter the country and perform the work physically. When allowed, the travel is associated with a mandatory quarantine periods upon entry to countries.

Gathering bans will impact PSM activities that require group interaction. Training is an example of this (Fig. 9). Although companies tend to develop online training, the majority of the current training are face to face, which make training an activity that is particularly vulnerable to pandemic restrictions. Four out of the six companies interviewed reported the suspension of all face-to-face in-house trainings during the COVID-19 pandemic. Two companies were able to at least partly fulfill the trainings needs by moving to online remote training.

#### 4.2.4.2. Impact of social distancing

Pandemic imposes social distancing restrictions to limit the spread of the pathogen within populations. Providing that social distancing measures are in place (along with the required sanitary measures), some degree of in person social interactions and gathering may be allowed by the company and the authorities. Social distancing requirement may prevent or limit the use of usual gathering facilities and venues for PSM activities. Indeed, the social distancing restrictions pose a limit the occupation of a room. Emergency shelters in place incident/crisis management room may not be adapted to the social distancing requirements. Staff/public evacuation plans may be affected by this limitation (Fig. 12).

Training venues (e.g. meeting rooms, classrooms, etc) may be too small to host the usual number of trainees and consequently require a different organization of the face to face training (e.g. the same

### Table 2

Summary of the root causes by category.

| Category            | Sub-Category | Root causes                                                                 | A | B | C | D | E | F | G | H | I | J |
|---------------------|--------------|------------------------------------------------------------------------------|---|---|---|---|---|---|---|---|---|---|
| Hazard identification|              | Pandemic not considered as credible scenario                                 |   |   |   |   |   |   |   |   |   |   |
|                     |              | Vulnerability of layer of protection to pandemic situations not evaluated    |   |   |   |   |   |   |   |   |   |   |
|                     |              | Epidemic disease contracted                                                 |   |   |   |   |   |   |   |   |   |   |
|                     |              | Quarantine                                                                   |   |   |   |   |   |   |   |   |   |   |
|                     |              | Worker health compromised but not diagnosed                                  |   |   |   |   |   |   |   |   |   |   |
|                     |              | Stress induced by the pandemic (welfare, job security etc.)                  |   |   |   |   |   |   |   |   |   |   |
|                     |              | Fatigue due to continuous shift with no sufficient turnaround               |   |   |   |   |   |   |   |   |   |   |
| Restrictions        |              | Reduced number of employees onsite due to restrictions                      |   |   |   |   |   |   |   |   |   |   |
|                     |              | Gathering bans                                                               |   |   |   |   |   |   |   |   |   |   |
|                     |              | Travel bans                                                                  |   |   |   |   |   |   |   |   |   |   |
|                     |              | Venue not adapted to social distancing                                       |   |   |   |   |   |   |   |   |   |   |
|                     |              | Evacuation plans (staff or public) not adapted to social distancing          |   |   |   |   |   |   |   |   |   |   |
| Financial           |              | Budget restriction imposed by pandemic                                       |   |   |   |   |   |   |   |   |   |   |
|                     |              | Cost per trainee too high (low number of trainees)                          |   |   |   |   |   |   |   |   |   |   |
| Supply chain        |              | Delayed shipment                                                             |   |   |   |   |   |   |   |   |   |   |
|                     |              | No alternative supplier identified                                            |   |   |   |   |   |   |   |   |   |   |
|                     |              | No local/regional supplier identified                                        |   |   |   |   |   |   |   |   |   |   |
|                     |              | Unavailability of spare parts onsite                                         |   |   |   |   |   |   |   |   |   |   |
| Others              |              | Resignation (pandemic related reasons)                                       |   |   |   |   |   |   |   |   |   |   |
|                     |              | Unavailability of stakeholders                                               |   |   |   |   |   |   |   |   |   |   |
| Remote working      |              | No remote working infrastructure                                             |   |   |   |   |   |   |   |   |   |   |
|                     |              | Hardware/software issues                                                    |   |   |   |   |   |   |   |   |   |   |
| Infrastructure      |              | Poor home internet connection                                               |   |   |   |   |   |   |   |   |   |   |
|                     |              | No dedicated electronic platform                                             |   |   |   |   |   |   |   |   |   |   |
| Methodology         |              | Documents not available in electronic format                                |   |   |   |   |   |   |   |   |   |   |

4.2.4.1. Impact of travel and gathering bans.

4.2.4.2. Impact of social distancing.
training may need to be delivered to smaller groups of employees to meet the training needs. The number of people per trainee per group may be too high to make the training affordable by the company such impacting the ability of the company to response to its training needs (Fig. 9).

