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Factors contributing to US chemical plant process safety incidents from 2010 to 2020

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ABSTRACT

Process safety incidents can result in injuries, fatalities, environmental impacts, facility damage, downtime & lost production, as well as impacts on a company's and industry's reputation. This study is focused on an analysis of the most commonly reported contributing factors to process safety incidents in the US chemical manufacturing industry. The database for the study contained 79 incidents from 2010 to 2019, partly investigated by the Chemical Safety Board (CSB). To be included in the study, the CSB archive of incident investigations were parsed to include only incidents which occurred at a company classified as 325 in the North American Industry Classification System (NAICS), assigned to businesses that participate in chemical manufacturing. For each incident, all of the identified contributing factors were catalogued in the database. From this list of identified contributing factors, it was possible to name the 'top three' contributing factors. The top three contributing factors cited for the chemical manufacturing industry were found to be: design; preventive maintenance; and safeguards, controls & layers of protection. The relationship between these top contributing factors and the most common OSHA citations was investigated as well. The investigation and citation history for NAICS 325 companies in the Occupational Safety & Health Administration (OSHA) citations database was then analysed to assess whether there was any overlap between the top reported contributing factors to process safety events and the top OSHA citations recorded for the industry. A database consisting of the inspection and citation history for the chemical manufacturing industry identified by NAICS code 325 was assembled for inspections occurring between 2010 and 2020 (August). The analysis of the citation history for the chemical manufacturing industry specifically, identified that the list of the top contributing factors to process safety incidents overlapped with the most common OSHA violations. This finding is relevant to industry stakeholders who are considering how to strategically invest resources for achieving maximum benefit – reducing process safety risk and simultaneously improving OSHA citation history.

1. Introduction

Process safety incidents are often low frequency – high consequence events involving loss of containment of hazardous materials resulting in impacts to personnel, the facility itself, the environment, and/or the nearby community. This is different from occupational safety, which typically involves incidents such as slips, trips and falls; generally thought of as higher frequency – lower consequence events. Numerous studies have been done analysing serious plant process safety related mishaps in search of factors contributing to incidents, so that others can apply the learnings to their operations and thus prevent or mitigate such events in the future.

Many articles, as well as books, have been published analysing process safety related events for lessons learned and opportunities for improving plant safety. Notable books include 'What Went Wrong?' by (Kletz, 2009) and 'Chemical Process Safety: Learning from Case Histories' by (Sanders, 2005). Being in their 5th and 3rd editions, respectively, many are seeking to learn how to prevent events based on factors that contributed to earlier events.

Further, process safety is the subject of many scientific journal articles. Kannan et al. (2016) summarize numerous efforts at developing databases of events and then analysing the incidents for common factors

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that contributed to the events. They used a web-based 'crawler' strategy to identify incidents and then categorized them into different incident types.

A recent study (Bhusari et al., 2020) examined process safety incidents across 14 industries including, refining, chemicals, agriculture, pharmaceuticals, manufacturing et al. Their analysis of 81 incidents found the most common factors contributing to events being safety culture, emergency preparedness, and mechanical integrity. Their analysis specific to ten global chemical plant events found the contributing factors to be: safety culture, training, operating procedures, management of change, PHAs (process hazards analysis), and emergency preparedness & response. A follow up study focused on the factors contributing to 73 global incidents in the pharmaceutical industry, with two incidents in 2018 & 2019 resulting in 29 fatalities (Maniar et al., 2020).

Marsh's latest bi-annual publication of the '100 Largest Losses in the Hydrocarbon Industry, 1974–2019' (Marsh, 2020) is sobering, with four incidents during the past two years among the 20 largest losses of all time. Two of the four were in the US. Of the 100 incidents, 39% were at refineries, 26% petrochemical plants and 24% upstream operations, with the current cut-off $175 M for an incident to make the list. They note an observed decline in risk tolerance at refineries, with plants over 30 years old more likely to experience losses. On the other hand, most incidents during the first decade of a plant's operation tend to be operations/human related. Marsh (2020) notes: 'The very best sites, with the most mature process safety cultures, have consistently shown it is possible to run a facility without losses across the duration of their lifespan, and across a range of external regulatory standards and oil prices' (Marsh, 2020).

The National Institute of Public Health and the Environment, RIVM of the Netherlands conducted an exhaustive study entitled, 'Fifteen Years of Incident Analysis' (Kooi et al., 2020). They examined 326 incidents involving hazardous substances from 2014 to 2018 where a common agency and technique was used to analyse the incidents. The incidents resulted in 5 fatalities and 125 injuries. While the incidents included in the analyses were within a broader scope of industries, 97% being covered by the EU Seveso III Directive, the incidents primarily occurred at chemical manufacturing sites, which will be addressed later in the Discussion section.

Also, Fyffe et al. (2016) and Baybutt (2016) both analysed CSB incident investigations in terms of common factors leading to incidents, which will be discussed further later. In our study, CSB incidents specifically in the chemical manufacturing industry were analysed along with a large database of OSHA violations.

This study, sponsored by the American Chemistry Council (ACC), was undertaken to examine serious process safety incidents in the US chemical manufacturing industry over the past decade to identify common factors contributing to incidents specific to this industry. In Chapter 2, the analysis of incidents investigated by the CSB and chemical manufacturing companies participating within NAICS 325 was conducted to determine the most common contributing factors. In Chapter 3, a review of thousands of incidents in the OSHA database for the top OSHA citations recorded for the chemical industry over the same timeframe was performed to compare with findings concluded from contributing factors analysis. Industry stakeholders can use key findings from these two analyses to improve their process safety performance.

1.1. *Factors contributing to incidents*

The term 'contributing factors' is used throughout this study, in lieu of the term 'causal factors.' Most often, there are many factors that have contributed to an incident, some of which may be related to the initiation of the incident, and others which may have increased the incident severity. A list of the contributing factors for the incidents described in this study is contained in Table 1. These contributing factors are commonly used factors that have been cited by others; including Bhusari

Table 1
List of contributing factors and definitions. (*: PSM Elements).

