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The role of interdependent contexts in accident progression

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Abstract: Understanding the level of independence of risk controls in a system is essential when conducting risk assessments (RAs). RAs are often influenced by multiple external and internal contexts. On 25th May 2021, a catastrophic failure occurred at Callide C power station in Queensland. The technical and organizationally focused investigation reports, indicated that the failure resulted from a top-down flow from decisions made at the stakeholder level, including altered operational strategies, asset management practices, and cost cutting. These decisions affected the corporate and organizational levels, ultimately impacting how risk management was conducted, how risk assessments were performed, and how risk data was collected, stored and monitored. Needing to explicitly consider the multiple stakeholder, organizational, and informational contexts highlights the challenge of recognizing and integrating system interdependencies in risk management decision-making. We applied a network analysis and graph theory-based approach to the Callide Unit C4 accident reports, to 1) visualize the accident by segmenting the reports into different events and linking them together to form a directed graph; 2) perform a constrained robustness analysis on this network to identify system vulnerabilities; 3) illustrate the cyclical relationships between system components. Key findings reveal that the board did not have the reach, influence or visibility of downstream process safety or management of change-related events. Furthermore, the technical contexts significantly contributed to the accident, highlighting potential hazards associated with the redundancy design. In this study, we have demonstrated the use of network analyses to better understand how context behaves as an influencing factor affecting interdependence among the components and their controls, and ultimately benefits the hazardous industries.

Keywords: Risk management, Network Analysis, Graph Theory, Context

1. Introduction

The importance of context before and during an accident happens has grown significantly over time. The focus of accident investigation to include more details regarding organizational context compared to direct technical issues or human errors (Dien et al. 2004) is evidence of this. It is essential to analyze the dependence between safety and protection systems to increase awareness and to avoid catastrophic events (Guo et al. 2018). Yet, failures can occur at various levels from national and government through board and systems management, down to procedures, equipment and individuals (Venkatasubramanian 2011), including the interactions between factors within these categories. For example, studies (Kaszniak 2009; Mannan 2012) have highlighted that contexts such as cost-cutting, weak safety culture, lack of incident reporting , and ineffective management of change were root causes of the BP Texas City accident.

Therefore, it is important to consider multiple contexts during RA, as systems in complex situations are subject to both external and internal forcing dynamics (Park et al. 2013), and failure can even be a part of normal operation (Perrow 1999).

1.1. Literature Review

To date, there exists many developed techniques for integrating context to utilize safety practices and risk management. For example, methods explore the influence of social context on organizational safety culture (Rao 2007), risk events (Dekker 2016), or dynamic interactions (Vierendeels et al. 2018).

Network-based techniques have been widely applied to model past accidents. The Safety and Failure Event Network (SAFE-Net) is used to represent and model the complex socio-technical systems, allowing for both technical factors and others like social and environmental (Klockner and Toft 2018). Seligmann et al. (2019) represented an accident scenario described with three different hazard identification methods into three networks to analyze the interactions between people, plant and procedural components. Other studies also model the interactions between physical units (Qi et al. 2021), component failures (Németh et al. 2011), accident-related risk factors (Zhou et al. 2021; Huang et al. 2020; Seligmann et al. 2019). Previous authors combined many causal scenarios in a particular accident type into a single, harmonized, causal network (Zhou et al. 2021; Liu et al. 2023; Qiu et al. 2021; Thoroman and Salmon 2020; Huang et al. 2020; Klockner and Toft 2018), but rarely analyzed individual scenarios (Huang et al. 2020; Seligmann et al. 2019). Such aggregation tends to lose specific features of the network and the unique characteristics of any single accident represented by the network.

This article applies a network analysis approach to integrate multiple contexts related to the Callide accident. This highlights the system interdependencies that were at play during the accident. The intention is to demonstrate that studying the structure of the Callide Unit C4 causal network enriches what can be learnt from this accident scenario to enhance RA practice.

