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Avoiding Engineering Catastrophe: New Insights from Data

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High-consequence, low-frequency events, such as toxic releases, fire, explosion, maritime losses and railway collisions are prevented and mitigated by good engineering practice throughout the lifecycle of an installation. However, all engineered barriers can degrade and subsystems can interact in a complex manner, which can make it challenging to assess how close a system is to a dangerous failure overall. Analyses after major incidents often show – with the benefit of hindsight – that a number of 'weak signals' of impending disaster were present, but these were only useful when analysed holistically.

In early 2018, the "Discovering Safety" programme was launched. This programme is being delivered through the Thomas Ashton Institute[1] and combines the strengths of the Health & Safety Executive and the University of Manchester and is supported and funded by Lloyd's Register Foundation. The programme addresses occupational safety issues together with process safety and allied technical safety topics. The focus of this programme is on using new data analysis techniques to extract valuable intelligence that will enable the prevention and mitigation of accidents, and improve 'plateaued' safety performance. A key project within the programme is the "Loss of Containment Insights" project. The project aims to create a source of intelligence by using data analytical tools on HSE's existing datasets relating to onshore loss of containment events and their precursors.

This paper outlines the stakeholder interactions which led to the development of the project, the approach taken, strengths and weaknesses of RAMS intelligence in the process sector and elsewhere and then proposals for next steps together with summary findings from data analysis carried out in 2018/19. A key goal surrounding the publication of the paper is to gain constructive feedback from process industry specialists to ensure that the project is successful and the outputs useful to industry.

Keywords: DATA, LOSS OF CONTAINMENT, RAMS, HSE

Background

The Thomas Ashton Institute, a collaboration between the University of Manchester and the Health & Safety Executive (HSE) launched in early 2018. The Institute carries out interdisciplinary research in the field of safety and health, covering both occupational safety issues and major accident hazards, including process safety management.

The Lloyd's Register Foundation (LRF) is a charity[2] with a mission to protect the safety of life and property, and to advance engineering education and research. LRF have provided funding for the *Discovering Safety Programme*, which aims to improve safety by generating insights from data, in particular large, under-utilised datasets.

The authors would like to thank the Foundation for providing funding and guidance for this important programme. The remainder of this paper describes *the Loss of Containment* project which is a set of process safety focused activities with an initial focus on the onshore process industries within Great Britain.

The role of data in preventing engineering catastrophe

High Reliability Organisation (HRO) theory emphasises the importance of paying attention to 'weak signals' which in aggregate demonstrate that control of hazardous processes is being lost (Weick, Sutcliffe, 2015). In the UK the Control of Major Accident Hazards (COMAH) regulations (HSE, 2015) and associated guidance means that operators need to review a range of process safety 'intelligence' from around the world – including lessons from accidents, near misses and technological developments impacting on understanding of hazards, risks and the effectiveness of control measures. There is also the need to use reliable data to inform formal hazard identification and risk assessment studies. In some of these study types, qualitative intelligence is useful to augment the study team's own knowledge, for example in those Hazard and Operability (HAZOP) studies not incorporating any frequency estimation. In other techniques some numerical data is essential, specifically to estimate the frequency of initiating events which could progress to a loss event or to estimate the probability of various prevention and mitigation barriers operating as intended. Such techniques requiring such data include Failure Modes and Effects Diagnostic Analysis (FMEDA), Layers of Protection Analysis (LOPA) and Quantified Risk Assessment (QRA).

Many operators draw on a family of datasets known collectively as Reliability, Availability, Maintainability and Safety (RAMS) sources to use in their formal risk assessment processes. However, these sources have declined in number over time with limited exceptions:

"Data collection activities were at their peak in the 1980s but, sadly, they declined during the 1990s and the majority of published sources have not been updated since that time." (Smith, 2017)

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[1] www.ashtoninstitute.ac.uk

[2] www.lrfoundation.org.uk

The decline in the availability of RAMS sources means that in some cases questionable alternatives are used, which led a HSE research report (Chambers et al., 2009) examining LOPA studies to conclude:

"The degree of rigour applied to LOPA studies, and in particular the data values used, vary widely. Some LOPAs were reliant on standards and other published sources of generic data for their initiating event and protection layer data values. While others used analytical methods such as fault trees and human reliability studies to synthesise more appropriate data for the site in question, many drew on inappropriate generic data or referenced inappropriate examples."