No.	Contributing Factors	Definition or Description
1	Safety Culture	CCPS defines safety culture as 'the common set of values, behaviour and norms at all levels in a facility or in the wider organization that affect process safety.' A weak safety culture implies lack of leadership, lack of a common understanding of each individual's responsibilities regarding safety, ineffective supervisory oversight, placing production before safety, ineffective safe management systems and not measuring proper personnel and process safety metrics.
2	Hazard Awareness and Identification	The process of identifying the hazards in the workplace that can cause potential harm to personnel, environment or processes and eliminating these hazards to reduce workplace incidents (e.g., ventilation and gas monitoring). This is a daily understanding of hazards across the workplace by the workforce, vs. higher level PHA. It is commonly done by a hazard assessment survey of operations, understanding of process safety information like safety data sheets (SDS), proper housekeeping for cleaner and safer workplace, equipment and materials, recording incidents and near misses.
3	PHA*	PHAs (Process Hazard Analysis) use methodologies including but not limited to Checklist, What if, HAZOP (Hazard and Operability) study and FMEA (Failure Mode and Effects Analysis). They are commonly done by a team consisting of representatives of operations, engineering, and maintenance. In the US, compliance with OSHA PSM requires they be performed at least every five years. Observed shortcomings may be lack of a PHA or inadequate/incomplete effort.
4	Operating Procedures*	Written operating procedures aligned with process safety that provide clear step-by-step instructions for safely performing tasks involved in each process. These typically include operating limits, safety and health considerations and safety systems, for multiple operating modes - initial start-up, normal operations, shutdown et al. as noted by OSHA PSM.
5	Work Permit System*	A work permit system is a formal written system used to control certain types of work (e.g., lockout/tagout, hot work, work at height or confined spaces) that are not part of routine operations and are potentially hazardous. The document typically specifies the work to be done and the precautions to be taken to mitigate hazards, typically reviewed and signed off on by site supervision. Observed shortcomings may include an absence of a system, documented inadequacies not remedied, and incomplete execution of an existing system.
6	Personnel Training*	Comprehensive program of on the job training (OJT) and informative/technical training of employees and contractors (including supervisors). Program is documented and includes periodic refresher training and assessment of competency. Emergency response duties and training for response are included for relevant personnel.
7	Mechanical Integrity*	Mechanical integrity programs are designed by companies to help determine the acceptable level of risk, engineering design standards, and the need for refurbishment/replacement as equipment reaches its useful life. The inspection, testing and maintenance of process equipment typically considers the hazards and risks of the operations, including such equipment as vessels, storage tanks, piping

(*continued on next page*)

Table 1 (*continued*)

No.	Contributing Factors	Definition or Description
		systems, relief systems, controls, alarms, and emergency shutdown systems. Examples of excellence include a documented mechanical integrity program with written procedures and a schedule for inspections and testing to ensure fitness for use during equipment's lifetime.
8	Safeguards, Controls & Layers of Protection	Barriers, such as instrumentation and control hierarchy, designed to address potential failures. Note, there is a probability of failure on demand for every safety device. A failure to function on demand for a safety device such as a rupture disc, PRV, secondary containment etc. or back-up power generator would constitute inclusion in this category.
9	Preventive Maintenance	Preventive maintenance is the periodic inspection and maintenance of equipment to reduce the likelihood of its failure or performance degradation. This is to determine that the equipment is safe to operate and to fix issues thus preventing major hazards due to equipment malfunctioning.
10	Management of Change*	CCPS defines Management of Change (MOC) as 'a process to ensure changes do not inadvertently introduce new hazards or unknowingly increase risk of existing hazards.' MOC includes a review and authorization process for evaluating proposed adjustments to facility design, operations, organization, or activities prior to implementation to make certain that no unforeseen new hazards are introduced and that the risk of existing hazards to employees, the public, or the environment is not unknowingly increased. Observed shortcomings may be lack of a MOC process, existing process but not utilized, or inadequate/incomplete process.
11	Contractor Management*	The expectation is that operators will consider safety performance and related training in the selection of contractors. The contractors in turn are expected to arrive on-site knowledgeable of safe work practices and potential hazards associated with their assigned role.
12	Design	Designs generally consider RAGAGEP (Recognized and Generally Accepted Good Engineering Practices), reflecting hazards, safety systems and instrumentation. Shortcomings may include an inadequate facility design, materials of construction, or lack of appropriate safety systems or barrier protection. Lack of consideration of potentially safer design.
13	Human Factors	Human and organizational issues, such as equipment related (e.g., valve location, lighting), sufficient staffing, as well as broader organizational issues. Often seen in terms of the interface between individuals, the equipment, and systems/procedures. Shortcomings can result in accepted 'normalization of deviance' by operators.
14	Facility Siting	Proximity of facilities to the public (i.e. residential housing, educational facilities, shopping areas, etc.), as well as location of on-site plant personnel to hazards. Considers analysis of consequences of flammable and/or toxic hazardous materials.
15	Pre-startup Safety Review*	Prior to restarting a facility the expectation is that a process will be followed to review the changes made, that they are per specifications, any PHA recommendations were followed, and employees/contractors have received related operator training associated with any changes.
16	Regulations and Regulatory Oversight	There are a variety of regulations (e.g., OSHA, EPA, DHS) that cover people in and outside a site, as well as the environment. May include periodic regulatory inspections/audits. An example of a shortcomings may be failure to meet inspection/audit expectations. Regulations typically set a minimum standard for compliance, so there may be areas or issues not necessarily covered by a specific regulation.
17	Natural Disasters	Natural disasters such as earthquakes, hurricanes and lighting can initiate catastrophic events. Designs and procedures should consider severe weather events such as hurricanes, earthquakes, 100-year floods, etc. This is separate and different from emergency response following an incident. This factor would be selected if there was a natural weather event involved, or if there was a documented failure to design for that event.
18	Emergency Preparedness and Response*	Equipment, processes and training should generally be capable of handling emergencies such as spills, fires, explosions, natural disasters such as hurricanes, and security breaches. Examples of excellence include written procedures, defined teams with clear roles and periodic training and drills, which may include appropriate external parties.

(2020) and Maniar (2020) in reviewing numerous global incidents. A few were specifically added as part of this study (e.g., facility siting & natural disasters). As one might expect, many of the contributing factors (9) are elements of OSHA Process Safety Management (OSHA, 2000) and shown with an "*" in Table 1. Similarly, Table 1 has many items in common with the Center for Chemical Process Safety's four pillars of process safety and twenty elements (CCPS, 2010), including safety culture, PHAs, operating procedures, asset integrity et al.

1.2. Database of US chemical plant incidents 2010–2020

One shortcoming of existing process safety related research is the absence of a database of incidents for analysis which identifies common root causes and contributing factors by industry. While some databases exist such as ASM (Abnormal Situation Management Consortium), eMARS (Major Accident Reporting System of the EU), IChemE, EPA RMP, and OSHA they all have various shortcomings in terms of scope, region, reporting limitations, and process for keeping it current. None of these databases contain all of the information needed to conduct an adequate analysis of all Tier 1 (API, 2016) process safety incidents by industry in a given country, as incident reporting and assignment of severity scores is inconsistent.

