The Use of System Dynamics Group Model Building for Analysing Event Causality within the Nuclear Industry

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Abstract

Currently the most frequently used tools for investigating and learning from industrial accidents are based on linear, reductionist models of event causality. It has been suggested that complex socio-technical systems exhibit non-linear behaviour, incompatible with these approaches. An alternative approach based on system dynamics group model building is proposed and investigated within the context of the civil nuclear industry. The success and feasibility of the approach is assessed though the analysis of a case study event by a group of industrial experts previously unfamiliar with system dynamics. A selection of the models produced are discussed. The investigation demonstrates the feasibility of the approach and its potential to provide additional insights and learning. A possible archetypal structure is also identified and described indicating the possibility of the discovery of further archetypes through this approach which could then be shared for contextual learning between organizations and industries.

Key Words: System Dynamics, Group Model Building, Accident Analysis, Archetypes, Nuclear Industry

Introduction

Generally the analysis of accidents is conducted to provide learning so that actions can be taken to prevent reoccurrence of the same or similar events. The learning from events is shared within and between organizations and industries in order to improve safety and efficiency. The most widely used tools for accident analysis are based on linear, reductionist models of systems and causality. They deconstruct and reduce events into their smallest component parts; causality is implied from one part to the next such that they can be traced backwards through a chain of cause and effect to discover the 'root cause'. Some specialise in technical failures, some in human failures and others in organizational failures or a combination of these.

These linear, sequential models of causality are the basis for the majority of tools used within the UK civil nuclear industry. They are often used alongside 'epidemiological' models such as the 'Swiss Cheese' barrier model (Reason, 1997), which go some way towards looking for latent errors in the wider organization. The Human Performance

Enhancement System (HPES) is extensively used and introduces a toolbox into the nuclear industry which includes ‘Barrier Analysis’, ‘Cause and Affect Analysis’ and ‘Event and Causal Factors Charts’ which are linear or multi-linear flow charts depicting chronological cause and effect chains of events.

These tools have been extensively used and demonstrated that they are useful at illuminating what happened and providing insight into the reasons behind the event. They shape the way events are thought about, analysed and learnt from. However, there is a growing recognition, especially within those who have studied complex socio-technical systems (Marais et al., 2004, Svedung and Rasmussen, 2002, Leveson, 2004, Le Coze, 2005, Reiman and Oedewald, 2007, Rasmussen, 1997) that the current tools are being pushed to the limits of their abilities by the complexity and characteristics of the systems within which they are being applied.

Perhaps the most interesting characteristics identified in these industries are the fact that they are accelerating faster than the regulatory and legal frameworks that oversee them (Kirwan, 2001) and that they are made up of non-linear cause-effect relationships (Le Coze, 2005) which are governed by feedback (Svedung and Rasmussen, 2002).

The Systems Theory paradigm is based firmly on the concept that the whole is greater than the sum of its parts. With this in mind any model or any tool that looks solely at discrete events or failures is not necessarily seeing the full picture. With a Systems perspective, the interaction between the components is more important than the components themselves. Likewise the nature of the connections and interactions between the components is often not linear. In reality complex systems are made up of components imposing controls on other components and receiving feedback from one another, adapting their behaviour accordingly. Therefore, it can similarly be concluded that any model or tool that does not take feedback into account is providing a limited view of the incident.

Studies and assessments of accident models and their associated tools (Qureshi, 2007, Hollnagel, 2008, Qureshi et al., 2007, Leveson, 2001, Sklet, 2004) provide an overviews of their development and show a move towards Systems Theory. One particular idea in this field is Normal Accident Theory (Perrow, 1984) which suggests that accidents can be a function of the complexity and coupling that exists within a system as opposed to the reliability of the social and technical components in isolation. Complexity is a way of describing the interactions and relationships that can exist or occur in the system, from linear to complex, while coupling refers to how quickly information or actions can propagate through the system. Wolf and Sampson (2007) demonstrated this theory with an analyses of oil refineries which showed those with more complexity and tighter coupling had more recorded accidents than those more linear with loose coupling. However this structural view can be seen by some to be too deterministic in its approach (Pidgeon, 1998).

According to Perrow Nuclear Power Plants are at the top of both spectrums, having highly complex interactions and being tightly coupled. Hollnagel (2008) revisited this classification, and suggested that the tools currently used (Root Cause Analysis, Human Performance Enhancement System, the Swiss Cheese Model) are all tailored towards industries with loose coupling and linear (or manageable) interactions. Following from these studies into complex socio-technical systems a number of accident models and event analysis tools have been developed in recent years which adopt a Systems paradigm of event analysis including the AcciMapping (Svedung and Rasmussen, 2002) Functional Resonance Accident Model (Hollnagel and Goteman, 2004) and the Systems Theoretic Accident Model and Process (STAMP) (Leveson, 2004).