Some texts provide means to ameliorate generic data by tabulating 'stress factors' – multipliers to adjust generic data based on environmental or duty conditions (Davidson and Hunsley, 1994), however it is difficult to assess the rigour of the evidence underpinning these approaches. One of these approaches indicates for example that a stress factor in a railway environment should be double that of a ship in exposed waters.

It is clear therefore that operators managing major hazards have an ongoing need for a range of process safety intelligence. At the same time the experience of the authors suggests that setting up elaborate new cross-industry data collection initiatives are likely to fail. It appears therefore that there is merit in better use of existing, disparate datasets around the world, including those not directly set up with process safety intelligence in mind.

HSE's existing datasets

HSE is the health and safety regulator covering Great Britain founded under the Health & Safety at Work etc. Act 1974. Within this remit HSE collects a wide range of data, including information which is required to be provided by law by employers. This includes incidents required to be reported under the Reporting of Injuries, Diseases and Dangerous Occurrences (RIDDOR) Regulations 2013 (HMSO, 2013). Many of the events reported under RIDDOR are related to occupational safety outcomes, such as injury accidents resulting from slips, trips and falls. However, others are highly relevant to process safety, such as loss of containment of specified quantities of flammable materials.

The authors are also mindful of the other datasets and data driven projects which have been developed, including the eMARS database – the Major Accident Reporting System which records relevant major accident events which are required to be reported by European Union (EU) member states and other nations on a voluntary basis.

COIN database

HSE also records information about regulatory interventions, such as inspections and investigations undertaken by its inspectors. HSE has a database called the Corporate Operational Information System (COIN) in which these interventions are recorded in some detail. COIN was put in place primarily to record a site-based history so that inspectors visiting can review previous interventions and site performance. The system has some reporting and analysis tools built in, but these are limited in scope. Key dimensions for the whole of the COIN database are provided in Table 1.

Table 1 - COIN Database Dimensions

Metric	**Approximate Value**
Company Records	3,000
Sites	11,000
Cases / Service Orders – 282846	350,000
Database Size (Data only)	430 Gigabytes
Document Attachments Size = 1350 GB (1.35TB)	1.4 Terabytes
Data Retention Period*	7 years from last related intervention

* within the live database, other information is retained elsewhere on a case-by-case basis

The COIN database contains three different types of data:

- Coded data – fields which hold either numerical/date data or a range of pre-determined options.
- 'Free text' – narrative added by HSE staff with limited or no structure.
- Document attachments – various PDF, MS Word, PowerPoint and similar documents which may originate from HSE or may be collected from employers – e.g. internal investigation reports.

A challenge with the database is that currently a seven-year data retention period is in place, which results in the deletion of records seven years after the last linked intervention. As an example, if an accident occurred that resulted in an enforcement notice then the seven-year period would not begin with the date of the accident but the last recorded information updated in respect of the notice – for example description of when / how the notice was complied with. In the future the project team intend to retain anonymised data for a much longer period for analysis purposes. Some data is also retained in other systems for longer periods depending on its type, but not within the COIN database.

A key object within the COIN database is a case or service order. A single case is created for each regulatory intervention, for example an injury accident which is investigated will have a single case with a unique serial number assigned. In some instances, a slightly different object called a service order is used but for practical purposes amounts to the same object. Each case will have its own coded data, free text and document attachments. The detail available and where it is stored depends on the type of intervention. It is important to note that the majority of data is recorded in free text fields or document attachments, which means that the Discovering Safety team are exploring text mining techniques to extract insight as part of this and other projects.

Loss of Containment Taxonomy

Following the Buncefield explosion and fire in 2005, a recommendation was made by the Buncefield Major Incident Investigation Board (BMIIB, 2012) that HSE and others should improve the collection of incident data on high potential incidents including overfilling, equipment failure spills and alarm defects within the major hazard sectors. Following this, several pieces of work were undertaken, including changes made within the COIN database to increase the coding available for loss of containment events.

