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A Refreshing Take: Analysing Accident Scenarios through Causal Network Topology Metrics

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Abstract

Accident causation investigation and even more hazard scenario identification are troubled by the complexity of interactions between three elements in a process facility: People, Plant and Procedures. Interactions are of various nature, such as physical change and information transfer, all influencing the process.

To facilitate investigation the digraph network was applied as the most flexible visual aid to describe a causal structure. Such structure consists of nodes and edges representing an event or condition in the accident scenario and a causal link respectively. Attributing the nodes and edges to the type of interaction, numbers of the same type can be counted, and so two metrics are developed:

- The *P3 Interaction Contribution* (PIC). This is the proportion of nodes and edges associated with an interaction between People, Plant and Procedures.
- The *Average Edge Weight*. This relates to the proportion of events in the scenario that are associated with the logical AND gate conjunction from its causes (incident nodes), where the event requires more than one simultaneous cause.

The technique was tried on four CSB accident descriptions. Interesting differences are seen. Also, in view of a paper accepted to be published in Safety Science the approach seems quite helpful in process hazard analysis.

1 Introduction

One of the most useful ways that lessons learned from past accidents can help support future sustainable operation is if those lessons are used to enhance an organization's ability to anticipate potential future accidents. Anticipating future accident scenarios ahead of time is what risk assessment is traditionally used for. But in the modern world, complexity in socio-technical process systems makes risk assessment difficult. This complexity is often linked to unforeseen, or difficult-to-identify scenarios which undermines anticipation efforts. Thus, the requirements to extract the best set of lessons learned from an accident investigation becomes even more critical, to support future risk assessment efforts.

This work seeks to demonstrate the use of two measures applicable to results of accident investigations, namely the accident investigation reports. Four accident reports previously generated by the US Chemical Safety Board were analysed. These are listed in Section 2.1. These measures are extracted from a *causal network* representation of the accidents, and are generally called *network metrics*. Network representations for modelling and analysing accident scenarios is a well-established practice, such as through the use of Fault Trees [1]. However, the directed graph or digraph network applied here allows feedback causation, not possible in Fault trees or Bayesian networks. A more recently established practice [2] is to study the topology of accident networks, through the extraction of various network metrics from that topology. The metrics applied here can be used to support accident investigators to reflect on the analysis they have performed and help them clarify whether they have extracted the most helpful or accurate set of lessons learned possible.

The first metric is called the *P3 Interaction Contribution* (PIC), a recently introduced metric for analysing accident in previous work [2]. The PIC is a relative measure of the contribution of so-called *P3 interactions*, or interactions between people, plant or procedures, to an accident scenario as a whole. This approach of categorizing process system components is well established [3, 4, 5]. The PIC can be an indication of how important causal links between fundamentally different component types can be to the generation and progression of an accident.

The second metric is the *Average Edge Weight* of the causal networks that represent the accident scenarios. This corresponds to the number of logical AND gates in the scenario. More edges participating in AND gates will show up as a lower overall *average edge weight* overall in the network. This is calculated by summing all the edge weights and dividing by the number of edges in the network. This metric is useful because more AND gates implies that more than one cause is required for the accident to progress, possibly implying that due to higher complexity it may be less likely to reoccur.

Either through using the PIC or the average edge weight measure, analysts currently investigating an accident can be lead to *question* whether the data they are collecting and the way they are writing the report is the most helpful or accurate for representing the accident. In this sense, then, using these network metrics alongside tradition accident analysis technique offers *a refreshing take* on generating lessons learned from past accidents, the purpose of which is to generate the best set of lessons learned possible to enhance the anticipation of future accidents, and thus the risk assessment efforts in an increasingly complex work.

This refreshing take is demonstrated by first describing a summary of the methodology used to generate the causal network diagrams and their metrics, in Section 2. Section 3 displays these results, with a short discussion given on them in Section 4. Section 5 summarizes the conclusions drawn and suggests avenues for future work.

2 Methodology

This section details the method used to extract and generate the networks from the CSB accident reports and calculate the two network metrics: the PIC and average edge weight.

2.1 Conversion of Accident Reports into weighted causal networks

The first step was to read the four accident investigation reports from the CSB website (www.csb.gov) that detailed the events surrounding the following four accidents:

- Barton Solvents [6]
- Valero Propane [7]
- ASCO [8]
- AL Solutions [9]

The text describing the accident events and how they were causally related, was then converted into a causal network. Each node of the network represents an *event* or a *condition* found in the relevant accident report. Figure 1 shows an example of the conversion process, using a section of text from the Valero Propane accident. The unique numerical identifiers assigned to each event are arbitrary.