This study focuses on US chemical plant incidents from the last decade (2010–2019) and only includes incidents where incident investigations or internal company analyses were conducted to identify contributing factors. This excludes incidents where investigations were either not conducted or not available (may be ongoing). The chemical manufacturing industry was bounded by considering companies with NAICS code 325 (North American Industry Classification System). The description of activity under each NAICS code 3251, 3252, 3253, 3254, 3255, 3256, 3259, are shown in Table 2.

There are several sources of data which can be referenced to determine participation in the NAICS code 325, with participation ranging from 9721 to 42,108 of total number of companies, between data sources such as US Census Bureau and websites such as NAICS.com. The US Census data was selected as the source for documentation of company classification as NAICS 325 with data up to 2017 SUSB Annual Data Tables by Establishment Industry (Census-Bureau, 2017), being used for this study to represent the number of companies participating in NAICS 325. (Note, 2017 was the most current data at the time of this writing). Currently, the number of US companies which belong to NAICS code 325 – Chemical Manufacturing is 9721. It is noted the count of members participating in the 325 NAICS code does not reflect the

Table 2
List of applicable NAICS codes (NAICS, 2020) for this study.

NAICS Code	Industry Group	Description
325	Chemical Manufacturing	This sector comprises establishments primarily engaged in manufacturing chemicals and chemical preparations, from organic and inorganic raw materials.
3251	Basic Chemical Manufacturing	This industry group comprises establishments primarily engaged in manufacturing chemicals, using basic processes such as thermal cracking and distillation. Chemicals produced in this industry group are usually separate chemical elements or separate chemically-defined compounds.
3252	Resin, Synthetic Rubber, and Artificial and Synthetic Fibers and Filaments Manufacturing	This industry group comprises establishments primarily engaged in manufacturing polymers such as resins, synthetic rubber, and textile fibers and filaments. Polymerization of monomers into polymers, for example of styrene into polystyrene, is the basic process.
3253	Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing	This industry group comprises establishments primarily engaged in manufacturing agricultural chemicals, including nitrogenous and phosphoric fertilizer materials; mixed fertilizers; and agricultural and household pest control chemicals.
3254	Pharmaceutical and Medicine Manufacturing	This industry group comprises establishments primarily engaged in manufacturing drugs, medicines and related products for human or animal use. Establishments in this industry may undertake one or more of several processes, including basic processes, such as chemical synthesis, fermentation, distillation and solvent extraction; grading, grinding and milling; and packaging in forms suitable for internal and external use, such as tablets, vials, ampoules and ointments.
3255	Paint, Coating, and Adhesive Manufacturing	This industry group comprises establishments primarily engaged in manufacturing paints, coatings and adhesives.
3256	Soap, Cleaning Compound, and Toilet Preparation Manufacturing	This industry group comprises establishments primarily engaged in manufacturing soap and other cleaning compounds and toilet preparations.
3259	Other Chemical Product and Preparation Manufacturing	This industry group comprises establishments, not classified to any other industry group, primarily engaged in manufacturing chemical products.

number of facilities that may be associated with each company (many of whom have multiple facilities).

The total number of chemical companies in each NAICS code 3251–3259 is shown in Fig. 1. It is noted that some companies may have multiple registration codes within 325. The top three NAICS codes for the industry were: 3256 (Soap, Cleaning Compound and Toilet Preparation), 3254 (Pharmaceutical and Medicine) and 3259 (Other) representing about 70% of companies in the chemical manufacturing industry.

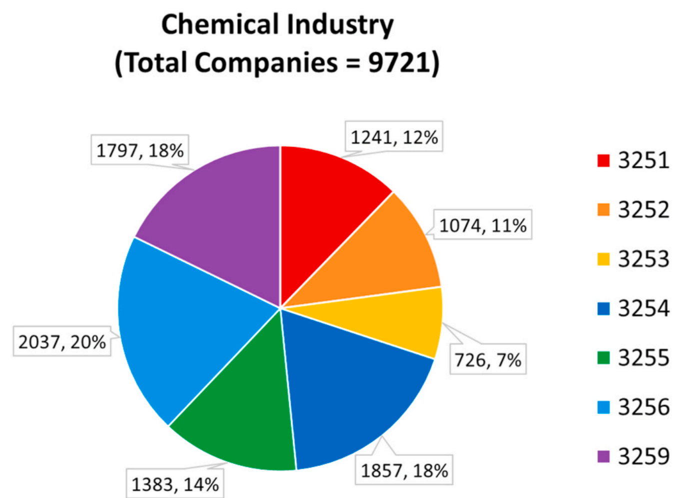

Fig. 1. Pie chart of number of US companies in each NAICS code for chemical manufacturing industry (Census-Bureau, 2017).

Seventy-nine (79) incidents with applicable NAICS codes and complete investigation reports were obtained from the CSB (Chemical Safety Board) database within the 2010–2019 date range (CSB, 2020) and from internal company incident data collected over the time period 2017–2020. The latter time period was limited by those events with reported contributing factors. Details from the incidents contained within the CSB database are summarized in Table 1A in Supplemental Information, in terms of incident, location, date of event, fatalities, and injuries. All 79 incidents included in the study were Tier 1 incidents.

Although the dataset is limited to 79 incidents, it is robust with incident investigations conducted for each, with a high level of analysis of the factors contributing to the events. The composition of the dataset in terms of total incidents and those associated with fatalities is shown in Fig. 2.

Incidents were further categorized in terms of severity, as defined in API/RP 754, Table D1 - Tier 1 Process Safety Event Severity Weighting (API, 2016). To determine an event severity, points are assigned when an event results in medical treatment, injury, fatality or multiple fatalities, respectively. Points are also assigned for monetary damages, quantity of material released, community impact and off-site

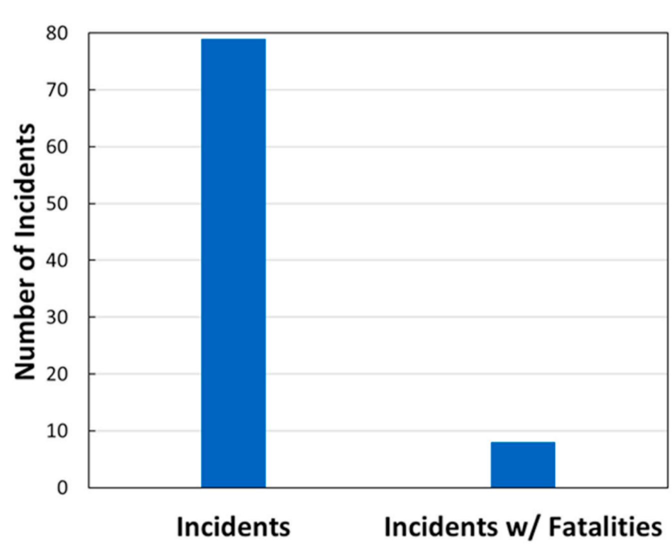

Fig. 2. Number of incidents and incidents with fatalities (2010–2020) for the chemical industry.

environmental impact.