Building on an earlier initial investigation (Carhart, 2009) the following sections propose the use of system dynamics group model building as a tool for event investigation. This is explored in an example case through a workshop of experts. The methodology used is discussed and analysed before the viability and potential of the tool is assessed through a critique and discussion of the output.

Previous uses of System Dynamics in Accident Analysis

System dynamics is proposed and investigated as an alternative tool for accident investigation, for communicating the learning points and to provide insight on which to base corrective actions. System dynamics has already been used in accident investigations, for example as contribution to a STAMP analysis (Leveson et al., 2003, Leveson, 2004) of events within the water industry and the aerospace industry.

The use of system dynamics in project management was used as a basis for Hansen and Golay's (1997) suggestion that it should be more widely adopted within the nuclear industry, specifically in such areas as risk analysis, the diagnosis of problems and testing of suggested mitigations. It has subsequently been used to understand factors behind the Chernobyl accident (Salge and Milling, 2006) and in specific areas concerning operational issues with safety case production at civil nuclear generation sites in the UK (Carhart, 2009). System dynamics has also been used to analyse the underlying causes of the Westray mine disaster (Cooke, 2003) and combat vehicle accidents (Minami and Madnick, 2009). Sterman (2001), Cooke and Rohleder (2006) and latterly Goh et al. (2010) have advocated its use to introduce Systems Thinking concepts to the analysis of major accidents.

Archetypes

By looking at the causal structure and dynamics behind the incidents and learning from them, the warning signs (events and behaviours) for high loss hazards become more apparent and the organization can be more prepared for their emergence. These warning signs may take the form of common patterns of behaviour or structure which are witnessed prior to an event. These common behaviours and patterns or system archetypes have been identified in various contexts by authors such as Senge (1990) and Wolstenholme (2003). Senge popularised the notion of system archetypes in The Fifth Discipline (Senge, 1990) in which he identified eight common behaviours which could be characterized by simple feedback loops and represented using basic causal loop diagrams. This lead to the identification of seven safety archetypes (Marais et al., 2006) and investigations into catastrophe archetypes (Mrotzek and Ossimitz, 2008).

Kim and Burchill (1992) suggested those working within the field of system dynamics had "downplayed" the power of simple pen and paper tools, placing emphasis on methodology and computer simulation. They argue from a Total Quality Management (TQM) perspective that simple pen and paper archetypes using system dynamics conventions can in fact be more powerful than many TQM tools.

A modular approach to the construction of system dynamics models was suggested by Wolstnholme and Coyle (1983) and later expanded by Wolstenholme (2003, 2004) who proposed the identification and use of basic system dynamic templates from which models can be built. These generic templates consist of a loop showing the intended consequences, and a loop showing the unintended consequences. The basic structures form problem archetypes and solution archetypes. Using this as a basis, he stated there are only four truly generic problem/solution archetypes. These four can be used to construct the eight archetypes identified by Senge implying they are indeed more generic. This of course does not suggest they are necessarily more useful at communicating the relevant issues but they may be useful for constructing models which do. Knowledge of these archetypes can help in diagnosing problems and prescribing solutions. An intention of using system dynamics and related tools as a means to investigate and explore accidents is to build a catalogue of models from which common patterns or archetypes can be identified. These can be communicated across and between industries, both in terms of precursor and solution archetypes so proactive action can be taken to prevent hazards emerging.

Group Model Building

During its early stages system dynamics was typically applied in a consultant/client engagement (Forrester, 2007), but over the past twenty years there has been increasing focus on group model building, actively involving the ‘client’ in the process of model building. Lane argues that the problem of the consultant as ‘*expert modeller*’ hinders successful interventions, that clients simply do not believe or trust models presented to them by an external consultant (Lane, 1992). Forrester (1991) argues that focussing on ‘measured data’ neglects the “far richer and more informative body of information that exists in the knowledge and experience of those in the active, working world” (p.5). Group model building has emerged as a methodology for not only gathering data from people, but capturing their interpretations of the causality present in the system (Vennix, 1999, Vennix, 1995, Vennix et al., 1992). It allows for greater integration of the stakeholders into the project. In a summary of the relevant literature Richardson et al. (1989) outline the key tasks in constructing system dynamics models in groups as;

