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Applying systems thinking concepts in the analysis of major incidents and safety culture

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ABSTRACT

In recent years, investigations into major incidents often highlight poor safety culture as one of the key causal factors. These investigations are often assisted by causal analysis tools that help to ensure that the investigation and the information captured are systematic. However, current causal analysis tools are not designed to analyse dynamic complexity of major incidents and safety culture, which arises from the interactions between actors and the temporal and spatial gaps between actions and consequences. This is because most causal analysis tools model events and causal factors linearly. In contrast, systems thinking, a discipline of seeing systems holistically, emphasises the circular nature of complex systems, i.e. cause and effect are not distinguishable. This paper proposes that traditional causal analysis tools and investigation should be enhanced with the use of systems thinking tools.

One of the systems thinking tools that is particularly useful in analysing major incidents and safety culture is causal loop diagrams. The diagrams can be used to explain the systemic structure sustaining a safety culture and identify effective interventions to improve the safety culture and prevent a recurrence of a major incident. The paper demonstrates the use of systems thinking and causal loop diagrams through a case study on Bellevue hazardous waste fire in Western Australia. The case study shows how different actors in the system, each acting in reaction to pressures that they are facing, produced and sustained a poor safety culture that was a major contributory factor to the fire in 2001.

1. Introduction

After INSAG (1986) introduced the term ‘safety culture’ in its summary report of the Chernobyl accident, investigations or inquiries into major accidents and incidents (for e.g. Baker et al., 2007; Cullen, 1990; Magnus et al., 2005; Sheen, 1987) frequently identified poor safety culture (or variants of the term) as a key contributor to the occurrence of the incident. This is not surprising because culture is defined as *the way things are done around here* (Schein, 1992, pp. 8–9) and it is usually *the ways things are done* or patterns of behaviour that trigger major incidents. One of the fundamental ways to improve safety culture is to analyse major incidents and ensure that behaviour shaping mechanisms (Rasmussen, 1997) are identified. The knowledge of these behaviour shaping mechanisms or systemic structures can then be used as part of the strategy to prevent a recurrence.

Learning from incidents is a fundamental approach in accident prevention. Besides inquiry reports, there are plenty of publications that share insights from causal analysis of major incidents (for e.g. Hopkins, 2000; Kletz, 1999, 2001, 2003) and many of them have identified cultural issues that led to the incidents. In addition, occupational health and safety (OHS) management system standards, such as OHSAS 18001:2007 (British Standards Institute, 2007) and AS/NZS 4801:2001 (Standards Australia and Standards New Zealand, 2001), typically specify requirements for procedures to facilitate learning and corrective actions at the organisational level. Even though learning from incidents is fundamental, the complexity of safety culture and major incidents calls for a more holistic approach. This paper proposes the use of systems thinking concepts (Senge, 2006) to achieve a clearer understanding of how underlying systemic structures create and sustain poor safety culture that can contribute to the occurrence of major incidents.

2. Causal analysis tools

There is a wide range of causal analysis tools which are frequently used to ensure thorough and systematic analysis of major incidents. Sklet (2004) evaluated 14 such tools and showed that most causal analysis tools identify a string of events that led to the incident and its consequences. The causal factors of key events will then be traced to identify “root causes”. Rasmussen (1997) identified six levels in socio-technical systems: (1) the work and technological system, (2) the staff level, (3) the management level,

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(4) the company level, (5) the direct government regulators and industry association level, and (6) the overall Government level. Each of these levels represents possible sources of "root causes". Due to the severity of major incidents, it is reasonable to expect causes at all these levels to be identified so as to prevent a recurrence effectively.

However, the analysis of cultural and systemic issues, especially those at company, regulators and industry associations, and Government levels, are extremely complex. The complexity at these levels arises because causal factors are inter-related and decisions of actors and the corresponding effects are usually separated in time. Senge (2006, pp. 71–72) calls this dynamic complexity, which is different from detail complexity (complexity arising from large number of variables). Unfortunately, most causal analysis tools, such as those evaluated by Sklet (2004), view cause and effect linearly and are not designed to model changes in the system across time, i.e. they are not designed to analyse the dynamic complexity of systems. These causal analysis tools are generally not designed to facilitate the development of strategies that will enable high leverage interventions. It is proposed that the usual causal analysis tools should be used to analyse the incident sequence and causal factors that are more immediate to the incident. Key causal factors can then be further analysed using tools designed to model dynamic complexity, such as causal loop diagrams (Senge, 2006).