For this study, incidents were divided into three groups based on their defined API severity score: 9 (medium), 10–45 (high), 45+ (very high). All the incidents investigated by CSB were scored as “very high” recognizing that the CSB generally investigates very severe incidents, generally with fatalities, huge economic losses, or significant community and environmental impacts. The number of events were grouped into the three severity score ranges, as shown in Fig. 3. In total, 12 incidents were scored “high”, eight had scores 20–29, four had scores 10–19. Thus 43 events (or 54% of the dataset) were incidents scoring 9, e.g., tank overfills, chemical releases with no fatalities or significant community or environmental impacts. Low severity scoring events below a 9 were not included in this study.

1.2.1. Operation mode during incident

The operation mode when the incident occurred was identified by the CSB investigation reports and through the companies' internal investigations. About 75% of incidents occurred during normal operations for both the chemical industry (Fig. 4), which is consistent with the analysis of Bhusari (2020) who found 69% of the 81 incidents studied occurred during normal operations. It was noted that these results have not been normalized to account for time spent in each operation mode.

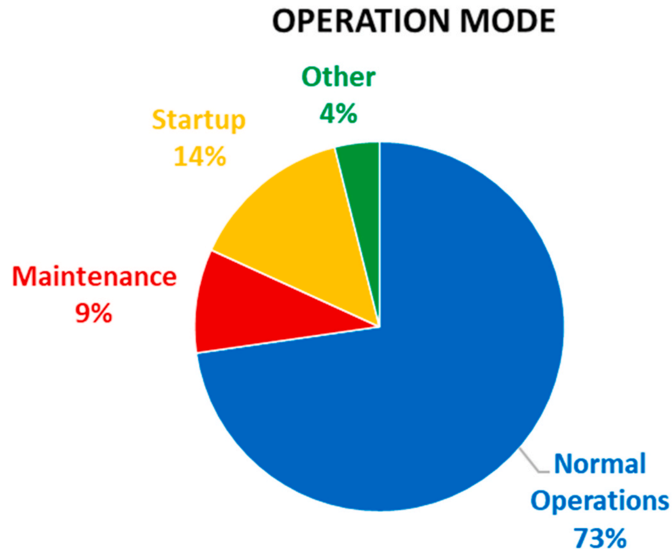

Fig. 4. Operation modes when incidents occurred.

1.3. Contributing factor analysis

The most common reported contributing factors were listed by incident severity: 9 (medium), 10–45 (high), 45+ (very high). Then, three groupings were created for this analysis, the 1st group included all incidents with a severity score of 9 and above (which includes incidents of medium, high and very high severity). The next group excluded the medium severity incidents, and only considered incidents with a severity score above 10 (keeping only the high and very high incidents). The third group included only very high severity incidents. By grouping the contributing factor findings in this way, it was possible to see whether the list of top contributing factors changed with increasing severity scores.

The list of the top five most common reported contributing factors is shown by severity ranking for the chemical industry in Table 3. Incidents were analyzed and assigned with multiple contributing factors listed in Table 1. The top five factors are presented in order of occurrence, with the most common factor at the top. Mechanical Integrity and Human Factors were only present in Group 1, which contained the medium, high and very high severity incidents. For Groups 2 & 3, Safeguards, Controls & Layers of Protection and Design are the top two in the lists, which were more common in the severe incidents. Other observations from Table 3, include: Preventive Maintenance and Design appears in all three subsets; Safety Culture and Emergency Preparedness and Response only occurred in the “very high” severity score group.

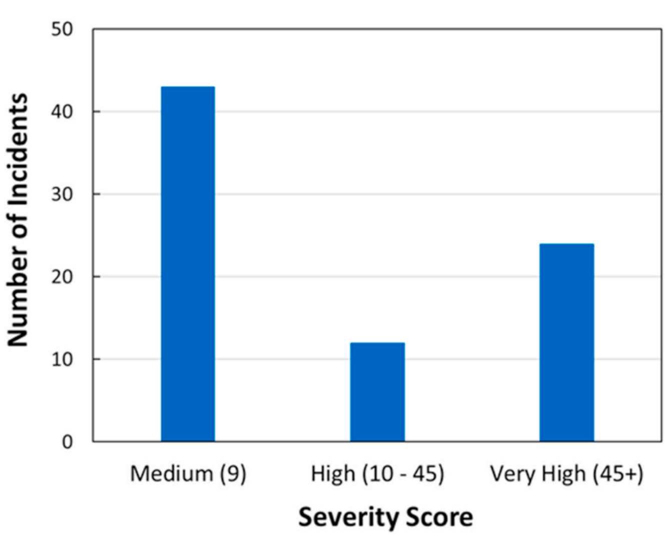

Fig. 3. Number of incidents from chemical industry (2010–2020) analysed by severity.

Table 3
Top five most common reported contributing factors for chemical industry by three groups of severity scores.

Severity Score	Top Contributing Factors
Group 1: Medium, High, Very High (9+)	Operating Procedures
	Mechanical Integrity
	Design
	Human Factors
	Preventive Maintenance
Group 2: High, Very High (10+)	Design
	Safeguards, Controls & Layers of Protection
	Operating Procedures
	Preventive Maintenance
	Hazard Awareness and Identification
Group 3: Very High (45+)	Safeguards, Controls & Layers of Protection
	Design
	Safety Culture
	Preventive Maintenance
	Emergency Preparedness and Response

The comparison of contributing factors by severity grouping was conducted to assess the impact of the severity score on the list of common contributing factors. It was determined that the ordered list of contributing factors changed with the severity score but with most contributing factors remaining the same.

It is prudent to think of the list of contributing factors outside of those that just result in high severity incidents. In order to understand how to prioritize the list of contributing factors, a weighted score was developed for each contributing factor. For each contributing factor occurrence in Group 1, 2, and 3, the contributing factor was weighted with 1, 2 and 3 points, respectively, reflecting the seriousness of the incidents in each group. The total weighted score of every listed contributing factor is shown in Table 4.

Design was at the top of the list, which was followed by Preventive Maintenance in 2nd place, and Safeguards, Controls & Layers of Protection in 3rd place. This finding can provide guidance on which contributing factors or management systems companies may want to focus upon for improvement opportunities. For chemical industry companies, a possible path forward might be to select a contributing factor from the top of this list, and develop resources to assess its performance and enhance, as appropriate.