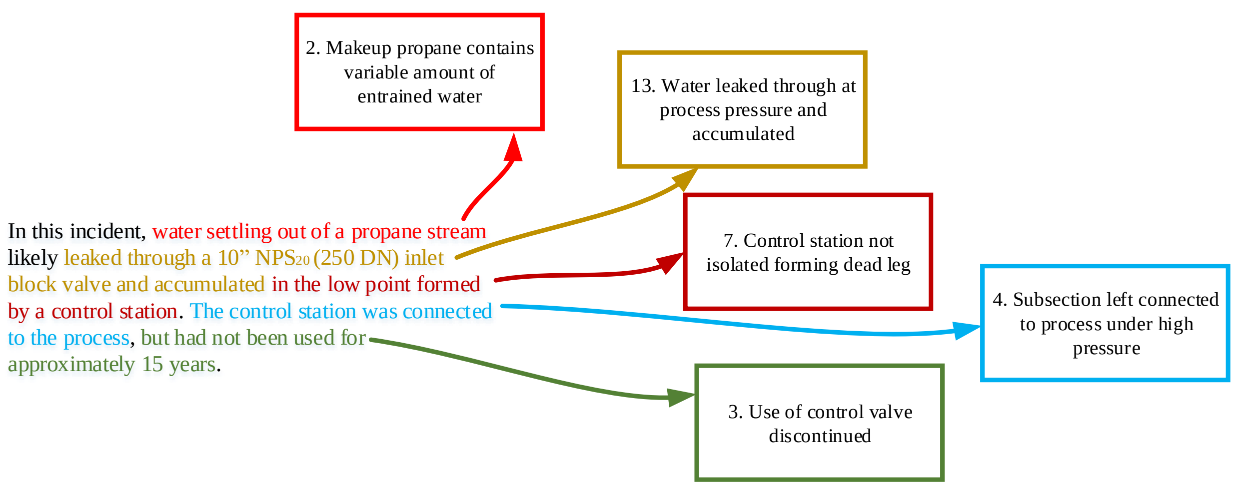

Figure 1 - Causal Network Event Extraction from Accident Reports

Based on the causal relationships extracted from the report, the numbered events were linked together. Weights were added to each edge based on whether the cause for a particular event was part of an AND gate or an OR gate, or a singular cause. Figure 2 shows how an OR gate is configured in the causal network used in this work.

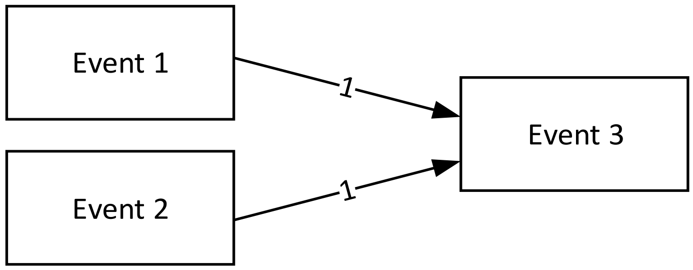

Figure 2 - OR gate configuration in a causal network

The events that comprise the list of causes in an OR gate with each have an edge weight of 1. This is to signify that they can each cause the latter event independently. If an event has only one cause, then the edge weight will likewise be 1.

Figure 3 shows two types of AND gates and how they are represented by part of a weighted causal network.

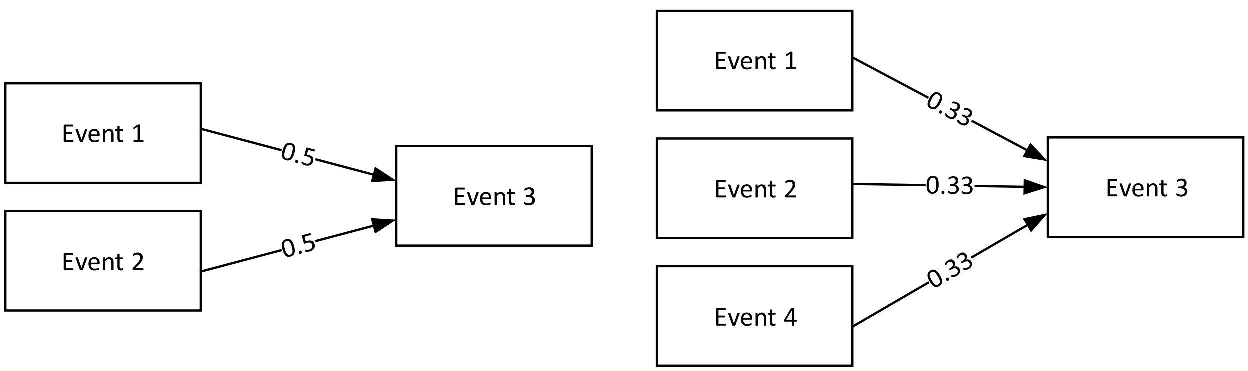

Figure 3 - AND gate configuration in causal network

The events that comprise the list of causes in an AND gate will have edge weights that sum to 1. Thus, a two-event AND gate will have two edge worth 0.5 each, and a three-event AND gate will have three edges worth 0.33 each (approximately 1).

2.2 Generating Network Diagrams

Once the weighted networks have been constructed as per the approach in Section 2.1, an *adjacency* matrix is constructed [5]. This matrix is a mathematical representation of the causal relationships between the events in a causal network. Figure 4 shows an example of how the example networks in Figure 2 and Figure 3 are represented as adjacency matrices.