4.2.5. Impact of budget cuts related to the pandemics on PSM

As mentioned in 4.2.1, financial losses associated with a pandemic may lead a company implement significant budget cuts which may result in the termination of employment. Such budget cuts may also impact PSM performances by inducing an improper selection of a new contractor (or change of contractor) with lower safety performances but within the available budget (Fig. 8). It may also impact the ability of the company to acquire tool(s), equipment, parts necessary for PSM activities (Figs. 7 and 10).

4.2.6. Impact of pandemics on the supply chain and PSM

The restrictions associated with pandemics severely affect the supply chain. The company may experience difficulty in their PSM related activities that require the use of third party contractors for routine operations, ITPM activities (Fig. 7), leading and participating HIRA (Fig. 4), providing safety related training (Fig. 9), audits, testing from laboratories, etc. The COVID-19 outbreak has highlighted the importance of having redundancy in operational expertise, supply chains and contractors.

Measures to overcome the challenges associated with the potential unavailability of third-parties should be considered. These may consist of identifying alternative regional/local third parties (e.g. in the same country) capable of delivering the same service and that be virtue of their physical location are available in case of travel ban. Another option would be to develop internal competencies to ensure in-house capabilities and expertise to temporarily perform the work when possible (e.g. internal subject matter expert and including HIRA leaders through process safety competency building programs, in-house course instructors, internal auditors, etc). The pandemic has also brought to light the necessity to identify critical training and to develop in-house expertise to conduct such training to avoid dependence on external parties.

4.3. Adapting PSM systems to remote working

As observed during the COVID-19 pandemic, pandemic restrictions and operation with reduced workforce has led to a sharp increase of companies adopting remote working. It is therefore important to adapt PSM systems to this relatively new working mode.

4.3.1. Remote working infrastructures

Companies need to have a robust system in place to ensure seamless remote communication between on-site and off-site employees. The absence of remote working infrastructure was found to have a considerable impact on the successful implementation of a PSM system in a pandemic environment (Table 2). This may require the company to ensure that employees have access to the Internet at home with a sufficient bandwidth to cater the larger than usual needs, that secured access to the information remotely (e.g. intranet) is available and that employees are adequately trained to work remotely. One of the six operating companies interviewed reported that they provided employee with company IT equipment and covered the cost of increasing the quality of home connection for their employee.

Companies should also be able to share critical information with third parties in a secure manner. This is particularly true for HIRA studies (e.g. HAZOPs) that are often conducted using contractors as leaders or technical experts for such studies. Another avenue where communication with third parties becomes critical is for the management of work that will be performed by contractors, which in many cases, represent the most considerable fraction on-site personnel. Therefore, the establishment of a communication platform with the third party or the management of access to the company information becomes critical to improve communication.

4.3.2. PSM procedures

Efficient remote working is only possible by providing the required information in an electronic format. This is particularly true of process safety-related information that is required to perform HIRA or ITPM. Equally, the processes/procedures that require multiple approvals and the formal documentation of activities (MoC, activities requiring a permit to work, etc.) should be capable of being implemented on an electronic platform. As an example, over the last years, many companies moved from a paper-based permit to work system to an electronic one (Ollif, 2008).

4.3.3. Remote working session

Remote working comes with group remote working session. The quality of the remote communication ensured by solid remote working infrastructures (4.3.1) plays an important role in the quality of a working session.

The company may choose to perform some PSM activities like HAZOP studies remotely. It is important to note such studies have been historically designed to be performed by a group of people gathered for several hours in a room. The traditional set up and duration of a HAZOP may not be adapted to remote-working (Fig. 4). As described in 4.2.3, employee fatigue or stress induced by remote working may impact the quality of the employee’s engagement during the session and ultimately the quality of the study. The interviews conducted with the operating companies confirmed this analysis.

An important aspect of conducting a HAZOP is the need for the team performing the analysis to visit the units under consideration with the P&ID in hand. This may not be possible because of the pandemic imposed access restrictions to the site and/or the unavailability of personnel to make the visit possible. In such scenarios, new technologies supporting virtual visits to the plant may need to be considered (Bin et al., 2018; Younes, 2016).

The quality of a PSM activities done remotely is also function of the facilitator skills to encourage active participation and keep engagement during the session.

In general, conducting HIRA studies remotely is an area that requires further studies.