3. Systems thinking and causal loop diagrams

One of the keys to systems thinking is recognising the circular nature of most systems. However, Western languages are generally not suitable for the description of circular relationships (Senge, 2006). In contrast, causal loop diagrams are designed to map the circular nature of cause and effect and demonstrate aspects of the system over time. The foundation of systems thinking is reflected in three basic processes – reinforcing feedback, balancing feedback and delays.

Reinforcing loops exist where a particular behaviour (either positive or negative) encourages similar behaviour in the future. A reinforcing loop, which amplifies the behaviour, is thus created. As the reinforcing loop continues, an accelerating growth or decline occurs. Fig. 1 is an example of a reinforcing loop where the safe behaviour and its positive consequences (e.g. commendation or award for the safe behaviour) creates a "virtuous cycle" that encourages growth in the safe behaviour.

Balancing feedback seeks to balance a behaviour or indicator at a certain level. With reference to Fig. 2, a company might be tracking a safety performance indicator ("Actual level"). The driving force for changes in the indicator is the size of the gap between the target and the actual levels. The safety indicator improves when the gap between the target and actual levels widens, possibly

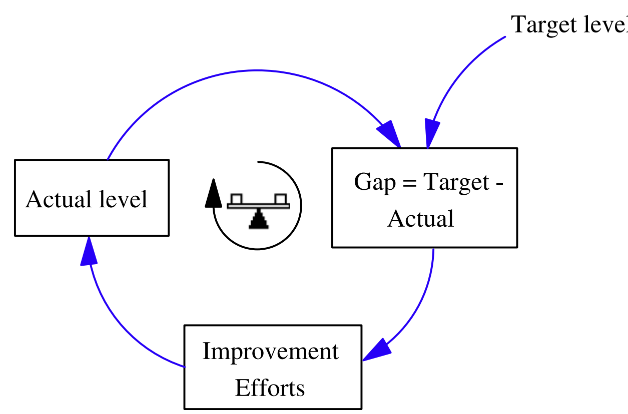

Fig. 2. Example of a balancing loop.

because more effort or resources are used to improve the situation. On the other hand, when the gap reduces, the pressure to improve might ease and hence the actual level tends to drop. Fig. 3 shows a simplified version of a balancing loop. As can be seen, the gap and target variables are now implicit.

Delays often occur between implementation of a certain program or action and the consequences of that action (Fig. 4). A lack of awareness of these delays can result in programs or actions being deemed unsuccessful prematurely. For instance, with a delay in the feedback from the positive consequence to the safe behaviour, management might assume that despite the introduction of the positive consequences (e.g. recognition scheme) workers are not motivated to have safe behaviours. Whereas in reality, workers might be beginning to notice the benefits of safe behaviour, but before the full potential of the measures can be realised the positive consequences are removed. It is noted that delays can occur within both balancing and reinforcing loops.

The field of systems thinking has developed generic causal loop diagrams that describe the systemic structure of a wide variety of management situations. These causal loop diagrams are known as systems archetypes. Systems archetypes aim to highlight the underlying structure of complex situations in a relatively simple fashion so as to facilitate identification of leverage in these situations. An example of a systems archetype, which will be used in the case study herein, is entitled 'shifting the burden' and consists of two balancing processes, one addressing the symptoms, the other the underlying or fundamental causes of the problem (Senge, 2006, p. 104) (Fig. 5). Symptomatic "solutions" can be very attractive to management, producing relatively quick positive results that focus on the symptoms and relieve the immediate pressure of the problem. The second balancing process focuses on fundamental solutions to the problem that are more sustainable but also

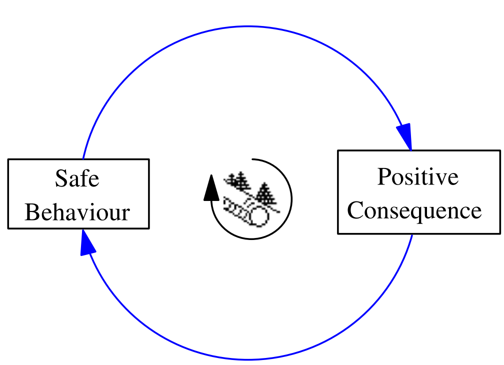

Fig. 1. Example of a reinforcing loop.

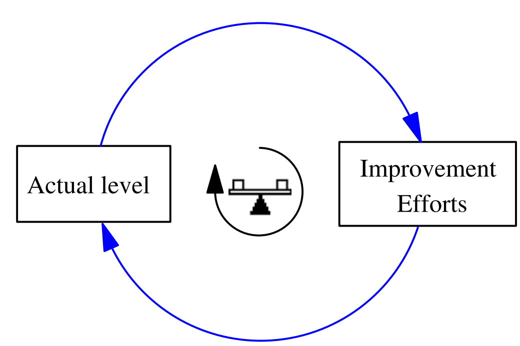

Fig. 3. Example of a simplified balancing loop.