- Eliciting information
- Exploring courses of action
- Evaluating situations

There is benefit in group model building as opposed to models being built by individuals. Groups are more likely to question one another, and although there is of course a risk of ‘group think’, it is certainly less of a risk than when performed by an individual. It has been shown (Shaw, 1932 cited in, Richardson et al., 1989) that groups posses a better ability to filter out false information than individuals. Groups allow for a range of expertise to be provided, as well as those of different backgrounds with different views. Group model building of system dynamics models also makes the participants explicitly discuss their otherwise implicit assumptions regarding causality (Vennix, 1999). There are many different potential approaches to conducting group model building. It could be conducted in a strongly structured way or weakly structured way, by presenting the group with a model and allowing them to discuss it, or producing one collaboratively step by step (Richardson et al., 1989). Practical approaches to designing a group model building engagement can be constructed from a growing literature on the subject (Rouwette et al., 2000, Rouwette et al., 2002, Vennix, 1999, Richardson et al., 1992, Andersen and Richardson, 1997, Oyo et al., 2009, Vo et al., 2007, Visser, 2007, van der Smagt, 2005, Rouwette and Vennix, 2006, Rouwette et al., 2009, Andersen et al., 2007, Vennix et al., 1992) .

Workshop

A one-day workshop was held in order to investigate the potential and practicality of using system dynamics through a group model building approach to analyse and investigate significant events. The workshop involved a group of nine experts from within the nuclear industry and related academic fields, including representation from the regulator authority, civil nuclear operators and safety systems research.

The scope of the attendees' expertise was diverse, though the majority had little or no previous experience of using system dynamics. The workshop used a criticality accident at a nuclear fuel conversion facility in Tokai-Mura, Japan in 1999 as a case study. Prior knowledge of this event was also varied. Some had a general understanding while others had studied the event previously. All of the participants were external to the event being investigated and there was no input from, or access to anyone directly involved in it. The information used was second hand, contained in the reports of official investigation bodies (Nuclear Safety Commission, 1999, International Atomic Energy Agency, 1999, US Nuclear Regulatory Commission, 2000) and collated through document analysis. The source of the information is important as it has an influence over the nature and scope of the models constructed.

Two weeks before the workshop the participants were given a brief information pack with some short descriptions of the event and the tools that would be used. They were also given details of where they could find out more information, should they be interested in doing so.

The group model building session was not intended to construct models to represent the mental models of the participants, but rather to understand the causality, development and evolution of the accident being investigated. In a different scenario, had some of the participants been directly involved in the incident, then it might be beneficial to explore their mental models with them using Causal Loop Diagrams.

The participants were not a 'client group' in that the task was not intended to produce a change in their thinking towards any event or system with which they are directly involved. They were aware of the experimental nature and that the analysis was of a system removed from their own. That is not to say that the potential learning points would not be applicable to them. The benefit of a systems approach on the comprehension and understanding of the group investigating the event was also of interest.

Purpose

The purpose of the workshop and the investigation as a whole was to assess the potential and feasibility of developing non-trivial system dynamics models at a sensible level of abstraction which provide useful insights, additional to those of the current approach, into soft issues that could be precursors to serious accidents. At this stage the models will not be used for prediction, instead the emphasis is on identifying ‘archetypes’ which could provide contextual learning and could be transferred between industries and organizations.

Assessing the potential is relatively self explanatory of any investigation into a particular tool or methodology. It was emphasised to the workshop attendees to clarify that the investigation was not explicitly concerned with achieving a particular level of success from the models and diagrams, and that the participants should not be disheartened should there be a negative outcome from a one-day workshop. The second point was to assess the feasibility of using system dynamics. Assuming it could be shown to be an insightful means of investigating an incident, it was also necessary to demonstrate its practicability. Even if the approach proved insightful it could not be judged as a success or a useful addition to the current toolbox if it was impractical to implement.

Thirdly the models needed to be constructed at a sensible level of abstraction, though exactly what that is depends on the particular case in question, the time and data constraints and the views of those involved in the group model building. The models should not be too complicated, but they should not be too trivial. The aim is for the models to provide insight into the structure of causality and underlying dynamics, while also demonstrating learning points that could be shared across industry boundaries. Whether or not these insights go beyond the current tools to give additional insight is also crucial to the assessment of the tool. A practicable tool is of little value if it does not enlighten the investigators into the causality of the accidents, and its ultimate successful adoption will be dependent on its perceived value at doing this. If it offers the same level of analysis as the current tools its uptake may be limited. It is possible however to argue that the added value comes from the systems thinking that is developed through the group model building of system dynamics models. Though the investigation may ultimately draw the same conclusions as analysis using the current tools, it will provide additional insight by modelling the situation in a different way, one that arguably better reflects the nature of the causality by exposing the underlying dynamics and feedback structure.