1.2. Callide Unit C4 Accident

A catastrophic failure happened at Unit C4 of the Callide C power station in May 2021. The unit turbine generator was destroyed, impacting the Queensland electricity transmission grid. The accident happened in the context of having a battery charger replaced. The new charger did not immediately maintain the unit voltage and caused a voltage collapse under the threshold a unit protection system – arc flap protection. The protection responded by assuming an arc had occurred, thus activating. This triggered the cut off the AC supply, a complete loss of the DC supply, causing the C4 turbine rotor to continue spin at 3,000 rpm without any protection, resulting in a catastrophic failure. There were clear technical causes for the accident, but the publicly available reports indicated that the contextual background played a significant role.

2. Research Methodology

This section presents a network analysis technique to identify contributing events and how they are causally connected from the context categories used in the reports, namely societal, stakeholders, board, corporate, site and technical. The method itself is called the Causal Network Topology Analysis (Caneta), which visualizes events and their causal links as a directed, weighted graph (Lin et al. 2023; Seligmann et al. 2024). In this paper, Caneta has been applied to the publicly available technical and organizational reports describing the Callide C4 accident as illustrated in Fig 1.

This study extends on the visualization of the causal network by assigning events associated with the levels where they occurred, within the organization. Topology metrics explain the similarities and differences between events from different context categories to help characterize the interacting nature of context in the genesis and progression of accident. These metrics are network mathematical measurements. For example, *degree* calculates the number of total causal relationships one event has with other events. Another process in Caneta, called robustness analysis, reflects system fragility by removing nodes and their related causal relationships from the network. Node removal is interpreted as preventing an event from happening. In this study the robustness analysis has been updated to a *constrained* analysis, allowing certain events to be inherently immune from removal. For

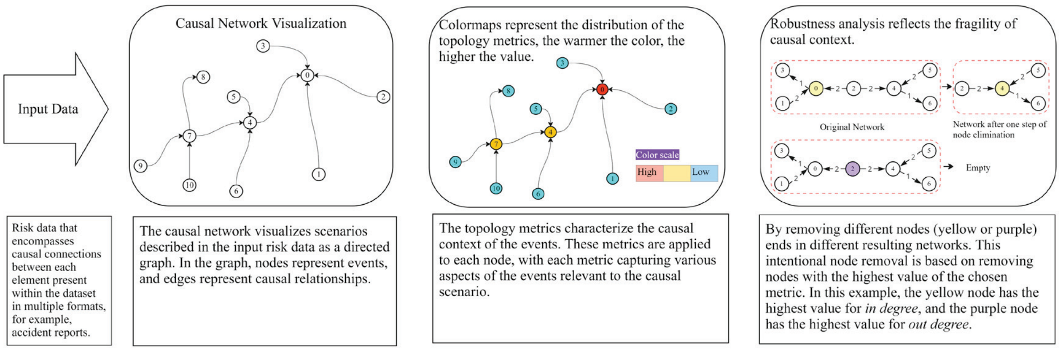


Fig. 1. The Caneta process (Lin et al. 2023; Lin et al. 2024)

instance, when analyzing an accident report, an event such as ‘a previous accident happened 3 years ago’ should not be seen as preventable. The analysis also illustrates and discusses critical vicious loops and cyclical relationships between the failure of system components.

3. Results

3.1. *Network Visualization and Metrics*

The direct outcome from applying Caneta to the Callide Unit C4 accident reports is the visualization of the causal network. As illustrated in Fig 2 a), the round circles with various colors and numbers attached are called nodes, representing events occurred during or before the accident. Lines connecting nodes are called edges, and arrows on the edges represent the direction of their causal relationships. The colors in Fig 2 a) represent 6 context categories where each event is classified according to the accident reports. These categories and events were assigned by experts who generated the reports (Heywood 2024).

Caneta offers 9 different network metrics for analyzing. Calculating metric values for each event results in 9 sets of data. These data are segmented across 6 categories, yielding a total of 54 data sets. Applying statistical analysis to examine the differences between these data sets provides additional insights into the relationships between metrics and the context of each event. Due to the non-normal distribution of the data, the Kruskal-Wallis Test (McKight and Najab 2010) is selected to evaluate significant differences across context categories for each of the 9 metrics. The results shown in Table 1 reveal that all metrics have significant differences across categories, as indicated by their p-values being below 0.05.