4.3.4. Remote training

Organizations may need to convert most of the training content into an electronic format and provide an electronic platform to disseminate the training (Fig. 9). With universities all over the world working to tackle the issues associated with remote teaching (Barton, 2020), it provides an opportunity for collaboration between industry and universities to increase the industry’s ability to pursue its critical safety training during pandemics. For training with a hands-on aspect, companies should be able to provide physical spaces big enough to accommodate enough personnel at once (Fig. 9).

5. Conclusion

The work presented in this paper is a step towards an analysis of the impact of a pandemic situation on the ability of companies operating major hazard facilities to keep controlling the risks associated to their operations. The approach chosen involved the analysis of the root causes of the failure to implement the selected Process Safety Management (PSM) elements using a Fault Tree Analysis (FTA) method.

The FTA showed that while pandemics do not directly impact equipment nor generate failures (or process deviation), they can impact the availability and reliability of layers of protection or equipment related to major hazard scenarios. The FTA also highlighted that unavailability of competent personnel, the operations with reduced
workforce, the lower employee performances, restriction measures (travel and gathering bans, social distancing), budget cuts and disruption of supply chain that result from pandemics and the shift towards remote working directly impact the implementation of PSM systems. The discussion of the FTA highlighted the need for organizations to:

- Ensure that pandemics are recognized a credible scenario in their hazard analysis and evaluate the impact on their risk profile;
- Put in place measures to ensure the continuity of the PSM related tasks through the identification of safety-critical tasks and critical safety personnel;
- Ensure redundancy of operational teams and critical personnel with a reduced workforce and prevention measures against the simultaneous unavailability of redundant teams;
- Develop PSM procedures and plans that consider the limitation associated with the pandemic and are adapted to remote working;
- Provide remote working infrastructures for the execution of PSM related activity remotely;
- Take the necessary measures to overcome the challenges associated with the disruption of supply chain through either the identification of alternative local third parties capable of delivering the same service that is less vulnerable to pandemic restrictions and/or developing internal competencies to ensure in-house capabilities and expertise to perform the work when possible temporarily;
- Proactively manage the workload of both employees working onsite and the ones working remotely in order to minimize fatigue;
- Proactively develop strategies to manage the mental health issues associated with the pandemic socio-economic climate and the isolation associated with remote working;
- Develop capabilities to provide remote training to personnel to pursue its critical safety training during pandemics.

Significant changes in the way process safety are managed in the industry and regulated mainly come as a response to major incidents such as the 1984 Bhopal and the 1976 Seveso incidents (Besserman and Mentzer, 2017). Similarly, the COVID-19 pandemic should be used as an opportunity to understand the challenges posed by a pandemic on the control of process safety risks and develop robust and resilient PSM systems to continuously ensure safe operations.

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.

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List of Acronyms

| Acronym | Full Form |
|---------|-----------|
| CCPS    | Center for Chemical Process Safety |
| COVID-19 | Coronavirus disease 2019 |
| ERP     | Emergency Response Plan |
| FTA     | Fault Tree Analysis |
| HAZOP   | Hazard and Operability |
| HIRA    | Hazard Identification and Risk Assessment |
| ITPM    | Inspection Testing Preventative Maintenance |
| LOPA    | Layer Of Protection Analysis |
| LOPC    | Loss of Primary Containment |
| MoC     | Management of Change |
| P&D     | Piping and Instrumentation Diagram |
| PSM     | Process Safety Management |
| PTW     | Permit to Work |
| US OSHA | United States Occupational Safety and Health Administration |

References

Bajpai, S., Gupta, J.P., 2005. Site security for chemical process industries. J. Loss Prev. Process. Ind. 18, 301–309. https://doi.org/10.1016/j.jlp.2005.06.011.

Barton, Daniel C., 2020. Impacts of the COVID-19 pandemic on field instruction and remote teaching alternatives: Results from a survey of instructors. Ecol. Evol. https://doi.org/10.1002/ece3.6628.

Baucher, M.-A., Kearns, P., Gyenes, Z., Heraty Wood, M., Baubion, C., Gamper, C., Radisch, J., Girgin, S., Krausmann, E., Necie, A., Guzman, O., Milligan, P.A., 2018. Towards an All-Hazards Approach to Emergency Preparedness and Response Lessons Learnt from Non-nuclear Events 104.

Besserman, J., Mentzer, R.A., 2017. Review of global process safety regulations: United States, European Union, United Kingdom, China, India. J. Loss Prev. Process. Ind. 50, 165–183. https://doi.org/10.1016/j.jlp.2017.09.010.