System dynamics has its roots in a functionalist domain. However, to limit an accident analysis within a social-technical system to the physical, mechanical and hard elements would be detrimental. The purpose emphasises the need to look at the soft aspects at the socio-technical interface and beyond, that develop in the system as precursors to the emergence of significant events in the form of structures and patterns of behaviour that develop states conducive to hazard.

The purpose also places special emphasis on the fact that the models were not going be used for prediction, but as a way of enhancing understanding and learning about the causality of these significant events which can be conveniently communicated and shared between different industries. This could be achieved by looking out for common precursor patterns of behaviour or structures in the form of generic archetypes. Although it would be unfeasible to produce models in a one-day workshop suitable for simulation, and gather the required data, the decision to not use the models for prediction at this stage was not based on this reasoning. The implications of this are discussed in a later section.

Method

The approach for the workshop was developed from guidance provided by Sterman (2000) and Wolstenholme (1992) who outline methodologies for constructing system dynamics models and Vennix (1996) who provides direction on the design of group model building projects. Vennix presents a flow chart which advises that once system dynamics has been identified as a suitable tool, the first question to ask is whether or not to use a preliminary model; that is presenting a group of experts with a prebuilt model for discussion and refinement. The use of preliminary models has been previously demonstrated (Vennix et al., 1988), but in this instance although a preliminary model was built from document analysis it was not used. The preliminary model was built in case the participants of the workshop encountered too many difficulties in constructing a model given the restrictive time constraints. In practice it was not required and the models were created from scratch.

On the day of the workshop, following introductions and a discussion of the purpose, the attendees were presented with a brief introduction to accident models, system dynamics and the particular event that was going to be investigated. This was seen as a necessity and therefore one of the “important exceptions” mentioned by Andersen and Richardson (1997) to their rule of avoiding long periods of one person delivering information to the rest of the group. The participants were then given time to read through the official reports, followed by discussions about the case over lunch.

The afternoon session focussed on analysing the event through the construction of system dynamics models. Although the workshop was investigating the potential and practicability of the approach, the aim of the model was ultimately the same as it would be in any accident analysis; to learn about the event, why it happened and then share this learning with others.

The first step involved identifying the who, what, where and when in order to define the system boundary and constrain the model. Defining the problem under investigation also required defining the time frame the model will look at, what important variables exists internally to the system, and what exists outside of it.

The important variables were derived from content analysis of the descriptions of the event in the previous accident reports. The participants did not all read the same accounts of the event. In order to make the process more efficient and stimulate debate the previous reports were distributed amongst the group.

To retain the group's collective ability to filter out false information without the potential detrimental effects of group elicitation, participants were asked to brainstorm variables individually on post-it notes. These were then organized by the group members into one of three columns;

- Stocks
- Variables
- Policy Variables

The contributors analysed this output, discussed the suggestions, grouped similar terms and refined the lists. In doing this the group worked towards an agreed concept of the system boundary.

The second stage worked towards forming a dynamic hypothesis; a theory explaining the observed behaviour in terms of feedback and control. The group began by discussing how the stocks were influenced. It quickly became apparent that the group were not yet comfortable with thinking in terms of flows, so the stocks were treated as pseudo-variables and the group instead began to identify feedback processes. In the course of the session the group went through several iterations of the same model to try and explain what were felt to be the most important issues from the case-study event.

The iterative nature extended beyond the one-day workshop. Some of the initial models had several issues regarding the way some of the variables had been defined, these are discussed in a later section. After the workshop the models were refined without the participation of the attendees to develop what could be thought of as preliminary models for a second workshop and group model building session. This maintains a higher level of group interaction and subsequent buy-in to the conclusions than may be achieved by simply presenting them with a preliminary model developed without their involvement. This method, building on Vennix's (1996) method, can be represented as in Figure 1.