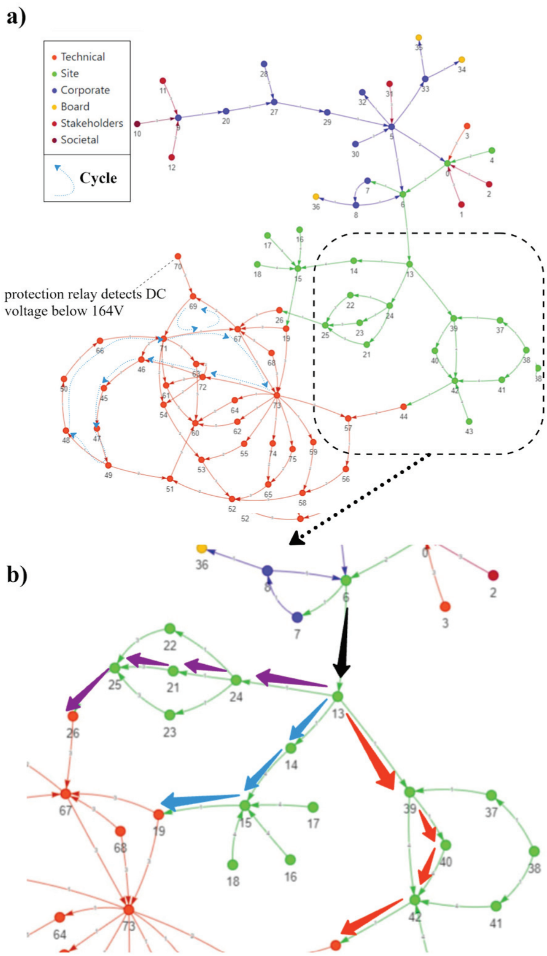
Dunn’s Test (Dunn 1964) is used as a post-hoc analysis to identify specific categories differences within the metric group. The outcomes are shown in Table 1. A p-value smaller than 0.05 indicates a significance difference between the compared datasets.

Table 1 suggests events within technical category can be distinguished from those within the stakeholders category by most metrics (*degree*, *in degree*, *strength, in strength*, *betweenness* and *in closeness*). These technical events can be further distinguished from site and corporate events using metric *in closeness*. In addition, metrics *out degree* and *out closeness* provide clear separations between board events and events in other context categories.

3.2. Robustness Analysis

As described in Section 2, Caneta provides robustness analysis which intentionally removes nodes and their causal relationships to other nodes within the network. This can be used to identify critical events in a causal network, as potential places to target actions from out of the accident investigation process. Here the 9 metrics being mentioned in previous sections are used to perform 10 *constrained* robustness analyses. For this specific accident, Table 2 contains nodes that cannot be chosen for removal. Node 38 is a previous accident and node 41 is the consequence of that accident. Node 60 is the final consequence of the accident being analyzed in this study.

Fig 3 shows the results for the robustness analysis, highlighting regions with both steep and flat gradients. In all analyses, removing the first node eliminates the final consequence event 60: ‘After 34 minutes motoring without protection, the shaft tore apart in nine locations’. Therefore,



Causal Pathway	Node IDs	Description
Start	13	Systemic issues with application of management of change process
Purple	24	Management of Change Not applied effectively [Flawed Process]
	21	Battery charger was not specified, designed / tested for the requirements of switching process, but only tested in its typical operational state & not as part of the system
	22	Battery charger were complications before incident, however there is no evidence that the operators and switching team were made aware of the issues
	23	Failure to implement effective process safety practices
	25	Decrease the likelihood of identifying and managing the risks associated with 'Change the Battery charger converts AC supply to DC supply'
	26	Change the Battery charger that cannot maintain Voltage above 164V & converts AC supply to DC supply
Blue	14	Lack of Awareness of Plant Status including issues with battery charger & status of automatic changeover switch
	15	No formal process safety risk assessment required to consider relevant risks
	19	Failure of Station DC supply via interconnection during maintenance of battery charger
Red	39	Interim Solution – Removal of Design Redundancy to Unit C3 and Station ACSs without management of change applied
	40	CS Energy Stated that Unit C4 disabled by CS energy by removal of fuses
	42	Unit C4 Automatic Changeover Switch Left in an Inoperable State
	44	Failure of automatic changeover switch respond then change over the DC supply to Station DC