1.4. OSHA inspections

The OSHA (Occupational Safety and Health Administration) inspection database represents a significant source of data. The database contains records of inspections by company by date, including inspections that might be related to either process safety incidents or from the more typical and numerous occupational safety incidents.

The number of inspections conducted by OSHA per year on companies with NAICS code starting with 325 were obtained from the OSHA open database (OSHA, 2020a). A decline in the number of inspections from (2010–2014) of approximately 20% was observed, with the number of inspections remaining relatively constant from 2014 to 2019 (Fig. 5). Despite the reduction in inspections, each year nearly 60% of inspections resulted in one or more citations issued by OSHA, as shown by the upper portion of the bars in Fig. 5.

The citations issued by OSHA to companies with NAICS codes starting with 325 over the last decade (2010–2019) were collected from the OSHA open database (OSHA, 2020a). The number of citations decreased markedly from 2010 and remained relatively constant after 2014, per Fig. 6. This data may be related to funding issues within OSHA, and variance on the process by which OSHA conducts programmed vs. un-programmed inspections. Compared to the 20% reduction in the number of inspections, over the last decade the number of citations declined by more than 40%. The drop in citations coincides with a reconfiguration of penalty amounts by OSHA, who has seen a similar drop in citations across various sectors. The average number of citations per inspection thus declined from 3.5 in 2010 down to 2.5 after 2014. In terms of citations, the overall performance of the chemical manufacturing industry improved notably from 2010 to 2014, but appears to have plateaued since 2015.

With regard to improvement, three subsets of the NAICS 325 code exhibited less improvement than the average: 3252 (Resin, Rubber, Fibers and Filaments), 3253 (Pesticide, Fertilizer, and Other Agricultural), and 3254 (Pharmaceutical and Medicine). These codes represent 36% of the 325 chemical industry.

The OSHA code's most commonly cited standard title for the chemical industry (NAICS 325) is the 29 CFR 1910.119 - Process Safety Management of Highly Hazardous Chemicals from the OSHA Regulations (Standards - 29 CFR) (OSHA, 2020b). The trend showing the number of citations issued on Standard 29 CFR 1910.119 is shown in Fig. 7. Despite the overall decreasing trend, a peak occurred in 2012 with about twice the number of citations that year. This may be due to a number of large incidents that occurred in the sector that year.

Table 4
Most significant contributing factors for chemical industry.

Rank	Contributing Factor	Weighted Score
1	Design	6
2	Preventive Maintenance	6
3	Safeguards, Controls & Layers of Protection	5
4	Emergency Preparedness and Response	3
5	Operating Procedures	3
6	Safety Culture	3
7	Hazard Awareness and Identification	2
8	Mechanical Integrity	1
9	Human Factors	1

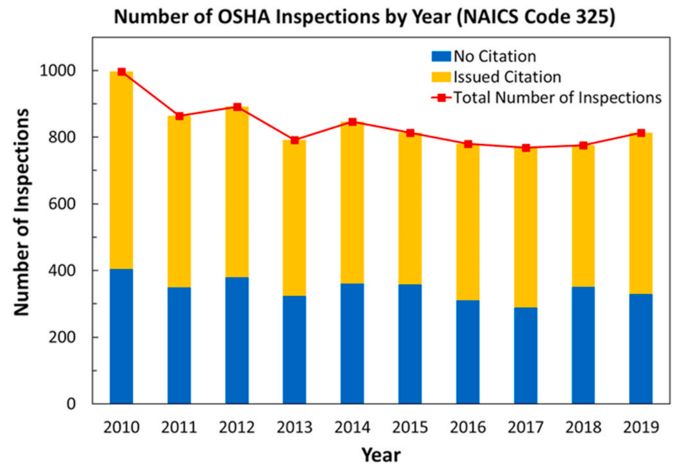

Fig. 5. Number of inspections conducted by OSHA (2010–2019) with and without issuing citations (OSHA, 2020a).

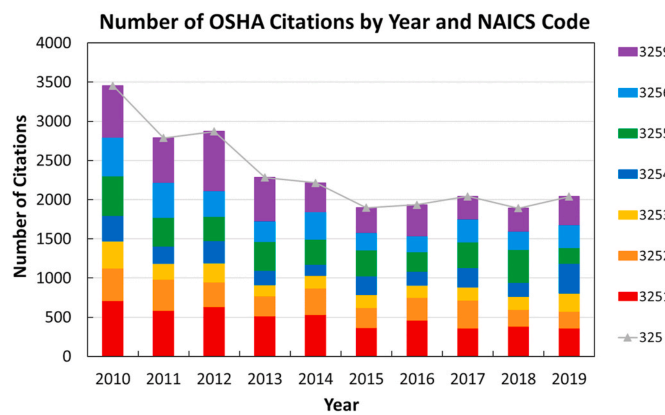

Fig. 6. Number of citations issued by OSHA (2010–2019) in each NAICS code (OSHA, 2020a).

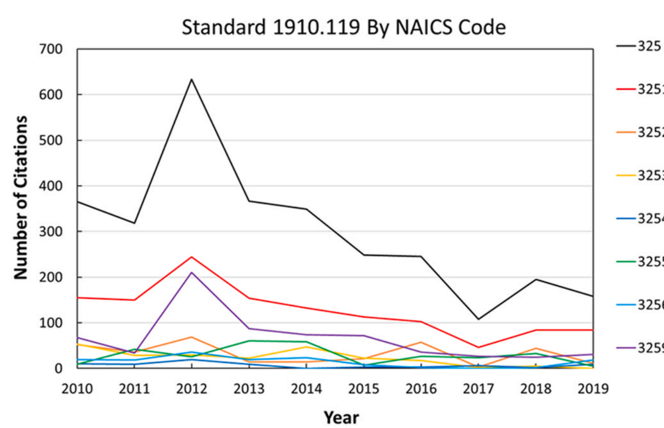

Fig. 7. Number of citations from Standard 1910.119 (Process safety management of highly hazardous chemicals) issued by OSHA (2010–2019) in each NAICS code.

1.5. Regulatory violations cited in OSHA inspections

The number of inspections in which at least one citation was issued were collected from the OSHA database for 2010–2020 (through August) for the seven NAICS codes noted in Table 2. The number of inspections with citations analysed in this study are shown in Table 5. The total number of inspections with citations for each NAICS code were parsed to extract information on the number of inspections with citations involving fatalities. This provided an opportunity to analyse the data for potential trends and to compare the inspection history of the chemical industry, within each NAICS sub-code. Over the time period 2010–2020 (August), the chemical industry has a rate of 0.52 inspections resulting in at least one citation per company (5067/9721).