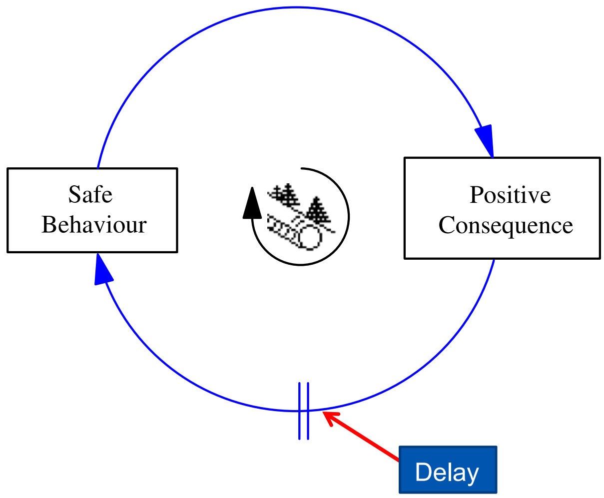

Fig. 4. Example of a delay.

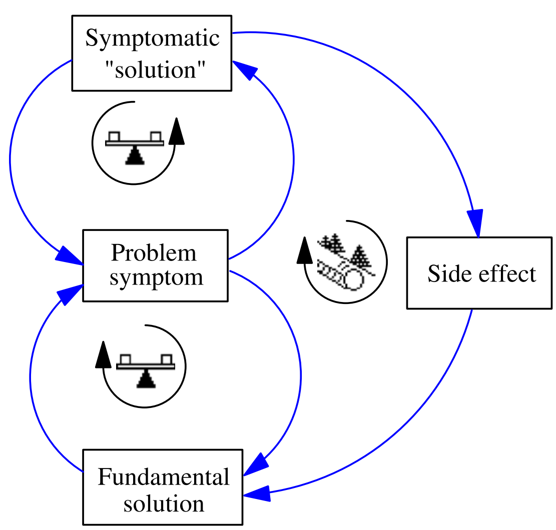

Fig. 5. A shift the burden archetype.

have a delay between implementation and results. Failure to recognise this delay contributes to the tendency to focus on the symptomatic solution. As resources are focused on the symptomatic solution, the fundamental problem and the capacity of the organisation to resolve the problem worsens (side effect). Systems thinking concludes that short-term efforts aimed at the symptoms can be useful, particularly to relieve the pressure as the delay from the fundamental solution is experienced, but long-term solutions to a problem must focus on the fundamental loop. This archetype will be discussed in more detail in the case study.

4. Case study

The case study herein describes the Bellevue hazardous waste fire that occurred in Western Australia in 2001. The causes of the fire, including direct causes, organisational factors and the contribution of regulators and government are discussed in detail in the inquiry report on the incident (EISC, 2002; De Vos and Spickett, 2005). This case study will analyse the incident to illustrate how causal loop diagrams and systems thinking can be used to understand how an underlying systemic structure creates and sustains poor safety culture that finally resulted in a major incident.

4.1. Background

Waste Control Pty Ltd. operated an industrial waste collection and recycling business in Bellevue Western Australia from 1989 until 2001 when a fire severely damaged the premises. The company collected waste solvents from the dry-cleaning, printing, and motor repair industries and also some hazardous wastes and was located in an area classified as industrial. This location was within 500 m of a primary school, 200 m from houses and 100 m from a main road and was considered acceptable by the relevant authorities. The company, which was for some time the only facility in Western Australia for the treatment and disposal of these types of waste, stored up to 2000 drums of waste material, which was well in excess of the license limits. The license conditions required that an up to date manifest list be maintained but the authorities did not receive this or any evidence of lists of substances and the volumes stored on the site.

The company was unable to comply with the license conditions as it was under-capitalised and had very low operating margins. This was compounded by tighter waste acceptance conditions at the disposal facility and resulted in a large stockpile of waste on the site. The authorities' response was to try to work with the company to resolve the problems arising from the conflicting demands of keeping the site open to remove waste from multiple sites around the metropolitan area and of concerns about the safe operation of the facility. The company still did not comply with the licence conditions and failed to repay funding provided by the government to assist in removing some of the stored waste. The company also did not submit a management plan as required by the authorities.