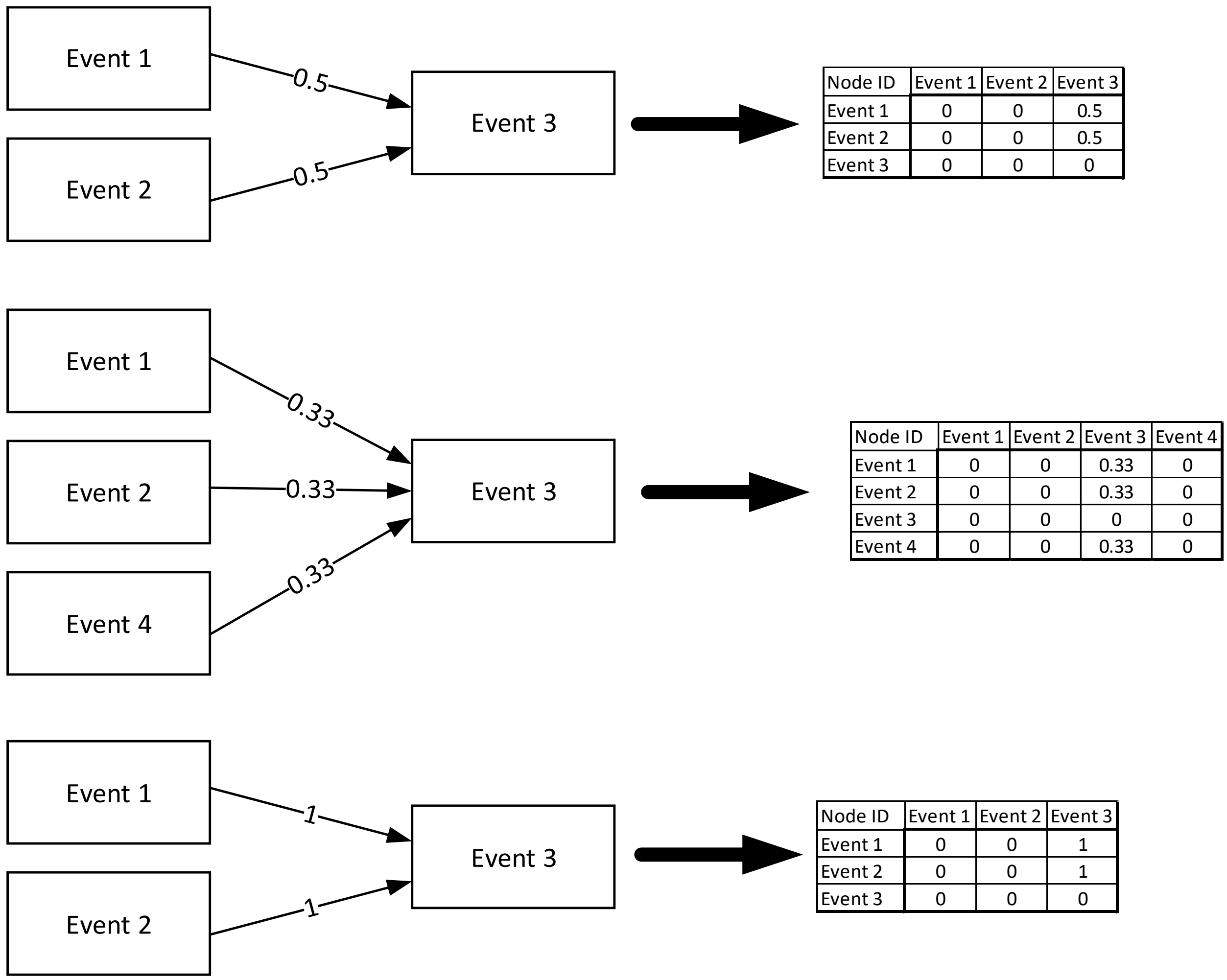

Figure 4 - Adjacency Matrices of Example Networks

These matrices are captured in MS Excel and are then imported into Matlab for network visualisation. Following the method detailed above, the causal networks that represent the four accident reports were generated and presented in Figure 5, Figure 6, Figure 7 and Figure 8.

2.3 Causal Network Metrics

The two network metrics applied to the accident networks in this work, as discussed in Section 1, are the P3 Interaction Contribution (PIC) and the Sum of Incoming Edges/Number of Edges.

2.3.1 P3 Interaction Contribution (PIC)

In previous work [2], the PIC metric was first introduced, with a summary included here. The PIC is a relative measure of the contribution of P3 interactions to an accident scenario as a whole. A P3 Interaction is counted as an association or a causal interaction between two different component types, from the following three categories: People, Plant and Procedures. P3 interactions can be found *within* an event description in a node, or *between* two different nodes, represented by an edge. There are four categories of P3 interaction: people-plant, people-procedure, plant-procedure and people-plant-procedure. The total number of P3 interactions were counted for each accident network and divided by the sum of the number of nodes (N) and edges (E) for that network, according to Equation 1.

Equation 1 - PIC Calculation

$$PIC = \frac{P3\ Interaction\ Count}{Number\ of\ Nodes +\ Number\ of\ Edges}$$

2.3.2 Average Edge Weight

The average edge weight for a causal network will indicate the proportion of causal links that participate in AND gates. A higher number of AND gates in a particular accident scenario may indicate that the likelihood of that scenario to be lower than an accident with more AND gates. This is simply because *more* simultaneous events or conditions needed to occur for that accident to progress. The average edge weight is calculated according to Equation 2.

Equation 2 - Average Edge Weight

$$Average\ Edge\ Weight = \frac{Sum\ of\ edge\ weights\ over\ whole\ network}{Number\ of\ Edges}$$

3 Results

This section contains the results of the analysis. Firstly, event lists for each accident are contained in Table 1, Table 2, Table 3 and Table 4. The weight causal network for each accident is presented in Figure 5, Figure 6, Figure 7 and Figure 8. The P3 Interaction count for each network, with the distribution of all the types of interactions between components, is shown in Table 5 with a corresponding plot for the P3 interactions count for each accident shown in Figure 9. Table 6 contains a summary of the network metrics for each accident.