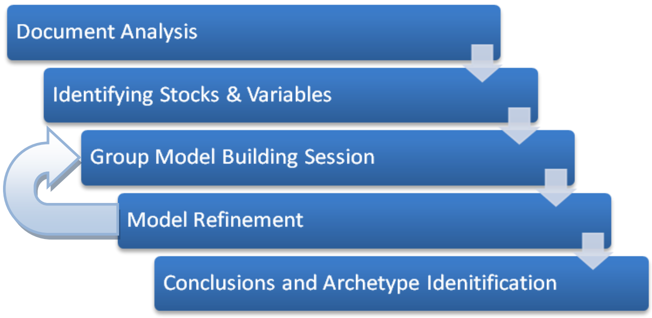

Figure 1- Outline of Methodology

Results

It is not the intention of this paper to discuss the event used in this study in any depth, or draw any detailed conclusions about the underlying causality, at least not to the extent a full accident investigation and analysis would. However, in order to discuss the models on a technical level, it is necessary to explain some of the terminology used, in particular the term 'Safety Culture' which was felt to be very important by the workshop participants. Culture is a very hard term to define, and safety culture may be interpreted differently by different people. Within the nuclear industry it is a well established idea, and despite its 'soft' nature, is accepted as a quantifiable entity. It can therefore be treated as a stock. Safety culture surveys are used throughout the nuclear industry on a regular basis in order to capture, quantify and benchmark an organizations safety culture. Nuclear Safety Culture is formally defined by the International Nuclear Safety Advisory Group in INSAG-4 (1991). Wiegmann et al (2002) found that despite different definitions of safety culture being used by different organizations there were actually many similarities. It tends to refer to the collective attitudes and values of the organization towards safety, and is acknowledged to affect the behaviours of the individuals.

Safety culture is measured by looking at the behaviours and attitudes present within the organization; elements which are a product of the culture. The fact that safety culture is measured in this indirect way creates a potential issue that needs clarification as it caused some confusion during the workshop.

If an individual within the organization has a questioning attitude then this is arguably the result of a good culture of safety. However when the organization comes to assess its tacit, somewhat intangible safety culture the presence of a questioning attitude within the employees is used as an indicator, gauged through interviews, questionnaires or similar means. This questioning attitude contributes to the perception that it has a good safety culture. The simple measured or inferred perception of the safety culture is a product of the attitudes developed by the actual more complicated and harder to define safety culture that exists in the collective of the employees. In other words the questioning attitude is a symptom of the safety culture, and this symptom shapes the diagnosis. An estimate of the safety culture is being inferred from the measurable things it influences or produces. There is nothing wrong with inferring the state of an inaccessible variable through measurement of its products where there is an accepted correlation. The fallacy is to then believe that this correlating product somehow causes the inaccessible variable to change, as it does the assessment of the inaccessible variable. The questioning attitude does not directly cause the actual safety culture to change as it does the measured and perceived safety culture. This is of course not to say that the symptomatic variable is not part of a larger feedback loop as monitoring the symptoms may result in corrective action. The danger arises from confusing the causal structure and dynamics of the diagnosis with that of the cause. When modelling physical systems such as filling up a sealed tank using an external gauge this situation can seem obvious, it is unlikely such a group of modellers would confuse the perceived state of the tank with the actual state. This difference is not so clear when dealing with tacit 'soft' variables such as 'compliance'. However, ultimately in the models produced at the workshop the value of the measured and actual concept of safety culture are treated as equals.

This section does not cover all of the models produced during the workshop; rather it focuses on two representations of one particularly interesting aspect which was discussed. The main learning points can be extracted and illustrated in order to communicate the most important issues. Some of these issues form the basis for potential archetypal structures of behaviour and are shown in Figure 2 and Figure 3 below.

Regulatory oversight was initially and logically believed by the group to be independent of the organization and its activities. It was therefore identified as a policy variable.

However in constructing the very first model at the workshop it became apparent that for the event and system under investigation the degree of oversight was influenced by the number of event reports (notifications to the regulator of abnormal occurrences or substandard conditions) the organization was producing. One perception of this situation is illustrated in Figure 2.