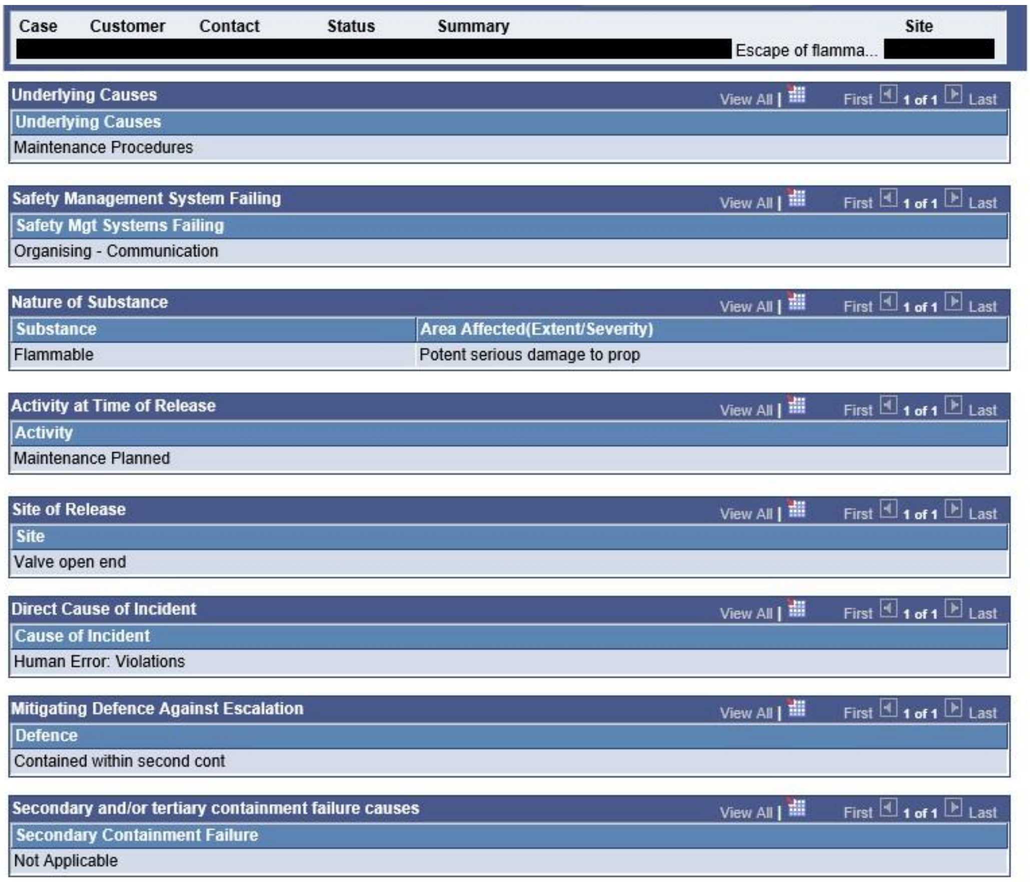

Figure 1 - Redacted Coded Fields Screen

Figure 1 shows a screen within COIN which requires users to input coded mandatory fields in some instances. While the screen is completed for many events (e.g. personal injury accidents), completion of all fields is only required for loss of containment events which are themselves a subset of RIDDOR Dangerous Occurrences (DOs).

RIDDOR requires the reporting of DOs where no injury occurs across all industry sectors and many of these may usually be unrelated to process safety – for example collapse of scaffolding on a construction site. There is also not a specific requirement to report all loss of containment events, instead there are several DO categories which are likely to cover some loss of containment events. Those DO categories which are considered likely loss of containment events and therefore force the completion of the full analysis screen in COIN are:

- Pressure system explosion, collapse, or bursting
- Electrical short circuit resulting in fire and explosion
- Process explosion, or fire resulting in 24-hour disruption
- Escape of defined quantities of flammable substances
- Escape of substance in quantities sufficient to cause death, major injury or any other damage to the health of any person (e.g. toxic substances)
- Various adverse events in pipeline systems

It should be noted that the above list is a simplified summary and full details of the reporting criteria are provided in the RIDDOR regulations.

It is also important to note that the definition of DOs in RIDDOR is much narrower than the range of near miss events that many in the process industry would want to record as part of a robust safety management system. Furthermore, it is known that RIDDOR is subject to underreporting, despite the legal requirement to do so. The level of underreporting varies by industry sector and is estimated from separate employee survey data in respect of injury accident events and not DOs. HSE's most recent estimate for average RIDDOR reporting levels for non-fatal injury accidents is around 50% (HSE, 2018). Dangerous Occurrence reporting levels have not been estimated.