Table 1 - Events in Barton Solvents Accident Scenario

Node ID	Node Description
1	Three compartment tanker arrived to fill storage tank
2	Tank contained ignitable vapour-air mix in head space
3	No precautions in place to stop ignitable vapour-air mix in headspace
4	MSDS did not indicate that vapour-air mix could form within tank
5	MSDS did not list precautionary measures beyond normal grounding and bonding
6	Barton pumped naphtha from three separate compartments to tank, requiring pipe to be removed and position on tanker changed
7	Air pockets introduced to fill piping when compartments changed
8	Stop-start filling of naphtha tank accumulating static
9	No manway or access to facilitate cleaning
10	No records of tank ever being cleaned
11	Employees scooped sediment from similar tanks
12	Likelihood of presence of sediment and water in naphtha tank
13	Liquid gauging system float has loose linkage at tape/float junction

14	Turbulence and bubbling from stop/start pumping and air ingress
15	Rapid static charge accumulation
16	Slack in gauge tape created
17	Linkage separated
18	Non-conductive liquid static prevention precautions not in place
19	Tank filled to point of maximum expected surface voltage
20	Spark occurred
21	Spark ignited vapour-air mix
22	Naphtha tank exploded
23	Tank flew into the air and landed 130 feet away
24	Two more tanks ruptured and released their contents into the fire
25	Intense fire caused contents of other tanks to over-pressurize and ignite
26	Debris was launched into adjoining community

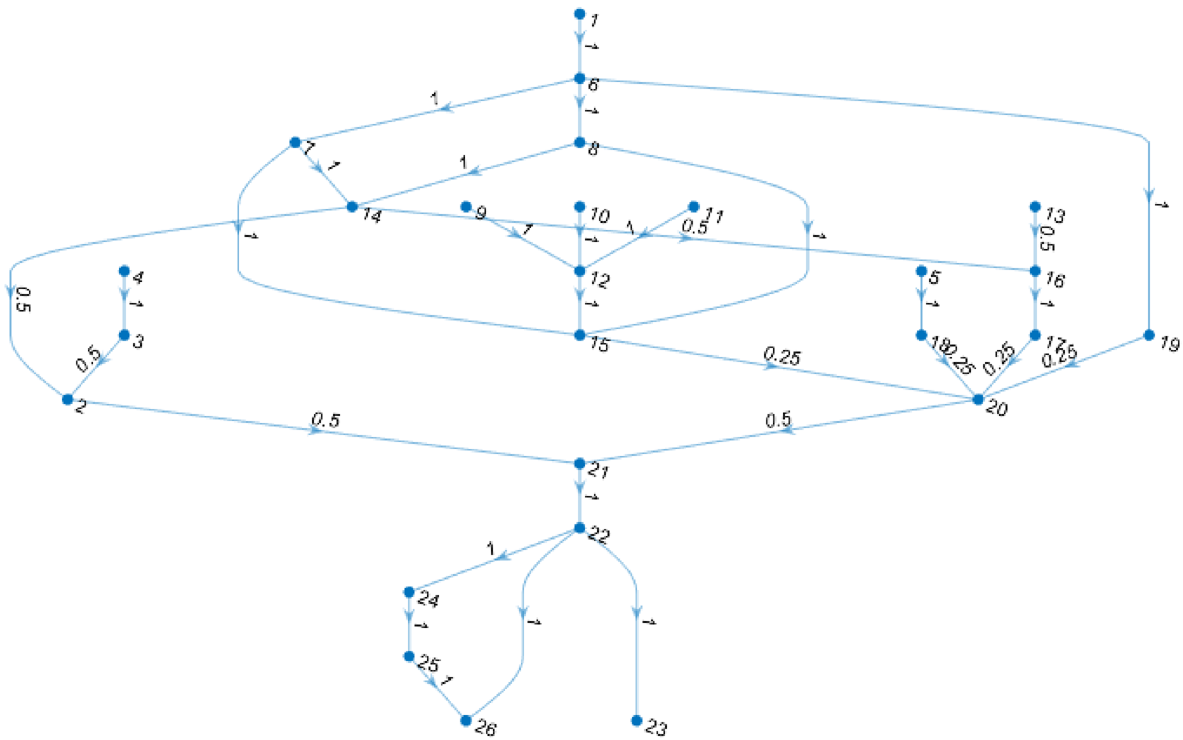

Figure 5 - Barton Solvents Causal Network

Table 2 - Events in Valero Propane Accident Scenario

Node ID	Node Description
1	Below freezing weather in morning
2	Makeup propane contains variable amount of entrained water
3	Use of control valve discontinued
4	Subsection left connected to process under high pressure
5	Block valves around control valve closed but subsection was not isolated with slip blinds
6	No formal process safety / change of management review conducted when control station removed from active service
7	Control station not isolated forming dead leg
8	American petroleum institute doesn't provide detailed guidance on freeze protection programs or sufficiently stress freeze protection of dead-legs
9	Freeze protection practices did not ensure process units systematically reviewed to identify and mitigate freezing hazards for dead legs
10	Control station not freeze-protected
11	Foreign object jammed block valve
12	Leak path created
13	Water leaked through at process pressure and accumulated
14	Water froze within pipe and expanded
15	Pipe elbow fractured along inner elbow
16	Air temperature rose
17	Highly pressurized propane released from fracture, since the ice sealing the fracture melted
18	High and shifting winds
19	Propane travelled downwind to boiler house or nearby fired heaters
20	Propane ignited and flashed back to leak source
21	Fire impinged on piping around No. 1 Extractor releasing additional propane
22	Rapidly expanding fire prevented access to manual isolation valves or local pump controls
23	API safety guidance does not address ROSOV use in process units handling large quantities of flammable materials
24	Valero closed ROSOV installation action item without verification
25	No remotely operable shut-off valves installed in PDA
26	Propane was unable to be isolated
27	API and Valero standards do not provide sufficient fireproofing guidance for pipe racks near high-pressure flammable units
28	Structural support was not fireproofed
29	Support column was impacted by high-pressure propane jet
30	Pipe rack collapsed
31	Multiple pipes failed discharging liquid petroleum products
32	Fire size/intensity rose significantly
33	Surrounding equipment damaged
34	Rapid spread of fire
35	Chlorine used as a biocide in adjacent cooling tower
36	PHA for system doesn't examine hazards of locating chlorine containers close to PDA unit
37	Three one-ton chlorine containers exposed to radiant heating from fire
38	All three containers vented varying amounts of chlorine when fusible plugs melted
39	2.5 tons of chlorine released
40	Butane storage sphere exposed to radiant heating
41	API-recommended practises do not require evaluation of adjacent process hazards in specifying location of deluge valves
42	Manual deluge valve located too close to PDA unit and could not be opened
43	Wind tended to move flames away from sphere
44	Near-miss - butane tank impinged with flame but did not fail. Minimal damage to tank
45	Plant personnel and contractors heard a 'pop' and saw propane cloud blowing from control station