Late at night in early 2001 a fire and explosions were reported at the site. The owner of the company was present and he advised that about 300,000 l of solvents, paints and mixed liquids and 30,000 l of perchloroethylene were stored at the site. The lack of a manifest meant that the exact details of the substances present were not known and so strategies for dealing with the fire were limited. Some residents were evacuated but allowed to return home after the fire had been controlled but later a second evacuation occurred after the event was declared as an official hazardous materials incident.

There was a substantial amount of damage caused to the premises and the air was contaminated by combustion products. Water that was used to control the fire was contaminated and discharged to the surrounding environment especially in low lying areas and a nearby river. An assessment of the contamination was carried out and as there was concern amongst the residents about potential health effects from exposures a health survey was conducted.

4.2. Incident sequence and causal factors

Fig. 6 summarises the incident sequence and consequences of the incident. The sequence has been modelled based on the modified loss causation model (MLCM) (Chua and Goh, 2004), which, like most other causal analysis tools, helps to facilitate systematic analysis of facts and causal factors in a linear fashion. In this paper, the causal analysis will focus on the breakdown (or initiating) event of the incident – the inadequately managed flammable waste material. The analysis is conducted based on a series of *whys*.

With reference to Fig. 7, one of the key reasons for the build-up of a large quantity of flammable waste was due to Waste Control's inability to ensure consistent and clear recording of the content of drums in accordance to the requirements of the disposal site (EISC, 2002, p. 31). Furthermore, the company was not able to ensure that the conditions of drums were adequate; this led to leaking of flammable waste material from the drums (EISC, 2002, pp. 119, 124). In

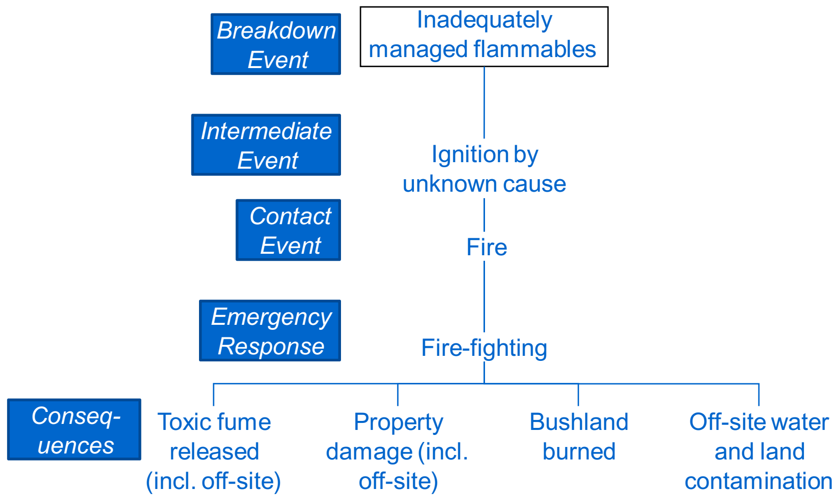

Fig. 6. Incident sequence of Bellevue fire.

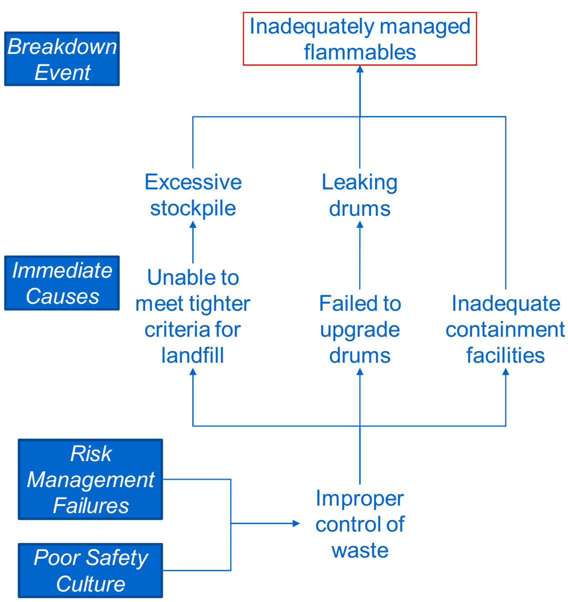

Fig. 7. Causal analysis of Bellevue fire.

addition, as highlighted in EISC's report (2002) the site had poorly maintained bunding and drums were stored in non-bunded areas. As a whole, the site was poorly managed and there was virtually no risk management of the highly hazardous waste.

The risk management failure also resulted in several other safety and health issues. For example, in 1996 WorkSafe WA found that Waste Control did not provide the necessary personal protective equipment (PPE), material safety data sheets (MSDS), and training to employees handling solvents (EISC, 2002, p. 117). Similar issues were again identified in 1999 (EISC, 2002, p. 120). It is apparent that the company had a poor safety culture and was not proactive in ensuring that the site was safe for its workers, the community and the environment.