Fig. 2. Causal network developed from the Callide Unit C4 accident: a) Network visualization. Each node represents an event identified in the accident reports. For example, node 70 is 'protection relay detects DC voltage below 164V'. Nodes in different context categories are colored differently, as indicated by the legend in the upper left corner. The cycles are represented using blue dotted arrow lines. b) Three key causal pathways support the accident flow from corporate and site level towards technical issues, including the event descriptions.

it is critical to analyze the results of the initial node removal process.

The red dotted circle region in Fig 3 a) represents the removal of site event node 6 'Issues with Key Systems like work management system', which results in nearly 40 nodes being removed from the network. After this particular node is removed the resulting network is divided into three sub-networks, shown in Fig 3 b). Key events in the largest upper sub-network include node 5, which leads to the key site node 0 and to the two board nodes 34 and 35. This sub-network also contains other events from board level to site level. The bottom left sub- networks start from node 38 which has been described in Table 2, and its cascading influential leading to technical issue node 44. The bottom right sub-network contains only technical nodes, representing how the 'failure of maintaining DC voltage below 164V' (node 67) and 'protection relay detects DC voltage below 164V' (node 70) together cause 'the AC incomer circuit breaker to open' (node 69) and 'loss of AC power' (node 71). Additionally, the loss of AC power triggers event 67. See Fig 3 d) for a detailed description of each event.

Table 1. Statistical analysis results

	Kruskal-Wallis Test		Dunn's Test results	
Metric	Statistic Measures	p-value	Difference (Category - Category)	p-value
Degree	19.19	0.002	Technical – Stakeholders	0.010
In Degree	15.12	0.010	Technical – Stakeholders	0.005
Out Degree	14.59	0.010	Board – Site	0.004
			Board – Technical	0.005
			Board – Corporate	0.010
Strength	15.67	0.008	Technical – Stakeholders	0.017
			Corporate – Stakeholders	0.036
Out Strength	18.55	0.002	Board – Corporate	0.030
In Strength	12.05	0.034	Stakeholders – Site	0.020
			Technical – Stakeholders	0.002
Betweenness	15.81	0.007	Technical – Stakeholders	0.030
In Closeness	39.23	<0.001	Technical – Site	<0.001
			Technical – Stakeholders	<0.001
			Technical – Corporate	<0.001
Out Closeness	12.37	0.030	Board – Corporate	0.013

Table 2. Constrained events

IDs	Event Description
38	January 2021 Incident - Double Unit Trip
41	C4 automatic changeover switch - Blown fuses
60	After 34 minutes motoring without protection, the shaft tore apart in nine locations

The black dotted circle region in Fig 3 a) indicates the removal of node 73 ‘Failure of DC supply to Unit C4 main switchboard & operate normally’, and the remaining network is represented in Fig 3 c). Compared to Fig 3 b) the nodes within the network are fully connected, indicating that even though targeting technical events might eliminate the consequence (node 60) of this particular accident, the Callide unit C4 might still experience the loss of both AC and DC supply. The remaining two metric analyses select similar technical events for removal and have a similar impact on the network structure as shown in Fig 3 c).