46	Plant personnel directed workers in the area to evacuate
47	Fire alarm activated
48	Emergency response team arrived and approached fire
49	Winds hampered stationary fire water monitors
50	Operators noticed deteriorating situation
51	Evacuation ordered 15 minutes after ignition began
52	Main feeds and fuel gas supply isolated by emergency services
53	Chlorine and sulphuric acid leaks made entry too hazardous
54	Fire extinguished 52 hours after ignition
55	4 workers injured, 3 suffering serious burns
56	10 Valero employees and contractors treated for minor injuries
57	Total shutdown of McKee Refinery for two months
58	Refinery operated at reduced capacity for nearly a year
59	$50 million in direct losses due to fire
60	Significant quantities of gasoline lost in fire
61	Spot shortages of reformulated gasoline in Denver, Colorado in weeks following fire

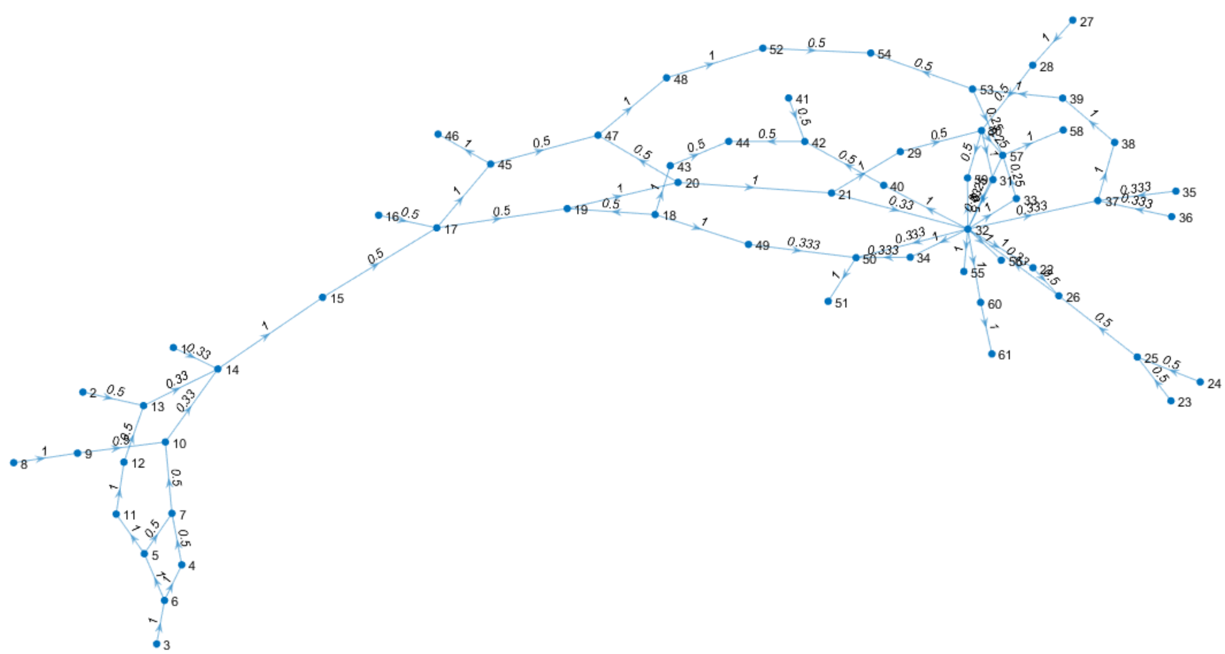

Figure 6 - Valero Propane Causal Network

Table 3 - Events in ASCO Accident Scenario

Node ID	Node Description
1	Workers shovelling snow south of shed where acetylene accumulated
2	Operator's manual did not address recycle water system
3	Operators had no written guidance on operation of recycle system or consequences on deviation from intended sequence
4	General procedures posted in generator room lacked guidance on appropriate sequence for adding water to the generator
5	Workers did not operate process consistently due to inadequate staff training / documentation
6	Generator was pressurized with acetylene gas before recycle water supply was established
7	City water supply valve closed prior to starting recycled water system
8	No source of pressurized water to prevent reverse flow of acetylene
9	1996 PHA didn't identify hazards created by decant water line drain in shed
10	Check valve in recycle water line did not use springs or guides to assist seating of plug
11	Plug is prone to misalignment
12	Check valve internals are prone to solid build-up such as scale
13	Check valve guide pin "hung up" on lower pipe nipple
14	Recycled Water "Found Closed" valve either open or leaked significantly in closed position
15	Acetylene was able to flow back through recycle water line
16	Acetylene leaked from the generator through to the shed through water recycle line
17	Heavy snowfall
18	Freeze Protection Practices in place: Decanted water line normally left open to protect from freezing
19	Lime shed had no ventilation
20	Shed contained a propane heater with a hot surface
21	Acetylene gas accumulated in lime shed through drain leak
22	Acetylene gas ignited upon contact with heater surface
23	Three workers were killed
24	One worker was seriously injured by the blast
25	Lime shed completely destroyed
26	Debris hurled up to 450 feet from the site
27	Two large holes were blown into the sides of adjacent building
28	Windows were shattered
29	Doors blown into building / knocked off their hinges/rails
30	PHA was not updated in 2001 as required
31	Conditions leading to explosion were unidentified