4.3. Behaviour over time chart

Fig. 8 shows the behaviour over time chart of three of the key variables in the case. Safety and environmental issues of the Waste Control site is represented by the continuous, upward trend line. As can be observed, safety and environmental issues are continuously being identified and reported by various parties. As highlighted in Fig. 8, three key episodes were noted: (1) in 1993, (2) in 1999 and (3) 2000–2001.

The first episode in 1993 was initiated by the Shire of Swan after being made aware of concerns from the public and neighbouring proprietors. What followed was a series of "mild" regulatory actions, for example, warning letters and inspections. During this period, it was identified that, among a number of non-compliance issues, there was an increasing amount of material stored at the premises. The episode ended in December 1993 when inspections by the Department of Minerals & Energy (DME) showed that non-compliance was considerably lower. However, follow-up inspections by different agencies between 1994 and 1998 showed that the site was still unsafe and the situation escalated and resulted in the second episode in 1999. In 1999, a building inspection by Midland Fire Station identified unsafe conditions at the site. This led to the involvement of DME and subsequently other agencies. Even during heightened monitoring by several agencies, an environmental incident occurred on 27 July 1999, where contaminated water was discovered running off-site. In addition, 2000 drums of waste were discovered onsite. Due to the financial predicament of Waste Control, it did not have the capacity to deal with the situation. The matter was brought to the attention of the Minister for the Environment and in September 1999 the Government decided to loan $100,000 to Waste Control to enable removal of 1000 drums of waste. The 1000 drums were removed in November 1999.

The third episode started almost immediately after the removal of the drums. Despite efforts by the Department of Environmental Protection (DEP) who tried to recover the loan, Waste Control declared that it could not repay the loan of $100,000 unless it was able to sell its secured assets. Meanwhile, safety of the site continued to worsen. In May 2000, another stockpile of waste was identified. This time more than 2000 drums were found at Waste Control and drums were found to be leaking. By February 2001, when the fire occurred, the DME and DPE were seriously engaged in prosecution actions against Waste Control.

4.4. Systemic analysis

From the actions of Waste Control and the way risk is managed, it could be seen that the company had a poor safety culture, but what caused the poor safety culture to develop and why was it sustained for such a long time? Some unseen "forces" or systemic structures may have been driving the actions of different parties,

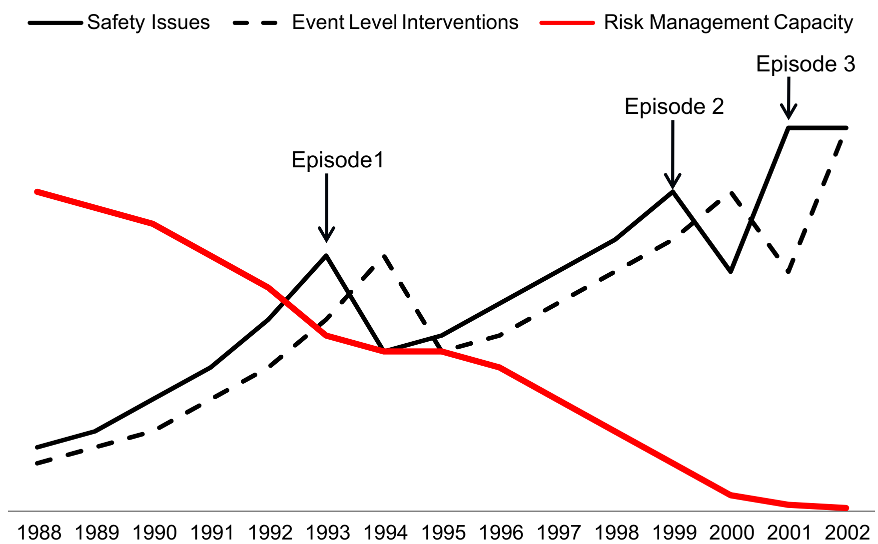

Fig. 8. Behaviour over time chart for some of the key variables.

making the actions taken "logical" at that point of time. To obtain a deeper appreciation of safety culture, it is essential to understand the systemic structures driving and maintaining the safety culture.

4.4.1. Regulators and government level

As can be observed from the case study, the actions by the different agencies are reactive and "event level" (Senge, 2006, p. 52), i.e. they do not improve the fundamentals of the company. This is despite the regulators being aware that their interventions were not effective in promoting good management (for e.g. EISC, 2002, p. 35). Even though not explicitly discussed in the inquiry report, it can be postulated that the risk management capacity of Waste Control had never improved. Instead the capacity to deal with the risk posed by hazardous wastes seems to have deteriorated over time (as represented by the downward line in Fig. 8). With the declining risk management capacity, each episode became more severe and finally resulted in the fire in 2001.