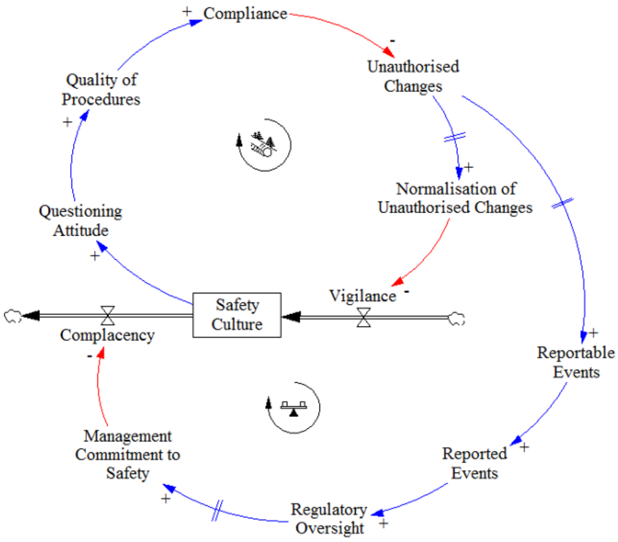

Figure 2 - First Potential Safety Culture Archetype

The top loop demonstrates the reinforcing effect of a good safety culture, as it encourages compliance, decreases the normalisation of unauthorised changes, therefore increasing vigilance for any outlining unauthorised deviations from approved actions and behaviours, strengthening the safety culture. Or if the opposite is the case an erosion of the safety culture results in unauthorised changes becoming accepted as the norm, this normalisation disguises the inherent danger in deviating from the approved process. Vigilance to these unauthorised deviations and the associated potential risks decreases, reinforcing the decline of the safety culture by reducing the means by which it is thought to increase. This is however balanced by the paradoxical notion set up by the feedback loop involving oversight. As safety improves, the number of reportable events, and therefore reported events can decrease. The paradoxical behaviour is induced if the regulator perceives this lack of event reports as an indication that the system is safe, and reduces the degree of oversight it provides. This may especially be the case if the regulator has limited resources or a preconceived notion that the system is safe. In this example the management's role is seen as reducing or preventing complacency and the erosion of safety culture (which is self reinforcing). But, with less regulatory oversight the management are also under the impression the system is safe and disconnected from reinforcing the importance of safely following the procedures as approved. This situation assumes the workforce is not proactively or maliciously acting in an unsafe way.

This draws parallels with the archetype "Decreasing safety consciousness" identified by Marais et al. (2006) and Cooke and Rohleder's (2006) models looking at learning from incidents in high-hazard industries. Marais et al. cite Amalberti (2001) to suggest that initiatives to reduce the number of reportable events can have the unintended consequence of reducing situational awareness and actually decreasing the safety of the system.

A different view of the same situation also posited from the workshop is shown in Figure 3. Here the role of management is seen as actively enhancing and strengthening the safety culture by developing and encouraging the awareness of potential hazards. This is subtly different from having a direct affect on complacency. The reinforcing loop produces a similar situation. If the safety culture declines, compliance declines and unauthorised changes become the norm. Again these unauthorised changes are not perceived as dangerous and so complacency develops as they become an accepted part of operation, this actively erodes the safety culture further. This time the balancing loop will drive up risk awareness if the safety culture declines and the number of unauthorised changes increases. The difference between the two models is that in Figure 2 a good safety culture is self-sustaining and the lack of oversight causes it to erode, in Figure 3 an improved safety culture does not automatically result in further improvement, this has to come from the oversight.