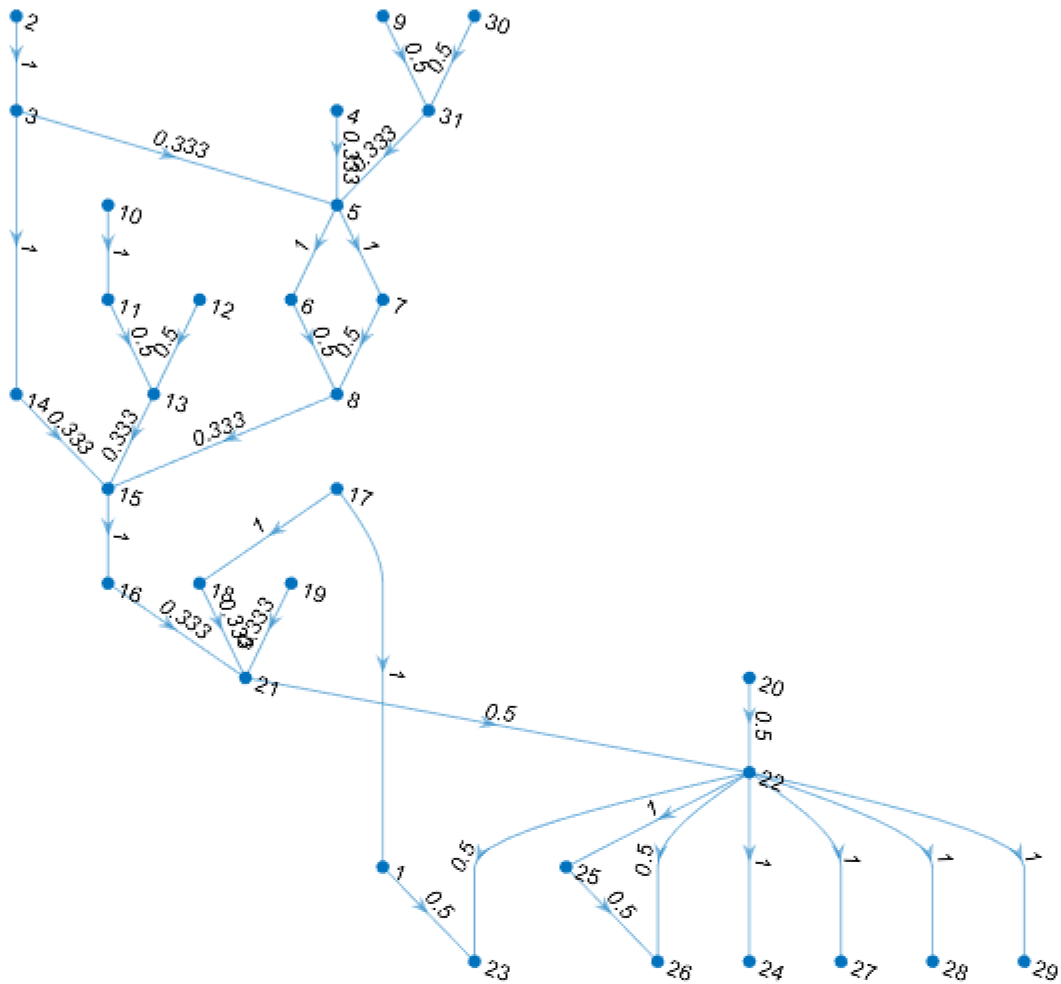

Figure 7 - ASCO Causal Network

Table 4 - Events in AL Solutions Accident Scenario

Node ID	Node Description
1	Weak safety management for handling titanium and zirconium safe storage and handling
2	Faulty blender identified
3	Insufficient temporary fix used
4	Metal blades continued scraping on metal casing
5	Spark occurred
6	Ignition of zirconium dust
7	Explosion
8	Lids not closed on equipment
9	Fire became airborne
10	Did not follow dust reduction recommendations or collection system, as recommended by standards
11	Mix of zirconium and titanium being milled (ground in to fine powders)
12	OSHA did not implement any combustible dust standard
13	Collection of dust on equipment
14	Fire spread

15	Water used for wash-down procedures
16	Hydrogen gas present in facility
17	Hydrogen gas caught fire
18	Barrels not in use left in production room instead of secondary storage facility
19	Barrels caught fire
20	Increased fire intensity
21	Operators at blender and presses died
22	Water deluge system activated
23	Insurance auditors commended facility and declared potential dust incidents are effectively controlled, not recommending a process hazards analysis.
24	Insurance auditors declared fire protection systems good process control
25	Damage caused throughout production area
26	Permanent shutdown
27	Electrical contractor received severe injuries
28	Electrical contractor in hydraulic room for maintenance
29	Management did not enforce lid closure on blender during operation
30	Housekeeping approach to dust control