In systems thinking terms, the behaviour over time chart displayed the characteristics of a "shifting the burden" archetype that was presented in Section 2. The situation in Bellevue fire can be considered to involve two sets of "shifting the burden" structure (see Fig. 9). Loops 1 and 2 depict the "shifting the burden" structure at the regulator and government levels. The problem symptom is the safety/environmental issues at Waste Control; the symptomatic solution is event-level interventions by the government and regulators; and the fundamental solution, would have been the building of risk management capacity at Waste Control. Both loops 1 and 2, are attempting to maintain safety and environmental issues at a tolerable level (no infringement or complaints). This systemic structure contributed to poor or reactive safety culture and absence of risk management system in Waste Control.

Focusing on loop 1 in the diagram, whenever safety and environmental issues were reported, the regulators stepped in with inspections, instructing Waste Control to remove drums and improve facilities and practices. Other event-level interventions include "show cause" letters and collection of evidence to prosecute Waste Control. Perhaps the worst event-level intervention is the Government decision to loan $100,000 to Waste Control to remove 1000 drums. None of these interventions improved the risk management capacity of Waste Control, which takes time to build (see delays in loop 2 of Fig. 9), but may have been perceived as some type of endorsement for the current management practices. However, despite the ineffectiveness of these measures, the regulators and government did not focus on the fundamental solution of improving the risk management capacity of Waste Control (loop 2 in Fig. 9) or attract an alternative service provider. This may have been due to the paradigm that regulators and government should see their role as advisory and only use strict enforcement as a last resort.

4.4.2. Company and industry level

Even though every time safety and environmental issues surface there will be pressure or desire to improve risk management capacity at the company level (loop 2 in Fig. 9), the pressure or desire to improve is limited by the safety culture in the company.

During the inquiry, the company director stated that the regulatory framework made it impossible for his company to fulfil its obligations (EISC, 2002, p. 10). The company director's comment may be referring to regulatory overload (Gunningham and Johnstone, 1999, p. 30). The company director appeared to have felt victimised. This can be interpreted from two angles. From the point of view of the company, they had to deal with numerous agencies and had been repeatedly threatened with prosecution or termination of licence to operate but no enforcement had been enacted. The company director might argue that it is the regulatory approach that facilitated the reactive culture at Waste Control, i.e. a culture where safety and environmental improvements are only done when instructed by the regulators. As long as they react, no actual prosecution will result. This is indicated in Fig. 9 as the unintentional contribution of Loop 1 on the reactive safety culture in Waste Control. However, from another angle, the management could have been perceived to be the source of the poor safety culture. The management and the company as a whole could have proactively chosen to change their culture (organisational and personal factors in Fig. 9). As shown in Fig. 9, both factors played a part in creating and sustaining the poor safety culture in Waste Control.

The reactive culture also had an impact on the company's investment in risk management capacity (loop 3 in Fig. 9) and encouraged the undercutting policy of the company (loop 4 in Fig. 9). As depicted in loop 3 of Fig. 9, investment in capacity would have brought about improvement in the company's risk management ability and with time, not only would the safety and environmental issues be better contained, the overall ability to manage the business would have improved, leading to better financial viability. However, the actual amount of investment in risk management capacity is heavily dependent on the company's culture and man-