3.3. Cycles in the Network

Various loop structures can be seen in Fig 2 a), highlighted with blue dotted lines and arrows. There are three cyclic paths:

(i) Node 6 -> 7 -> 8 -> 6
(ii) Node 67 -> 69 -> 71 -> 67
(iii) Node 67 -> 73 -> 72 -> 46 -> 45 -> 47 -> 48 -> 50 -> 66 -> 71 -> 67

A cycle in a network is a closed path, starting from one node and travels back to the exact same node, forming a closed loop. Cycle (i) consists of corporate and site events, starting from event 6 ‘Issues with Key Systems like work management system’ at the site level. This triggers corporate event 7, ‘Assurance program identifies longstanding issues with systems’ which further leads to event 8, ‘Assurance Program only addressed symptoms but not core issues’. Since the core issues remain unsolved, event 6 appears to be caused again.

Cycles (ii) and (iii) consist technical events only. Cycle (ii) describes how a voltage drop causes the loss of AC supply. This direction can also be reversed. Cycle (iii) is a larger sequence where the voltage drop (node 67) triggers the loss of unit switchboard (node 73) and corresponding protection components for the turbine (nodes 63 and 46). Consequently, the steam turbine fails (nodes 45, 47, 48, 50) to generate unit AC power (nodes 66 and 71) and cannot maintain the voltage (node 67).

4. Discussion

4.1. Network Visualization and Topology metrics Interpretation

From Fig 2 a), all three key causal pathways start from issues with key systems, such as the work management team (node 6). Fig 2 b) illustrates the three pathways related to the 1) no process safety

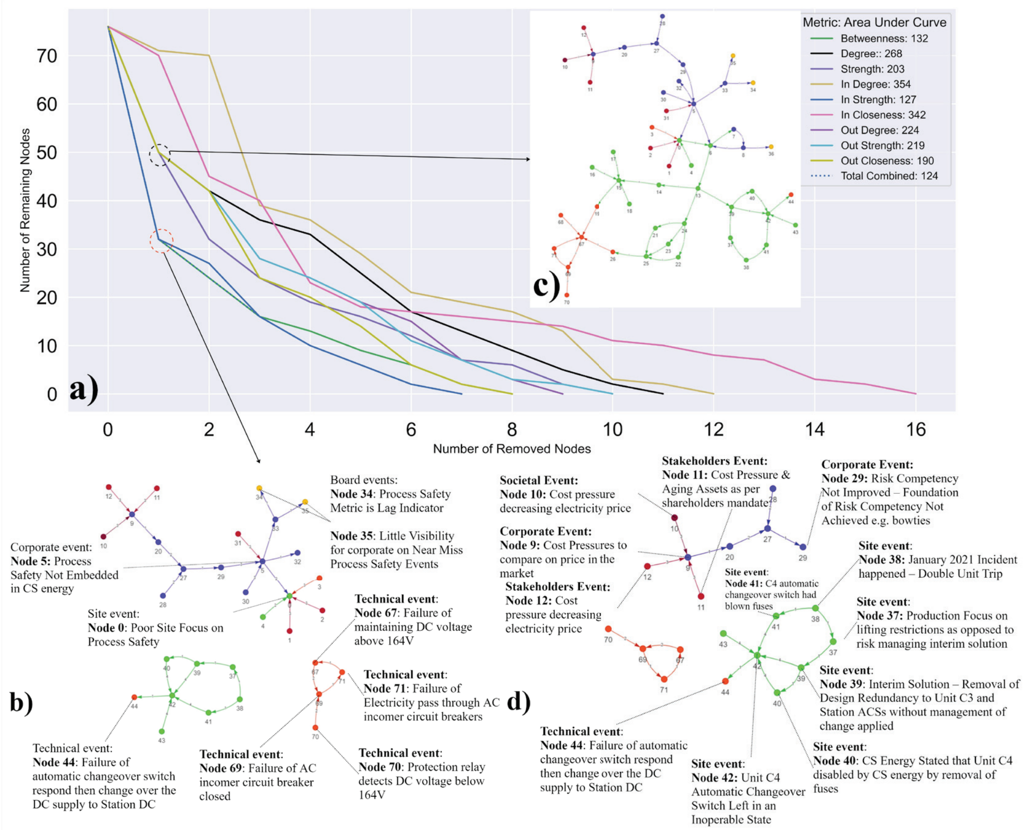


Fig. 3. a) Robustness analysis results; b, c) How the steep or gentle line gradients being represented in the network; d) Resulting network structure after removing node 5 (1 more step of robustness analysis)

safety assessment on the action of changing the component, and 3) the lack of effective actions following the previous accident.