The current recording system is relatively detailed – for example the 'Direct Cause of Incident' field contains 35 options to select from. Many of these are hardware related - such as 'Corrosion under lagging'. In terms of Human Factors, there are four explicit selections that can be made, these are:

- Human Error: Slips
- Human Error: Lapses
- Human Error: Mistakes
- Human Error: Violations

However, there are also many other selections which could potentially involve human factors issues, some examples include:

- Drive away
- Impact / dropped object
- Incorrect installation
- Incorrect isolation
- Inadequate procedures
- None / faulty indicator
- No level alarm / trip

There are also several selections which appear to involve hardware issues, but which are likely to link in some way to human performance – for example human factors in the design process.

More generally, the key challenge to gaining new human factors insights from large data sets will be the quality of information and the underlying investigation of root or underlying causes. Human factors-related information is often overlooked, even by seasoned investigators, if they have not been specifically trained to identify such data. Similarly, if a human factors element is not overlooked entirely, it is oversimplified. Often, investigations will point to generic 'human error' or 'human factors' as the single cause of adverse events, rather than looking for the underlying performance influencing factors[3] that shape human behaviour.

Although the accuracy of data and analysis is important, tolerance of uncertainty will be crucial. Better use of data analytics will provide both human factors and safety specialists with a new and rich ways of collecting and analysing patterns of human

[3] http://www.hse.gov.uk/humanfactors/topics/pifs.pdf

behaviour. New computational methods will allow us to derive meaningful, actionable cause-effect relationships, which have not been previously described, and support decision-making in these areas.

Early analysis

The Loss of Containment project and the wider Discovering Safety programme has been designed to be iterative – to deliver early value and demonstrate capabilities at concept stage before refinining. In addition, the intention is to use existing GB data held by HSE to develop approaches which can later be augmented with other international datasets from a wide variety of public and private sector organisations. Accordingly, the team have recently completed some basic analysis of the coded data relevant to Loss of Containment events reported as RIDDOR dangerous occurences (DOs).

A HSE SQL[4] database specialist created a replica of the live COIN database to provide an electronic resource for all of the Discovering Safety projects. Coded data was converted into comma separated value (CSV) files and free text entries were provided as plain text. Document attachments in various formats (e.g. PDF, Word, Excel) were also converted to plain text. All records were linked together as in the live database by a case serial number. Therefore, for each case separate files exist for coded data, free text and multiple document attachments as text files with images and metadata removed.

The open-source data analysis package 'R Studio' was then used to perform some basic analysis on the coded records associated with DOs considered as loss of containment events (LoC). In order to do this the wider DOs dataset was filtered by DO type and all those entries not relevant to LoC events deleted based on the criteria described in section 2.2. The dataset was then subject to processing to improve confidence in data quality. As an example some entries were removed as they had no associated information around causation, in most cases because they were open investigations within the live database. This processing resulted in a dataset size of 464 DO records which were all incidents occuring prior to May 2018.

Firstly, the coded field 'underlying causes' was simply extracted and plotted as a histogram which is shown in Figure 2. This shows that issues with Hazard Analysis or Risk Assessment were recorded as the principal underlying cause within the dataset. This shows only the first such cause as recorded in the database, the system allows additional underlying causes to be added for each incident which have not been considered in this basic exploratory analysis. There are also a small number of incidents where a cause could not be established due to uncertainty during the investigation (recorded as "Unknown") or where "Not Applicable" was recorded which would include incidents where the measures in place had reduced risk to tolerable levels but the incident had occurred due to residual risk. Figure 2 shows the number of events on the y-axis, not a percentage.