Often, multiple citations are received following inspections, and the trends associated with the total number of citations per NAICS code were analysed. The total number of citations in this study are shown numerically in Table 6 and graphically in Fig. 8.

Compared with Fig. 1, even though 3254 has 18% of the number of companies, it only accounts for 10% of total citations. Codes 3251, 3252, 3253, 3255 and 3259 all thus have larger shares of total citations. With regard to the citations with fatalities, which were usually associated with the "very high" severity score incidents, codes 3259 and 3251 have the two largest shares which combined are over 60%.

The total number of citations per company for the chemical industry per NAICS code are shown in Fig. 9. The industry average is that each company in code 325 received about 2.5 citations. Companies in code 3251 (Basic Chemical Manufacturing) received more citations than the average around 4.0, while codes 3254 (Pharmaceutical and Medicine Manufacturing) and 3256 (Soap, Cleaning Compound, and Toilet Preparation Manufacturing) were below the average, around 1.5.

Citations were further analysed to determine the frequency of specific regulatory violations (e.g., 1910.119, …) by NAICS code and for the total seven NAICS codes. Four levels, from general standard part and subparts to more specific standard titles, were used to categorize the cited codes. Top code sections cited during 2010–2020 (split by total citations and citations with fatalities) are shown in Table 7 for 325 and in Table 8 for 3251. The summary Table 7 for 325, is generated based on the results of all NAICS codes. Table 8 of 3251 is an example to display the frequency of violated codes, with this code representing the largest share of total citations. Specific results for the other codes (3252, 3253, 3254, 3255, 3256, 3259) can be found in the Supplemental Information.

Code 325 includes all companies which participate in chemical manufacturing. Since the number of citations both with fatalities and the totals are relatively large, the trends observed with respect to code citations are noteworthy. It is noted that Part 1910 – Occupational Safety and Health Standards is the top code violation in inspections with at least one citation, with fatalities, and with total citations in Table 7. Further, the number of citations corresponding to this code are an order of magnitude or more, larger than the next most cited code. There is a notable match in the cited codes for "citations with fatalities" and "all citations", where the OSHA Act of 1970 is also commonly cited.

Information on three further subclasses of Part 1910 were explored and tabulated in the second row (Standard Subpart) of Table 7. Subpart H – Hazardous Materials was the top most cited code in all columns indicating remarkable consistency across citations and across industrial entities. The 2nd to 5th most cited subparts were also consistent, despite some variation in the order: I - Personal Protective Equipment, Z - Toxic and Hazardous Substances, J - General Environmental Controls, and S - Electrical.

As the analysis continues to further subparts, in the 3rd row (Standard Title) of Table 7, "Process Safety Management of Highly Hazardous Materials" is at the top (Standard 1910.119). There is more variation in the other top 5 OSHA titles violated, with 1910.1200 - Hazard Communication, and 1910.134 - Respiratory Protection arising in both columns.

Within Standard 1910.119, as shown in the 4th row (Standard 1910.119) of Table 7, the top five codes are remarkably consistent for all citations with and without fatalities. They are: (j) Mechanical integrity, (d) Process safety information, (e) Process hazard analysis, (f) Operating procedures, (l) Management of change. An exception is in the chemical industry with fatalities where (g) Training is the 5th code instead of (l) Management of change.

In order to help reduce citations issued by OSHA and improve the occupational safety performance, Standard 1910.119 - Process Safety Management of Highly Hazardous Materials is an important code upon which companies may wish to focus during internal reviews.

The relationship of common contributing factors to process safety incidents determined from incident investigations and results from analysis of OSHA citations was assessed. In Table 4, the top nine contributing factors were listed for the chemical manufacturing industry based on their weighted scores calculated from Table 3. A mapping of the top contributing factors to the top ten OSHA standards was completed (Fig. 10). The mapping demonstrates that the most common contributing factors to process safety incidents are also some of the most commonly cited OSHA regulations.

Seven out of nine contributing factors can be mapped to one or more OSHA standards. Particularly, five contributing factors are mapped to Standard 1910.119 - Process safety management of highly hazardous materials. These five include:

- Preventive Maintenance, Mechanical Integrity -> (j) Mechanical integrity
- Emergency Preparedness and Response -> (n) Emergency planning and response
- Operating Procedures -> (f) Operating procedures
- Hazard Awareness and Identification -> (d) Process safety information

The "Design" and "Human Factors" contributing factors could not be linked to the commonly cited OSHA standards. "Design" may be a consideration in some of the noted standards, such as Electrical, while "Human Factors" may be addressed in other standards, including various aspects of training programs.

Table 5
Number of inspections collected from OSHA and analysed in this study per NAICS code.

NAICS Code	# Inspections with Fatalities	Total # Inspections
3251	53	1098
3252	20	747
3253	18	339
3254	8	645
3255	10	641
3256	10	674
3259	26	923
325	145	5067

Table 6
Number of citations collected from OSHA and analysed in this study per NAICS code.

NAICS Code	# Citations with Fatalities	Total # Citations
3251	249	4952
3252	73	3107
3253	92	1999
3254	33	2446
3255	56	3455
3256	57	3172
3259	289	4706
325	849	23837

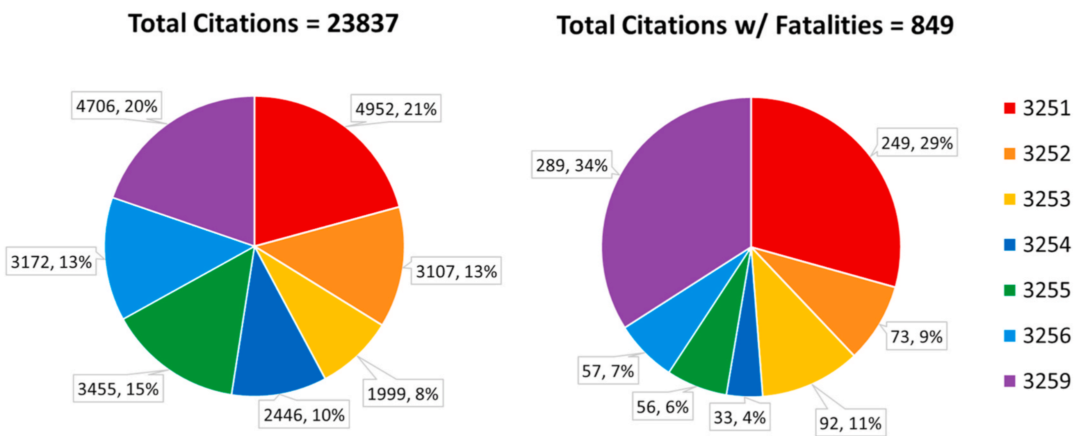

Fig. 8. Number of total citations and citations with fatalities issued by OSHA (2010–2020) in each NAICS code for the chemical industry.