The experts who generated the reports suggested that if CS Energy (the company who operates the Callide C power station) had well-embedded process safety (node 5), it would have prevented node 6 from occurring. This in turn would stop the propagation towards the final consequences through any of the three key causal pathways.

Table 1 indicates *in closeness* characterizes technical events apart from events in other context categories. Many of the technical events have, on average, higher *in closeness* scores than events in the other context categories. A higher value of *in closeness* indicates that the events are indirectly connected to many other events causally 'upstream', often through multiple paths (Lin et al. 2024). The *in closeness* results show that the experts tended to investigate many possible root causes and their causal pathways to the actual accident technical events, tracing back towards the upper level of the organization.

Another finding from Table 1 is that metrics *out degree* and *out closeness* characterize board events differently from other events. These two metrics assess the ability of events to cause other events, and how tightly events are connected to all other downstream events (Lin et al. 2024). All board events have 0 *out degree* and *out closeness* - they have no consequences in the accident reports. This indicates that events related to the board did occur in relation to this accident scenario, there were no flow-on effects from the board that influenced the downstream technical issues, where the final accident event occurred. This may indicate that the board did not have the reach, influence or visibility of downstream process safety or management of change-related events.

4.2. Robustness Analyses Interpretation

As described in Section 4.1, embedding process safety is crucial to cut the 'bridges' towards the final consequences. Fig 3 b) shows the network after eliminating node 6. What if nodes 5 and 0 are also prevented, assuming CS Energy prioritizes process safety? Fig 3 d) illustrates potential causes and consequences, even if the actual consequence of the Callide Unit C4 accident - turbine shaft tore apart – is avoided. The presence of event 29 reveals that pressures from societal and stakeholders level onto corporate still exist, leaving an unimproved risk competency. Event 44 highlights the impact of shifting focus from risk managing to production. The bottom right technical issues still occur and depend on each other, leaving potential hazards or threats regarding the redundancy design.

As written down in the accident reports : '*With respect to the likelihood of CS Energy identifying the risk that the loss of DC supply to Unit C4 would trigger the loss of AC supply, it is highly unlikely that the mechanisms for the loss of AC could have been anticipated (the mechanism is dependent on the specific nature of the DC collapse)*'

However, as previously discussed, this potential possibility remains underlying until it is revised as crucial after robustness analysis. The issue of AC and DC supply independency will be expanded upon in the next section as well.

4.3. Cycles

As presented in Section 3.3, there are three cycles in the network. Cycle (i) highlights the importance of addressing core system issues (related to node 6) directly rather than just the symptoms (related to node 8). Robustness analysis identifies node 6 as the key event of the three key causal pathways. If only symptoms are addressed, then node 6 will remain a permanent issue within the organization.

Cycles (ii) and (iii) both relate to system reliability and independence. The Callide C4 Unit has AC and DC supplies for two sets of turbine protection systems, but they are interdependent. According to the reports, three key factors are 1) the battery charger, 2) the battery charger replacement, and 3) the lack of effective actions after the previous accident. Robustness analysis reveals that their upper-level causes are related to process safety focus (nodes 0, 5). Here, the technical context has been shown to contribute significantly to the accident.

5. Conclusion

This paper presents a graph theory approach, from three different perspectives to analyze the accident happened at Callide Unit C4 power station. The skeleton of the accident scenario is well presented through the causal network, including the context categories. The interpretation of the topology metrics characterizes the similarities and differences in these contexts by which events in the scenario are classified in the accident reports. System reliabilities and interdependencies have been assessed as well and expanded in Section 4.

The approach presented in this paper provides researchers, managers and operators with an opportunity to understand how various contexts affect the system, offering deeper insights into the accident.

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