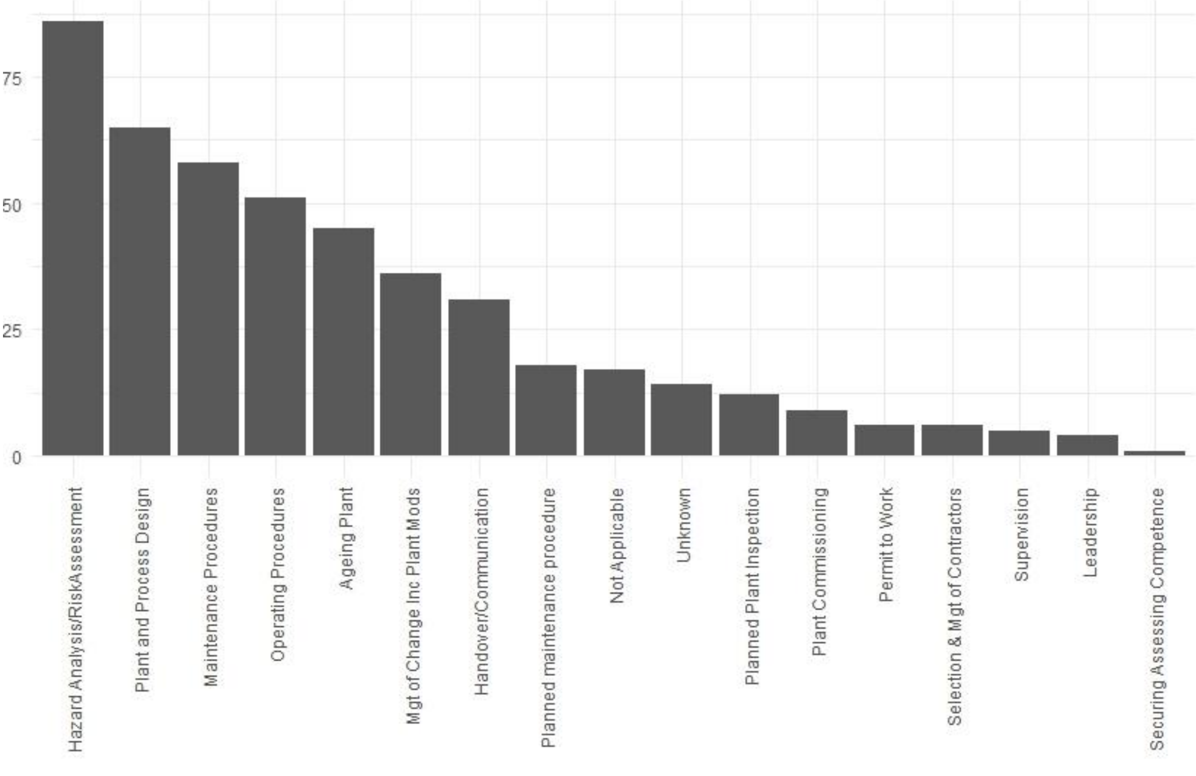

Figure 2 - Recorded Underlying Causes

Please see important caveats and limitations around this data described in the body of the paper

[4] Structured Query Language – a programming languages used with databases where there are relations between several different data fields.

From the recorded underlying causes, one was selected for further analysis at this proof-of-concept stage. Given the project teams experience of Ageing and Life Extension (ALE) issues it was decided to focus on the subset (N=45) of these 'Ageing Plant' cases and assess another field linked to these. The coding system is particularly helpful, in that, a detailed plant item list exists for the 'Site of release' field, right down to individual process plant items. R Studio code was written to extract all instances of the plant item involved in the release for the ageing plant cases and this was plotted as a histogram which is shown in Figure 3. Again the y-axis shows number of events, not a percentage. Whilst the potential value in undertaking this analysis can be seen from the output, it is also apparent that there are a number of drawbacks. Firstly, there is a large proportion of 'not applicable' entries and secondly, the relatively low size of the original events dataset and even smaller subset means that for many plant items there are only single instances, which reduces the confidence that wider lessons can be extracted from such analysis.