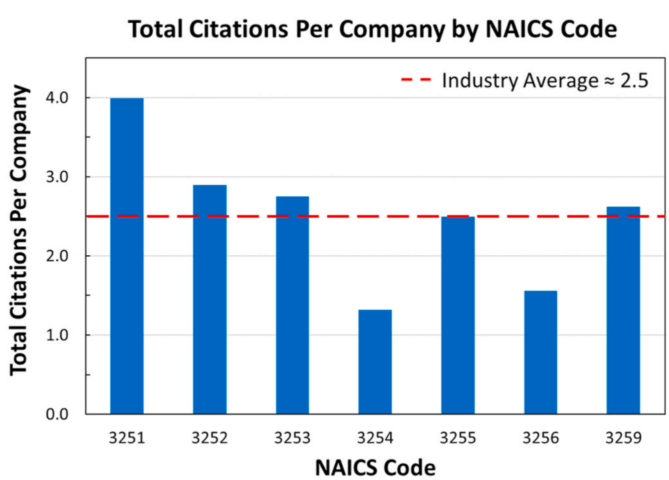

Fig. 9. Number of total citations per company issued by OSHA (2010–2020) in each NAICS code for the chemical industry.

2. Discussion

There have been a few recent studies examining factors leading to incidents based on CSB accident investigations. Fyffe et al. (2016) developed a database using 60 CSB investigations from 1988 to 2012. Their thematic analysis in terms of OSHA PSM found several common factors leading to incidents: design, standards, PHA, emergency response, hazard recognition, operating procedures, preventive maintenance et al. Four of these top seven are in common with the factors contributing to chemical plant incidents found in our analysis: design, emergency response, operating procedures and preventive maintenance.

Another analysis of 64 CSB incident investigations was conducted by Baybutt (2016). They concluded that design, safeguards, operating procedures and preventive maintenance were the top four factors contributing to incidents. These four factors are consistent with our analysis, with emergency response also among our top five factors (but 10th in the Baybutt study). It is noteworthy that both the Fyffe et al. (2016) and Baybutt (2016) studies used a broad spectrum of CSB investigations, while the former is in fact entitled ' … chemical industry accidents … ' The current study focused on CSB investigations for companies specific to the NAICS 325 'Chemical Manufacturing' code.

As noted in the Introduction, the RIVM study 'Fifteen Years of Incident Analysis' involving hazardous substances (Kooi et al., 2020), also included a broader industry segment of facilities than the NAICS 325 code examined in this study. While the RIVM study did not assess the factors contributing to incidents, several of their findings are noteworthy. Similar to our findings, 60% of incidents occurred during normal operations vs. ~75% in our study. Furthermore, their analysis found that the more severe incidents occurred during maintenance (20%), representing 4 of the 5 fatalities in the incidents examined.

In this study, the incident database used for the contributing factors analysis is not limited to the public CSB investigations for companies with the NAICS 325 code. A number of internal process safety incident reports which are not open source are also investigated. This combined larger dataset leads to a more comprehensive analysis on the most common contributing factors, although similar conclusions are drawn from previous studies. Additionally, the conclusions from contributing factors analysis are also supported by over 23,000 OSHA citations collected on each NAICS code sector. The most cited OSHA codes analyzed in this massive dataset demonstrates notable consistency with the contributing factor analysis results. Top cited OSHA codes also occur in the top contributing factors. These two analyses together can be regarded as a guideline to industry stakeholders to improve their process safety performance. Chemical manufacturing companies can start with the most relevant and significant codes and factors based on the NAICS code.

Design, Preventive Maintenance, and Safeguards, Controls and Layers of Protection are listed as the top three contributing factors in Table 4. Of course, each of these factors may reflect multiple shortcomings, specific to an operation or incident, which would need to be addressed in a program to upgrade company processes. For example, the Husky Superior refinery fire & explosion in 2018 (CSB, 2020) had all three noted causative factors, due to failure of the spent catalyst slide valve intended to prevent hydrocarbons from flowing into the air side of the unit. Similarly, the DuPont phosgene toxic chemical release of 2010 (CSB, 2020) had both Design and Safeguards, Controls and Layers of Protection as causative factors, due to the use of hoses made of inadequate materials and shortcomings in site safeguards. Initiatives to improve one's operations will need to ensure the appropriate aspects of the contributing factors are addressed.

In Table 4 safety culture is listed as the 6th most prevalent significant factor contributing to incidents. Some might argue that safety culture contributes to every incident, while in most instances it is earmarked as a contributing factor where a clear deficiency was noted. For an organization to successfully implement the improvement opportunities noted in this study in terms of factors contributing to industry, an organization's safety culture or organizational health can be expected to play a role. A paper by Mannan et al. (2013) lists ten key attributes of a strong safety culture, including leadership, resources and learning from prior incidents. To accomplish the latter per guidance from this study, will generally require (1) leadership to convey the understanding that improvement is necessary and truly valued, and (2) allocation of the necessary resources and timetable to implement the desired action plan.

Table 7
Most frequently cited code sections for NAICS code 325.

Citation Type	Citations involving Fatalities (Total Citations = 853)	#	All Citations (Total Citations = 23837)	#
Top 3 OSHA Standard Part	Part 1910 - Occupational Safety and Health Standards	713	Part 1910 - Occupational Safety and Health Standards	19921
	OSH Act of 1970	18	Part 1904 - Recording and Reporting Occupational Injuries and Illness	461
	Part 1926 - Safety and Health Regulations for Construction	7	OSH Act of 1970	271
Top 5 OSHA Standard Subpart	1910 Subpart H - Hazardous Materials	184	1910 Subpart H - Hazardous Materials	4374
	1910 Subpart J - General Environmental Controls	122	1910 Subpart I - Personal Protective Equipment	3236
	1910 Subpart I - Personal Protective Equipment	112	1910 Subpart Z - Toxic and Hazardous Substances	2788
	1910 Subpart S - Electrical	75	1910 Subpart J - General Environmental Controls	2430
	1910 Subpart Z - Toxic and Hazardous Substances	61	1910 Subpart S - Electrical	1780
Top 5 OSHA Standard Title	1910.119 - Process safety management of highly hazardous chemicals.	136	1910.119 - Process safety management of highly hazardous chemicals.	3020
	1910.146 - Permit-required confined spaces.	67	1910.134 - Respiratory Protection.	2166
	1910.134 - Respiratory Protection.	51	1910.1200 - Hazard Communication.	1836
	1910.132 - General requirements.	49	1910.147 - The control of hazardous energy (lockout/tagout).	1677
	1910.1200 - Hazard Communication.	41	1910.178 - Powered industrial trucks.	898
Top 5 OSHA Standard 1910.119	1910.119(d) Process safety information	26	1910.119(j) Mechanical integrity	615
	1910.119(f) Operating procedures	26	1910.119(d) Process safety information	594
	1910.119(e) Process hazard analysis	16	1910.119(e) Process hazard analysis	542
	1910.119(j) Mechanical integrity	16	1910.119(f) Operating procedures	521
	1910.119(g) Training	11	1910.119(l) Management of change	224

Table 8
Most frequently cited code sections for NAICS code 3251. Note: Only the top 3 or 5 standard parts or subparts are shown, therefore counts may not sum to totals shown.