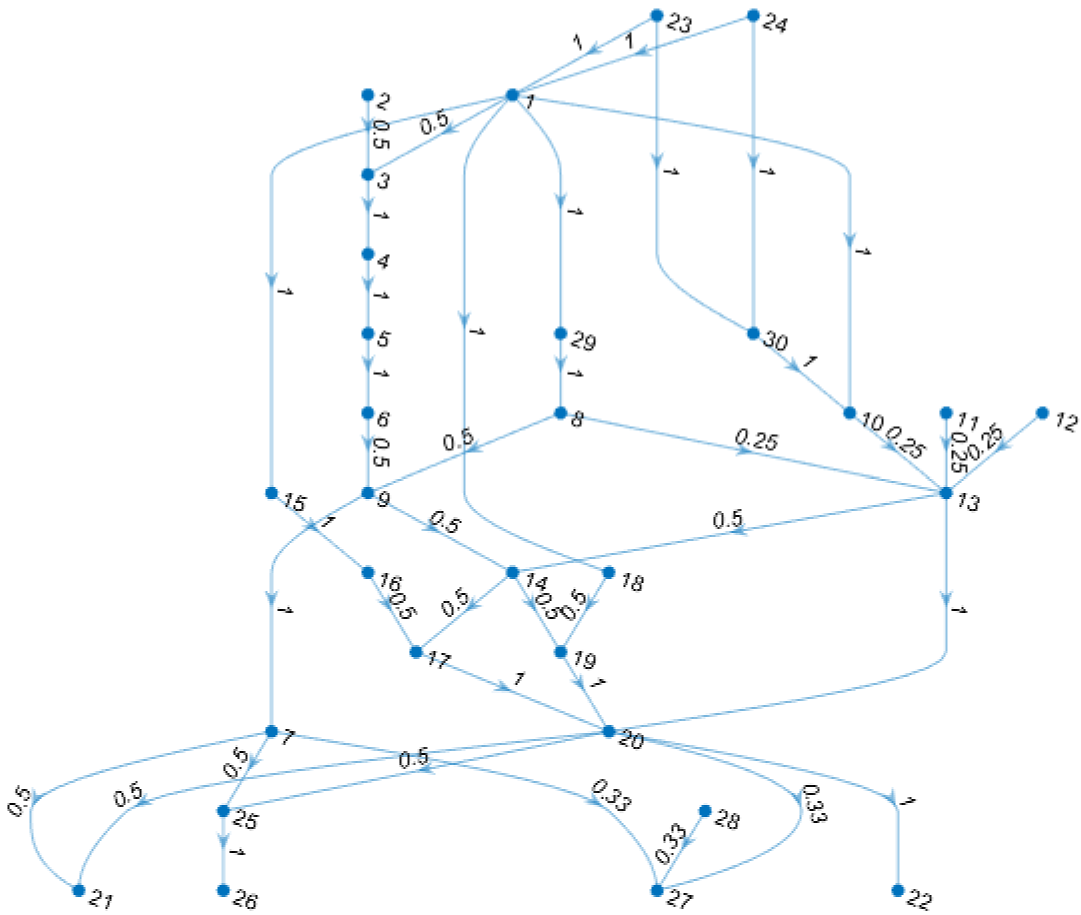

Figure 8 - AL Solutions Causal Network

Table 5 – P3 Interaction Count

Type of P3 Interaction	Barton Solvents			Valero Propane			ASCO			AL Solutions		
	Within	Between	**TOTAL**	Within	Between	**TOTAL**	Within	Between	**TOTAL**	Within	Between	**TOTAL**
People	0	0	0	2	0	2	2	0	2	0	0	0
Plant	11	0	11	27	0	27	13	0	13	13	0	13
Procedure	1	0	1	6	0	6	3	0	3	1	0	1
People-People	0	0	0	2	0	2	0	1	1	0	0	0
Plant-Plant	6	20	26	12	43	55	7	19	26	3	19	22
Procedure-Procedure	0	0	0	0	1	1	0	0	0	0	0	0
People-Plant	**4**	**6**	**10**	**10**	**20**	**30**	**3**	**5**	**8**	**8**	**9**	**17**
People-Procedure	**0**	**0**	**0**	**1**	**0**	**1**	**2**	**1**	**3**	**0**	**0**	**0**
Plant-Procedure	3	4	7	0	4	4	0	0	0	3	2	5
People-Plant-Procedure	1	1	2	1	5	6	1	8	9	2	11	13
P3 Count	**8**	**11**	**19**	**12**	**29**	**41**	**6**	**14**	**20**	**13**	**22**	**35**