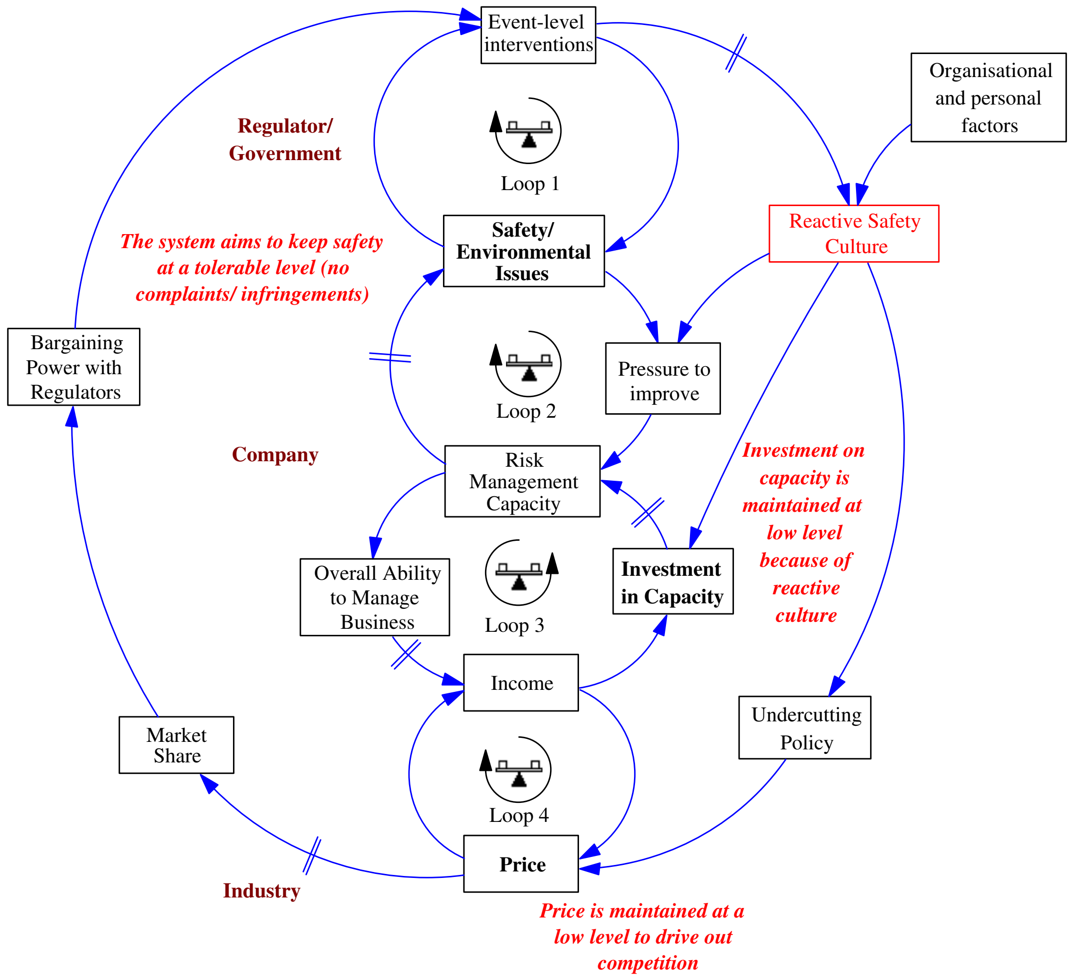

Fig. 9. Causal loop diagram for Bellevue fire case study.

agement philosophy. With a reactive culture, it is not likely for the company to be willing to allocate many resources to building capacity. This is worsened by the fact that the level of income is limited due to the undercutting policy (loop 4 of Fig. 9), which allowed Waste Control to create an "unsustainable and artificial market dominance" (EISC, 2002, p. 10). Each of these factors contributed to the failure of Waste Control to improve its risk management capacity. However, the company did not realise how it had facilitated its own downfall by persisting with its undercutting policy.

The side effect of the monopoly (in Western Australia) was the increase in bargaining power with the regulators (see Fig. 9) that may have contributed to the prevention of prompt tough actions by the regulators and government. For example the regulators may have been reluctant to terminate Waste Control's licence because of concerns that the termination would force businesses to use service providers in the Eastern States and smaller businesses that were not able to absorb the higher cost might resort to illegal dumping of waste (EISC, 2002, p. 40).

4.4.3. Leverage

One of the key purposes of systemic analysis is the identification of points of leverage. In the context of safety culture, high leverage interventions would refer to putting in low cost mechanisms that shape safe organisational or individual behaviour. It is noted that cost of intervention refers to the total cost in the long-run and it is measured in relation to other interventions. In a "shifting the burden" structure, actors can become addicted to the symptomatic "solutions" (loops 1 and 4 in Fig. 9), especially when pressures build up. In the case study, the public pressure that the regulatory bodies faced and their lack of resources made them compelled to demand improvement in key safety and environmental issues through event-level interventions like warnings, notices and inspections that did not focus on risk management capacity of Waste Control. Similarly, market pressures encouraged Waste Control to maintain its undercutting policy. Both the event-level interventions and low price of service produced the side effects which encouraged further adoption of the symptomatic solutions.

Ideally, the "shifting the burden" situation should be avoided or at least the level of adoption of symptomatic solutions should not be entrenched (Kim and Anderson, 1998, p. 32). Senge (2006, pp. 109–110) advised that for achieving leverage in a "shifting the burden" structure there is a need to strengthen the fundamental solution and simultaneously weaken the symptomatic response. To strengthen the fundamental solution there must be a disciplined focus on long term vision and sustainability. Early attention on the fundamental solution will lessen the pressure to resort to the symptomatic solution. In the case study, the development of risk management capacity required a long term view from both the regulators and Waste Control. Regulatory interventions could have been designed to encourage risk management in the company. See Gunningham and Johnstone (1999) and EISC (2002, pp. 97–101) for discussions on the regulatory options to encourage risk and safety management systems in companies.