Citation Type	Citations involving Fatalities (Total Citations = 249)	#	All Citations (Total Citations = 4952)	#
Top 3 OSHA Standard Part	Part 1910 - Occupational Safety and Health Standards	210	Part 1910 - Occupational Safety and Health Standards	4246
	OSH Act of 1970	9	Group 16. Control of Hazardous Substances	115
	Part 1904 - Recording and Reporting Occupational Injuries and Illness	6	Part 1904 - Recording and Reporting Occupational Injuries and Illness	71
Top 5 OSHA Standard Subpart	1910 Subpart H - Hazardous Materials	63	1910 Subpart H - Hazardous Materials	1413
	1910 Subpart I - Personal Protective Equipment	31	1910 Subpart I - Personal Protective Equipment	573
	1910 Subpart J - General Environmental Controls	29	1910 Subpart J - General Environmental Controls	521
	1910 Subpart S - Electrical	27	1910 Subpart Z - Toxic and Hazardous Substances	519
	1910 Subpart Z - Toxic and Hazardous Substances	14	1910 Subpart S - Electrical	298
Top 5 OSHA Standard Title	1910.119 - Process safety management of highly hazardous chemicals.	48	1910.119 - Process safety management of highly hazardous chemicals.	1265
	1910.147 - The control of hazardous energy (lockout/tagout).	19	1910.134 - Respiratory Protection.	345
	1910.132 - General requirements.	17	1910.212 - General requirements for all machines.	328
	1910.305 - Wiring methods, components, and equipment for general use.	16	1910.147 - The control of hazardous energy (lockout/tagout).	279
	1910.134 - Respiratory Protection.	13	1910.178 - Powered industrial trucks.	168
Top 5 OSHA Standard 1910.119	1910.119(j) Mechanical integrity	14	1910.119(j) Mechanical integrity	279
	1910.119(f) Operating procedures	8	1910.119(d) Process safety information	252
	1910.119(d) Process safety information	7	1910.119(e) Process hazard analysis	234
	1910.119(e) Process hazard analysis	7	1910.119(f) Operating procedures	219
	1910.119(h) Contractors	5	1910.119(l) Management of change	85

Successful adaption of the learning opportunities this study provides, calls for organizational health, with leadership visibly and convincingly expressing the importance of process safety and use of appropriate related KPIs (key performance indicators). Marsh (2020) contends that organizational health and internal capability is 'the overarching glue' that holds together efforts to improve management systems that address factors contributing to incidents; they are interdependent. More broadly McKinsey (Keller and Price, 2011) contends that high performing companies must build capacity to learn and keep changing over time, and provide nine elements essential to organizational health: accountability, capability, coordination and control, culture and climate, direction, leadership, innovation and learning, external orientation, and motivation.

While well beyond the scope of this study, a strong safety culture will include leadership's tolerance for risk, insistence of thorough incident investigations, adoptions of upgraded practices based on internal/external incidents, resources allocated to process safety, and career development of those in this discipline. This study can provide guidance on where to look for process safety improvement opportunities, but successful implementation will generally need active engagement by all levels of an organization while fostering an environment with a strong safety culture and organizational health.

3. Recommendations

There is tremendous value in analysing industry process safety incidents, with trade associations encouraging the reporting and collection of such data. Giving considerable thought to the type of data collected (e.g., identification of contributing factors, severity) will enable robust subsequent analysis.

A priority list of commonly reported contributing factors for Tier 1 process safety incidents for the chemical manufacturing industry has been established through this study. Companies may want to assess how

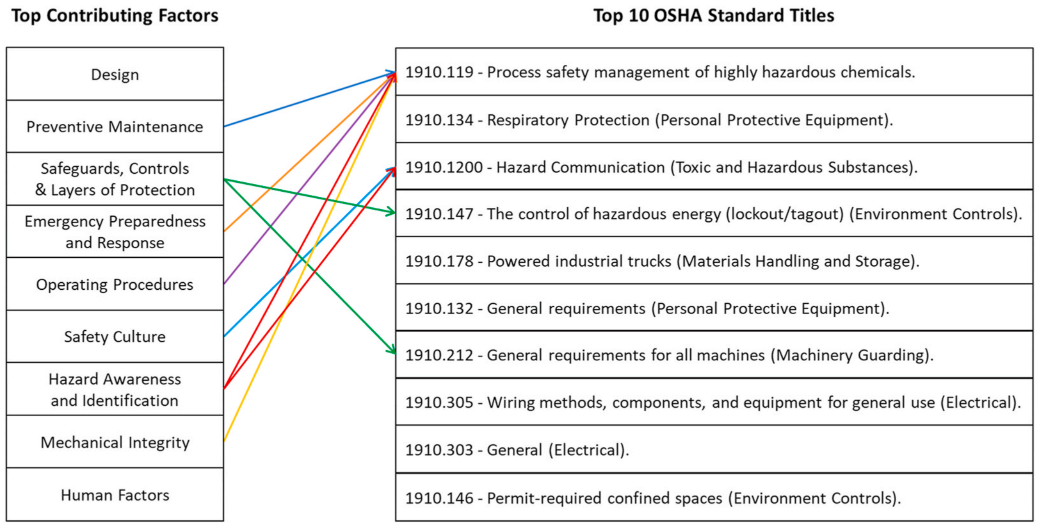

Fig. 10. Mapping of most significant contributing factors to most frequently cited OSHA standards (NAICS code 325) for the chemical industry.

these findings compare with any similar internal studies, and thoughtfully consider possible next step(s). The latter might be a limited number of initiatives designed to improve company performance relative to key contributing factors such as operating procedures, emergency preparedness, etc. A key question is how one's existing management systems address these areas (many of which require regulatory compliance).

Another approach might be to focus on those incidents that resulted in fatalities and identifying whether there are any unique contributing factors to those incidents, as well as learnings from specific incidents involving high risk chemicals that have the potential for more serious exposure consequences.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jlp.2021.104512.

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