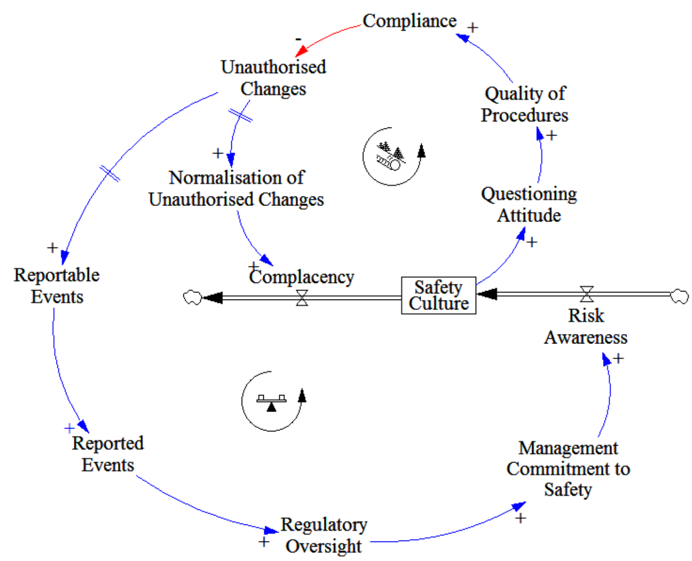

Figure 3 - Second Potential Safety Culture Archetype

The workshop discussions and output demonstrated that there can be more than one view on the same situation. This of course presents the issue that there is more than one ‘correct’ model that could be constructed. But constructing these models made the underlying assumptions explicit, and illuminated the differences in approach and thought. In fact, when represented in this way it becomes clear that ‘Complacency’ and ‘Risk Awareness/Vigilance’ are potentially the positive and negative conceptions of the same mechanism. The differences arise from the definition of the terminology rather than significant alternate views of the structure. This said, both models share the same sense of potential for a hazardous situation to develop. The real paradox is that an organization with a genuinely good safety culture will produce event reports as it is driven to learn from all of its incidents and near misses and conversely an organization with a poor safety culture will not be driven to learn and may not report as many events despite having more. This is a situation where the number of event reports does not necessarily reflect the number of incidents. In such a situation it would be incorrect to assume that a poor safety culture and a more unsafe system are indicated by a large number of near miss and event reports. If the management or regulator believe this to be true then the system can be allowed to progress further and further towards a hazardous state, to a point where a small deviation can cause it to fail in a significant way. This situation, as was seen in the event being studied, is clearly represented by slightly modifying the two models above to make the ignorance of the actual number of events, and the incorrect emphasis on the number of event reports clearer. This is shown in Figure 4 where the dotted line shows the missing connection. With this situation two reinforcing feedback loops are set up with no balancing loop which would be provided by the missing connection.

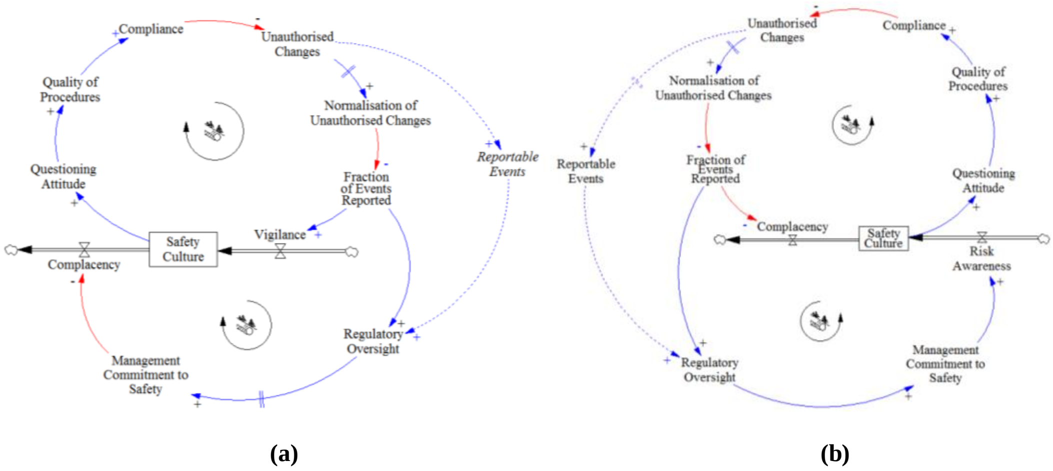

Figure 4 - Error of Reported Events over Reportable Events

Discussion

Modelling the incidents using SD and Causal Loop Diagrams presented three interesting challenges – i) dealing with soft variables, ii) deciding whether simulation is necessary, and iii) the question of validation, Interestingly, these are not independent and their resolution is discussed here.

Initially, the most difficult challenge was how to deal with ‘soft’ variables. These variables, which include terms such as ‘compliance’ or ‘commitment’ are important to the behaviours which emerge from the system, however, there is often no objective methodology for their measurement, and no agreed dimensions. Assuming it were possible to assess them on an agreed or dimensionless scale, the quantitative nature of their influence on other variables is unknown or difficult to capture. Finding them in our group modelling exercise was not unexpected; for example, system dynamics models of NASA safety culture include similar soft variables (Leveson, 2005). There is an argument for capturing and quantifying such information from experts. Research methods from the social sciences routinely deal with such variables through the theory of scale types (Stevens, 1946). However, Coyle (2000) warned that simulations using these types of variables could be a misuse of the tools, going so far as to label it “absurd” (p.238). This warning is based on the grounds that quantifying terms that have no easily defined meaning suggests a misleading level of accuracy. Acknowledging that this is the case Fowler (2003) however suggests that these variables must be included, even if the results are "less than perfect from a numerically scientific perspective"(p.140). If these 'soft' variables are not included, then a mathematically consistent model can be used to run simulations, but it would imply that the omitted factors have no impact on the system. Including them may result in unsatisfactory simulations. In both scenarios there is a risk of producing misleading results. However, our purpose was to look for useful archetypes and these can be purely qualitative in nature and not require simulation at all. It has been argued (Coyle, 2000, Wolstenholme, 1999, Wolstenholme and Coyle, 1983) that building the models, providing it is done rigorously, can be beneficial as an enhancement to linear thinking even without simulation. This is also sufficient for the purpose of identifying structural and behavioural archetypes.