Weakening the symptomatic response requires exposing the ineffectiveness of these measures. Waste Control had to acknowledge that maintaining a low price would not work in the long run and also had to understand the importance of investing in good risk management systems. The regulators should have acknowledged that inspections, "show cause" letters and even prosecution does not lead to positive safety culture and good management in the industry. For actors to realise and acknowledge the futility of symptomatic response, public or third party reviews and feedback is often necessary. This is where measures such as "community right to know" (EISC, 2002, p. 101) and mandatory third party audits on companies and regulators are important. Despite the problems of symptomatic responses, they cannot be removed abruptly; they have to be weakened gradually as the fundamental solution is strengthened. If the regulators had aimed to promote risk management and safety culture in Waste Control, event-level interventions should not have been stopped totally. Instead inspection should have continued, but the emphasis of the inspection should be geared towards identifying management system and cultural issues. Similarly, if a company is to move away from undercutting as a strategy, it has to begin with a gradual increase in prices and it has to communicate with its clients, possibly with the regulators softening the increase in price over time.

5. Discussion

The importance of systemic structure has been highlighted in numerous publications, albeit in different terms. Rasmussen (1997) discussed it in the form of "behaviour shaping mechanisms". Similarly, Dekker (2002, p. 34) emphasised that "multiple factors – each necessary and only jointly sufficient – are needed to push a complex system over the edge to breakdown". In addition, Marais et al. (2006) customised several systems archetypes to suit organisational safety situations. In line with these earlier works, this paper proposes that to improve safety culture the systemic structure influencing the safety culture has to be understood. As illustrated in the case study, typical causal analysis tools will help to present facts of the case and key causal factors systematically. The key causal factors can then be further analysed in causal loop diagrams highlighting the systemic structure at play.

To understand how culture is created and sustained, there is a need to adopt a systems perspective when analysing major incidents. As shown in the causal loop diagram in Fig. 9, there is effectively no identifiable root cause. From the perspectives of Waste Control, the regulators and the Government, each seemed to be doing the "right" thing in view of the pressures that each was facing. However, unintentionally, each actor contributed to the poor safety culture and the worsening of the situation that finally resulted in the fire. Understanding systemic structure will help organisations understand the possible negative consequences of their decisions on safety culture and result in the design of more effective safety culture interventions. A systems perspective also helps to reduce the tendency to victimise or blame a particular group or organisation for the major incident, thereby increasing the chances of identifying effective preventive measures.

Despite the potential advantages of systems thinking and causal loop diagrams, they are basically an analytical tool that facilitates a more effective way of seeing reality and summarising dynamically complex situations. It still boils down to the people that use the tool for its full potential to be realised. Not only must the analyst be competent, there is a need for a systems-oriented paradigm to be adopted. It is also noted that each incident or situation can be modelled in different ways, i.e. there is no "right" model. The key to a good model is in its usefulness. In the context of safety culture, the value of a causal loop diagram is judged based on its ability to facilitate identification of interventions to improve safety culture and sustain positive safety culture. Furthermore, traditional fact-finding and investigation skills are still fundamental to any analysis of major incidents. Therefore, to improve safety culture through systemic analyses of major incidents, causal loop diagrams and systems thinking cannot work in isolation from other traditional investigation and causal analysis tools.

6. Conclusions

Major incidents present a rich source of information for understanding safety culture. Most of the time, safety culture is created as a by-product of the systemic structure put in place unknowingly by the joint actions of different parties in the system. This is demonstrated in the case study on Bellevue fire, where an amalgamation of the reactions of different parties to the pressures they faced, finally resulted in the fire. The reactions of each party usually appears to be necessary from each party's point of view, but from the systems angle the reactions promoted poor safety culture and were detrimental to the overall safety of the system.

Even though traditional causal analysis tools are useful and necessary, they model cause and effect linearly and they are less effective in representing the complex interactions between multiple actors and factors across time. It is proposed that causal loop diagrams, a systems thinking tool, should be employed in analysis of major incidents so that the systemic structure that contributed to the incident can be more readily understood. Better understanding of systemic structures can then facilitate the design of more effective safety culture interventions. The use of causal loop diagrams could facilitate the early identification of emerging problems in companies so as to introduce interventions that improve risk management capacity rather than event-level interventions. In addition, it is believed that more research and application of systems thinking concepts will improve the overall effectiveness of safety, health and environment management.

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