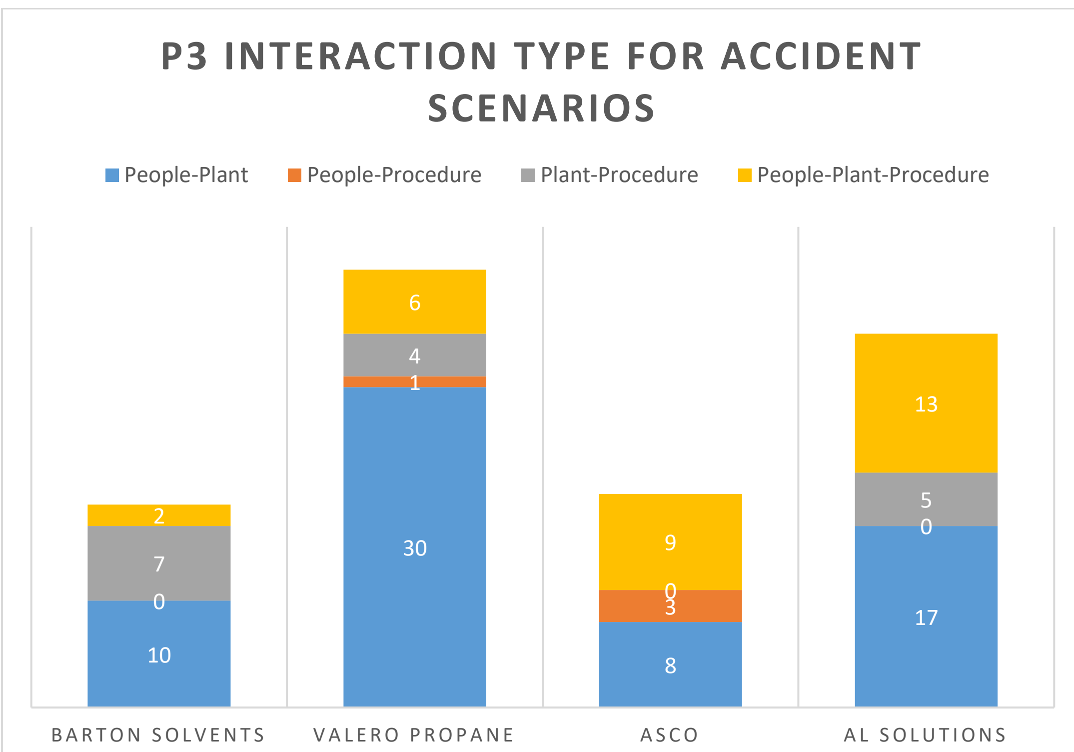

Figure 9 - P3 Interaction Type Plot

Table 6 - Network Metrics

Metrics	Barton Solvents	Valero Propane	ASCO	AL Solutions
Number of Nodes (N)	26	61	31	30
Number of Edges (E)	31	73	34	41
Sum of Edge Weights	25	49	22	29
Average Edge Weight	0.81	0.67	0.65	0.66
P3 Count	19	41	20	35
PIC	0.33	0.31	0.31	0.49

4 Discussion

Initial inspection of the networks in Figure 5, Figure 6, Figure 7 and Figure 8 reveals that they both have similarities and differences. Barton and ASCO have a series of initiating causes, focussing in on a few central events, which happen to be nodes 21 and 22 in both networks. AL Solutions and Valero have a more complex structure, and yet visual inspection reveals that they appear to be quite different from each other. In terms of the number of nodes and edges, Barton (26 N – 31 E), ASCO (31 N – 34 E) and AL Solutions (30 N – 41 E) are all similar sizes, shown in Table 6. Valero Propane is considerably bigger (61 N – 73 E). Thus, as is expected, Valero has the highest P3 count, but this is simply because it is a larger network. The PIC for Barton (0.33), Valero (0.31) and ASCO (0.31) are all similar, with AL solutions (0.49) having the largest. And yet the contribution of different types of P3 interactions for each scenario differs, as shown in Figure 9. Barton has the high average edge weight (0.81), where Valero (0.67), ASCO (0.65) and AL Solutions (0.66) are very similar.

A lower average edge weight indicates that Valero, ASCO and AL Solutions would potentially harder to identify ahead of time than Barton, during risk assessment, since more simultaneous events or conditions need to be in place for them to progress. Conversely, an accident with a high average edge weight may tend to be easier to identify but harder to stop, since on average there are more independent paths along which the accident can progress. This is the situation where there are more independent causes per node and/or more OR gates.

Thus, once the average edge weight useful questions that investigators could ask themselves could be:

- Did I expect that degree of AND gates in the scenario?
- If my average edge weight is very high, is the causal progression really that simple? Could there actually be other conditions hidden that I just haven’t found yet, that contribute to the accident?
- If the average edge weight is very low, does that really mean this situation will be hard to identify in the future? If so, what can we embed in the lessons learned about new monitoring practices that could be implemented? Have we considered monitoring practices at all?

These kind of questions could push them to look further into the scenario until they are thoroughly satisfied that they have captured it accurately.

Similarly, the PIC for each scenario could help investigators ask the following kinds of questions:

- For ASCO, does the P3 interaction type distribution in Figure 9, suggest that perhaps the lessons learned should include recommendations that combine people-plant-procedure interactions, and people-plant interactions, in roughly equal measure?
- Since the PIC is almost 0.5 for AL Solutions, does that mean that the lessons learned should be related to P3 interactions at least half the time?
- For Valero Propane, does the lower PIC mean that P3 interactions are not that significant for the scenario as a whole? And does the high proportion of P3 interactions that a People-plant (Figure 9), and the high proportion of plant and plant-plant interactions in Table 5, mean that we don't have to strongly consider the impact of procedures at all?

The above hypothetical questions demonstrate that metrics like the PIC and the average edge weight, used during accident investigations, could be effective *reflective practice tools* to enhance the results. Using the metrics to form a series of checking questions, for example, could remove threats of complacency in the analyst's practice. One of the benefits of metrics based on topology of causal networks is that they are generic tools that can be used flexibly in many different circumstances to support accident investigation.

5 Conclusions and Future Work

This paper demonstrated the use of two causal network metrics applied to accidents previously investigation by the CSB. Then, intention was to show how the PIC and the average edge weight could be used to support reflective practice activities during the investigation activities themselves, with the goal of generating the best set of lessons learned possible.

Further explorations with the PIC and the average edge weight would be to calculate them for many accident reports that the CSB has produced, and see if there is a correlation, such as if a high PIC corresponds with a lower average edge weight, meaning more AND gates in the scenario. If so, then more P3 interactions would indicate that an accident scenario is harder to identify, but easier to arrest. Thus, the two metrics may be more deeply related than first thought.

We hope this paper is *a refreshing take* on the activity of accident investigation, spurring a renewed interest in how accident reports are written and investigations carried out, to maximise the benefits of them for identifying causal structures potentially leading to mishap and so enhancing risk assessment in a complex world.

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