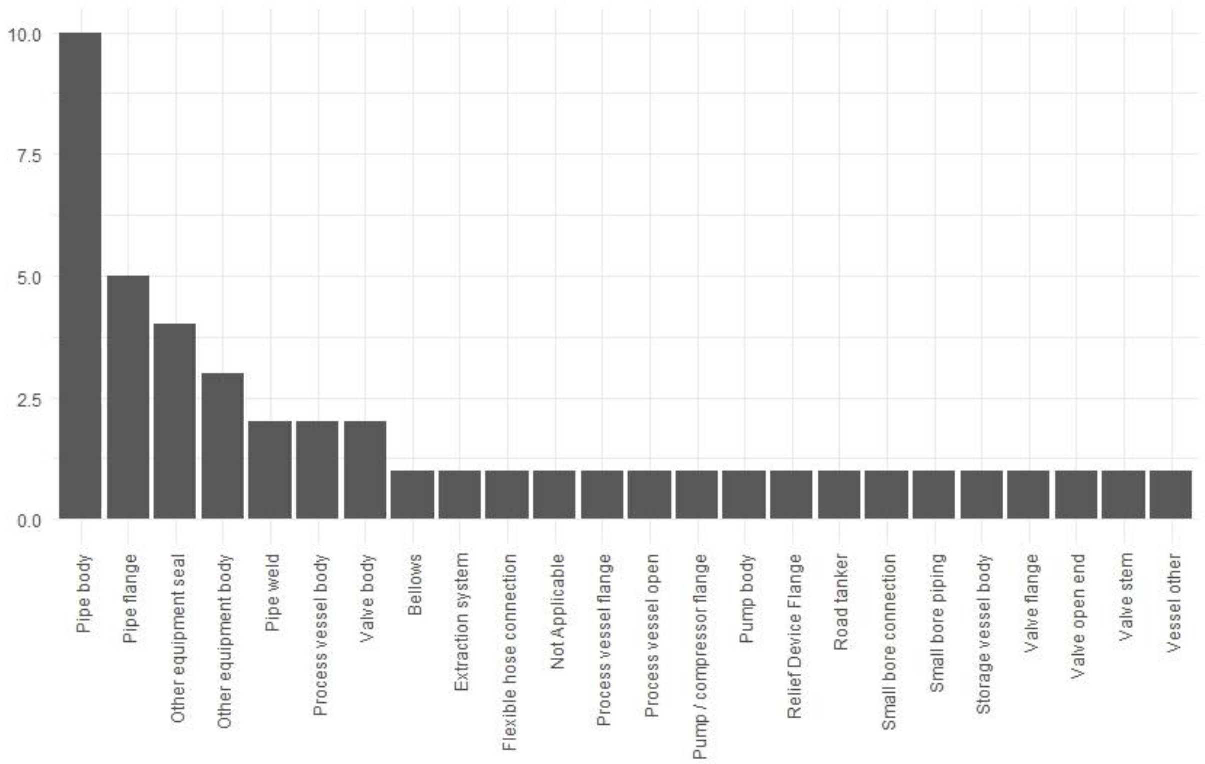

Figure 3 - Recorded Site of Release for Ageing Plant Cases

Please see important caveats and limitations around this data described in the body of the paper

The large number of ageing plant cases involving 'pipe body' is perhaps surprising. The expectation prior to analysis was that plant items which provide an interface or have moving parts would be more likely to fail and therefore be causative of the LoC DOs. Further analysis is planned to better understand this since the current analysis does not allow any robust conclusions to be draw as to why this is the case. Some possibilities HSE specialists are keen to test are:

- These cases involve Corrosion Under Insulation (CUI) issues which has conventionally been an industry issue and been more complex to resolve through inspection than exposed pipework.
- Poorly performing organisations neglect the fundamentals of asset integrity but replace less costly interface and moving part items for production reasons.

There are also likely to be other possibilities which are only possible to discover through more detailed analysis and increasing the number of records under consideration.

Limitations of the existing analysis

At this early stage in the project, the existing analysis has been done to prove the concept that some value can be extracted from the dataset. In addition, the preparatory data extraction and conversion has been completed to make future work more efficient and not dependent upon running multiple bespoke queries on the live database. It was also intended to highlight early on any drawbacks in the existing data, so that the team could develop approaches to ameliorate this, in consultation with process safety professionals working in industry.

The main challenge highlighted by the existing analysis is that the number of records in the database with detailed coded fields completed is very small when compared to the size of the database overall. Whilst some high-level findings to inform other work are valuable, it is likely that the greatest value to the process industry would be to develop a multi-factor analysis that better explains detailed causation. In the case of loss of containment events with ageing plant as an underlying cause, it would be useful to know in more detail whether, for example:

- There was a total absence of an asset integrity programme, or flaws in an existing one?
- Whether the cause of failure was due to a backlog of safety critical maintenance which would have detected and rectified the degradation process if correctly carried out?
- Whether the failure was associated with degradation or instead parts obsolescence associated with ageing plant?

A further challenge is that the whole of the COIN dataset covers Great Britain (England, Scotland and Wales) only, whereas it would be more powerful to be able to compare events across and within other countries in both the developed and developing world. The short data retention period (7 years) is also challenging when attempting to carry out time-series analysis.