Bin, N., Sahar, M., Ani, S., Karahiko, S., Yoshiomi, M., Hirotsugu, M., 2018. HAZOP Analysis Management System with Dynamic Visual Model Aid Division of Industrial Innovation Sciences. Department of Intelligent Mechanical Systems, Polytechnic Manufacturing Astra.

Blanc, I. H. le, 2020. A brief historical review of the great pandemic of 1918 : the Spanish flu. Eubios J. Asian Int. Bioeth. (EJAB) 30, 81–83.

CCPS, 2007. Guidelines for Risk Based Process Safety. John Wiley & Sons, Inc.

Center for Chemical Process Safety, 2020. CCPs Monographs: Risk Based Process Safety during Disruptive Times. Insights for Managing Process Safety during and Following the COVID-19 Pandemic and Similar Crises [WWW Document]. URL. https://www.aiche.org/chemneted/2020/04/insights-help-your-company-manage-process-safety-during-covid-19. accessed 8.30.20.

Center for Chemical Process Safety CCPs, 2020a. CCPs Monographs: Reflections from Global Process Safety Leaders during and Following Pandemics. Best Practices for Managing Process Safety presented by a select panel of leaders worldwide [WWW Document]. URL. https://www.aiche.org/sites/default/files/html/ccps/556/441/reflections-from-global-process-safety-leaders-on-pandemics.html. accessed 8.30.20.

Center for Chemical Process Safety CCPs, 2020b. CCPs Monographs: Reflections from Global Process Safety Leaders during and Following Pandemics. Best Practices for Managing Process Safety presented by a select panel of leaders worldwide [WWW Document]. URL. https://www.aiche.org/chemneted/2020/04/insights-help-your-company-manage-process-safety-during-covid-19. accessed 8.30.20.

Center for Chemical Process Safety CCPs, 2010. Guidelines for Risk Based Process Safety, Guidelines for Risk Based Process Safety. John Wiley & Sons, Inc. https://doi.org/10.1002/9780470925119.

Green, L.M., Karabayaeva, A., 2020. Managing virtual workers - strategies for success. IEEE Eng. Manag. Rev. 48, 166–172. https://doi.org/10.1109/EMR.2020.2990386.

Khan, K.S., Mamun, M.A., Griffiths, M.D., Ullah, I., 2020. The mental health impact of the COVID-19 pandemic across different cohorts. Int. J. Ment. Health Addiction. https://doi.org/10.1007/s11469-020-00367-0.

Latino, M.A., Latino, R.J., Latino, K.C., 2020. Root Cause Analysis Improving Performance for Bottom-Line Results, fifth ed. CRC Press Taylor & Francis Group, Boca Raton.

Mathur, A., 2020. Gross Negligence, Lack of Training Caused Vigaz Gas Leak: Report. India Today.

Mesa-Gomez, A., Casal, J., Muñoz, P., 2020. Risk analysis in Natch events: state of the art. J. Loss Prev. Process. Ind. 64 https://doi.org/10.1016/j.jlp.2020.104671.

Ollif, S., 2008. All systems go. Saf. Health Pract. 26, 46–48. https://doi.org/10.1016/j.saphpr.2008.05.002.

Vaughen, B.K., 2020. Understanding and managing the risk during transient operations. Process Saf. Prog. 39, e12146. https://doi.org/10.1002/prs.12146.

Walsh, B., 2020. Covid-19: the History of Pandemics. BBC Future.

Wang, J., 2018. In: Wang, J.B.T.-S.T., CT of, H.-S.T.O. (Eds.), Chapter 11 - Safety Analysis Methods for Train Control Systems. Academic Press, pp. 309–354. https://doi.org/10.1016/B978-0-12-813304-0.00011-6.

World Health Organisation, n.d. Weekly operational update on COVID-19 - 23 August 2021 [WWW Document]. URL. https://www.who.int/publications/m/item/weekly-operational-update-on-covid-19-23-august-2021. accessed 8.24.21.

World Health Organization, n.d. Global Process Safety Leaders during and Following Pandemics. Best Practices for Managing Process Safety presented by a select panel of leaders worldwide [WWW Document]. URL. https://www.aiche.org/chemneted/2020/04/insights-help-your-company-manage-process-safety-during-covid-19. accessed 8.30.20.

World Health Organization, n.d. Weekly operational update on COVID-19 - 23 August 2021 [WWW Document]. URL. https://www.who.int/publications/m/item/weekly-operational-update-on-covid-19-23-august-2021. accessed 8.24.21.