The underreporting in RIDDOR may introduce an element of bias, in that, there may be different findings within those operators with poor compliance with RIDDOR. It is also not possible from the current analysis to distinguish between subsets within the process industry, for example, whether there would be different profiles within the tank storage sector when compared with fine chemical manufacturers.

The use of a coding taxonomy is helpful, but also poorly covers the links between causation. For example, high workload leading to a backlog in planned plant inspection, leading to a failure to mitigate the effects of ageing mechanisms.

Further bias may be introduced in that the dangerous occurrences reported are, by definition, cases where mitigation may have prevented injury to workers and / or the public. These may not be as reliable as other precursors to major accidents, which are not required to be reported under RIDDOR.

Personal injury accidents relevant to process safety

There are clear differences between occupational and process safety which have been well documented, including most notably after the Texas City Refinery explosion in 2005 (Baker et al, 2007). At a site level a focus on injury accidents as a metric of process safety performance is clearly a flawed approach.

However, at a GB level, personal injury accidents dominate the events which are formally reported and recorded by HSE. The experience of the project team suggested that a proportion of those personal injury accidents occurring in the process industry may have had relevance to process safety. In particular, there are known to be injury accidents resulting in relatively minor reversible injuries to workers resulting in an absence from work or normal duties for over seven days, where good fortune resulted in an outcome which could have been much more severe. In relation to loss of containment events, small leaks of harmful substances may lead to minor injuries (e.g. superficial burns), but have had the potential, under slightly different circumstances, to lead to the release of tonne quantities of materials with onsite and offsite process safety implications.

The team manually searched the COIN database for some examples of such events and two examples are provided overleaf.

Example 1

One employee sustained burns to their ankles when a high temperature and caustic liquid mixture flowed over their chemical resistant shoes and came into contact with their ankles. This resulted in several weeks off work, but the individual is expected to make a full recovery. The incident was reported to HSE as a RIDDOR over seven-day injury accident.

The incident occurred during a post-reaction cleaning operation on a chemical reactor when the vessel was being filled with a caustic cleaning solution whilst agitation and heating were applied. The intention was to heat the solution to approximately 65°C and to fill the vessel to 90% capacity. Level control was due to be achieved by manual dipping. Temperature control was also monitored manually, as the vessel had no instrumentation and no high-level alarms fitted. There was some confusion as to whether the vessel needed to be filled to 100% capacity to clean the upper levels of the vessel and fittings.

The incident occurred when either level control was lost and the vessel was overfilled onto the upper reactor floor, or when temperature control was lost and boiling occurred. In addition to the lack of instrumentation, there was also no written operating procedure for reactor cleaning operations at the time of the incident.

This injury accident, whilst only briefly outlined here, clearly provides process safety insight in respect of process plant design as well as operational procedures. Failure to achieve level and temperature control in the process industry has been associated with many major accidents causing on and off-site implications.

Example 2

One employee sustained superficial burns to their face following a short duration flash fire resulting in approximately two weeks off work on medical advice. This was reported to HSE as a RIDDOR over seven-day injury. Had no injury occurred this incident would not have needed to be reported as a DO since it would not meet the criteria for a process fire as it did not result in 24-hour plant stoppage.

The incident occurred when the employee was adding a powder to a reactor which already contained significant quantities of the solvent Methyl Ethyl Ketone (MEK) which had recently been 'splash filled' into the reactor contrary to company recognised good practice. The powder was dispensed directly from the polymer bag it was supplied in and it is believed this may have created a static spark which ignited the solvent vapours present in the reactor following the splash loading of solvent. The area around the reactor port was designated an explosive atmospheres (ATEX) zone 1 area and there is no evidence of any unsuitable equipment having been brought into this zoned area prior to the ignition. The process operator filling the vessel was wearing anti-static footwear. Once ignition occurred, a flash fire resulted at the reactor port causing superficial burns to the operator who was standing upright decanting the powder. The fire was rapidly and completely extinguished by a second process operator closing the reactor lid shut.

Clearly this is another injury accident with the potential to have escalated into a large-scale process safety event given the large amount of solvent present in the reactor and the presence of other adjacent processes and employees.

It is clear from this brief manual review that there is data recorded in the COIN system categorised on an occupational safety basis, which could generate insight for process safety professionals. The challenge in extracting this information is that whilst there is some basic coding of RIDDOR accidents, much of the detailed description exists in free-text fields or in associated document attachments. In order to successfully extract relevant process safety events, the team will need to develop text mining algorithms that can analyse large volumes of data with minimal manual intervention, whilst generating sufficiently low numbers of false-positives. Some of the other challenges anticipated are:

- It is possible that bias could be introduced, as process industry events resulting in personal injury may differ in some key ways from events that do not result in any personal injury but have the potential for escalation. Indeed, it may be the case that as in Example 2 above, employees who are present may prevent escalation and the potential for off-site effects, but suffer injuries whilst doing so.
- There is significant underreporting of RIDDOR accidents, this is known to vary widely across sectors and is likely to vary between operators within the same sector. It is possible that underreporting is inversely correlated with process safety performance such that extracting lessons learned from such events would underrepresent the nature of failings in poorly performing organisations.
- The level of detail available in incident investigations recorded in COIN varies according to the nature of the incident and its outcome. The information may be held within different attachments – for example where detailed forensic engineering is carried out this is likely to be recorded in a separate attachment from an investigation summary.

In spite of these and other considerations, it is suggested that there is value in the project team exploring the value in text mining of process safety events from personal injury data, subject to regular review to understand the limitations of the approach.

Previous work

A comprehensive piece of work was previously undertaken by the Health & Safety Executive (Lisbona et al, 2011) to analyse 975 Loss of Containment events using the software tool "Storybuilder". This involved detailed coding of incidents which had occurred between 1991 and 2009. This work was particularly powerful given that this analysis preceded the detailed coding of data within the COIN database and so provides further assurance that text mining techniques from narrative records can produce great value. Since this work was undertaken, the tools and culture within data science have progressed enormously. As a result it is the project team's aspiration to move to an almost 'real-time' data repository available to industry professionals with the ability for queries to be developed in a bespoke manner by users and the ability to refresh analyses as new data accumulates rather than having to await periodic publication.

Conclusions

It is clear that appropriately developed techniques for extracting valuable process industry insights from uncoded free text data, commencing with HSE's own COIN data could unlock a previously underutilised source of intelligence. The experience of applying these techniques on GB data will enable a better roadmap to be developed to augment the GB data with worldwide sources. Engineers, managers, operators and regulators are 'time poor' – creating elaborate data collection regimes will result in failure. Letting software do the 'heavy lifting' on data which already exists, but is poorly structured, is a pragmatic way forward.

Moving forward the plan is to conduct further analysis on the coded data but also commence text-mining techniques with the personal injury accidents as described in section 2.5. However it is most important that these and other projects incorporate feedback from industry to develop and refine approaches which are most helpful to industry.

Feedback & engagement

The project team are keen to engage with the global process industry community to receive feedback and suggestions to further develop the project over the coming months and years. The team can be contacted via discoveringsafety@hse.gov.uk and would welcome all feedback but would particularly welcome comments on the following topics:

- Signposts to global sources of process safety intelligence which could augment our GB data sources in the longer term, particularly any which exist holding data for process industries in the developing world and / or unstructured / underutilised datasets. It would be particularly useful to focus on onshore data since this does not to benefit from global initiatives that exist in the offshore oil & gas sector.
- Challenges previously experienced in-company or across-sector which have arisen in respect of data collection, analysis and sharing of process safety learning.
- Types of insights which would be most valuable to emerge from the work – for example what process safety questions would users most want answered from robust analysis?
- What type of model would enable the sharing of intelligence on a sustainable and user-friendly basis?

Whilst the project is at a relatively early stage at present the team are keen to explore the possibilities for collaborating to create a searchable resource which would assist end users with duties under COMAH to review learning from worldwide process safety events. Ideally this resource would allow the segmentation of the process industry such that, for example, an operator of a tank storage facility could filter intelligence in a different way to a batch manufacturer of fine chemicals. Such an approach would make it easier for users to ask questions tailored to their sector, for example:

- What proportion of loss of containment events in the tank storage industry result from overfilling?
- Which plant items are particularly vulnerable to management of change issues?
- How are plant start up/shutdown related incidents changing over time?

As with the earlier questions, the project team are keen to seek detailed feedback from users as to how such a resource could work in practice to best assist those wishing to improve process safety performance for the benefit of us all.

Disclaimer

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