Others (Homer and Oliva, 2001) working in this area have concluded that simulation nearly always adds value and is therefore favourable over causal loop diagrams. Furthermore they suggest that even with significant uncertainties the results of simulations would never by more misleading than trying to interpret the diagrams. Lane (2008) warned that only those experienced in simulating system dynamics models should consider stopping at the diagram stage if it were necessary to do so. Only those aware of the potentially counter intuitive results observed through simulations will be conscious of the dangers and common mistakes of logic that can occur from analysing static diagrams. If the nature of the investigation means the analysis must be conducted using static causal loop and stock and flow diagrams then of course these dangers cannot be discounted. There is no doubt that a rigorous dynamic simulation is preferable to a static diagram, however for some situations rigorous simulation is not possible. The extra effort required quantifying soft variables and their relationships in order to produce a satisfactory model for simulation might not be justified by the quality of the results. The question of what constitutes quality is important, but in terms of practicality for this application the debate needs to be reframed in terms of the original purpose.

The purpose of an accident investigation is to learn about the causality in order to prevent reoccurrence of the event. The purpose of identifying archetypes is to generate insight into patterns of behaviour and the underlying structure of the causality that could be precursors to incidents, these insights can then be used to modify those behaviours before an incident does occur i.e. the systems is self aware and changes itself, the simulation then becomes moot. Identifying archetypes allows experts in system dynamics to suggest corrective or preventative actions. When an existing archetype is recognised within an organisation the corresponding guidance on correction or prevention can be introduced. Also, it has previously been demonstrated (Senge, 1990, Kim and Burchill, 1992, Marais et al., 2006) that un-simulated causal loop diagrams like those produced here are sufficient for communicating archetypal structures

This investigation set out to assess whether the approach has the potential to provide insights that the current tools based on the classic linear and reductionist models of event causality do not. The case study discussed in this paper certainly suggests that this is the case. The conclusions may be similar to those of the original investigations, and the structures of the models may reflect archetypes already identified, but the process of group model building delivered an insight into the causality that the existing tools would not. The engagement and understanding of the participants can be enhanced. The investigation also aimed to assess the feasibility and practicability of the approach. Although there was a degree of refinement after the workshop to clear up some issues, the majority of the models were constructed or discussed during the one-day workshop, with little or no prior knowledge of system dynamics or the event. More time would be required to draw any firm conclusions about the event, but it is certainly conceivable that the approach could be practicable in incident analysis, both as part of active investigation and retrospective learning.

While it is not possible to identify common precursor archetypes from one case study, the fact that a structure similar to archetypes already proposed was developed, describing similar behaviours, suggests it is possible.

For qualitative models the question of validation revolves around the structure of the model and the relationships it documents by experts or those involved in the event being investigated. (Barlas, 1996) regards validation as part of a "purposeful social contract" in which the structure of a model generates a "causal descriptive" correspondence with observed behaviour, do we get "right behaviour for the right reason?" (p.187). System dynamics models are ideally suited to this appeal to structuralism or as Lane puts it "*rerum cognoscere causas*" (Lane, 2001a, Lane, 2001b). When we contrast this position with a logical positivist view that our model is an objective representation of the real world we can thus avoid the question of whether the model is right or wrong, it is merely one possible model on a continuum of usefulness. In this case, usefulness is part of the aim of any event investigation – to learn and make corrective actions so as to prevent recurrence and ultimately to make the system safer. Again it has already been discussed that a group model building approach can add value by providing an alternative view of the event to that presented by existing techniques, and as such can give a richer understanding of the causal factors that require attention.

Within large organizations, studying accidents and undesirable events goes beyond the initial accident investigation. Often a safety culture is nurtured through continued learning and discussion of these events across industries. The benefits of the systems approach also stand for their application in this area. The use of system dynamics in school and college education has been discussed by Forrester (1992), where he says "Students are stuffed with facts without having a frame of reference for making those facts relevant to the complexities of life" (p.5). A similar criticism could be directed at 'learning organizations' that encourage their staff to continually improve and develop their knowledge particularly in the area of safety and industrial accidents. The level of operating experience available can be overwhelming, with no framework as to how these descriptions of events can be applicable in a meaningful way. In discussing an approach to an effective incident learning system Cooke and Rohleder (2006) reiterate the need to go beyond the identification of 'root causes' to analyse causal structures.

The importance and nature of learning in high-hazard industries has been investigated in great detail, with Carroll et al. (2002) among others, providing insight and overview. They suggest that their studies of nuclear power industry investigations revealed they were focused on local process without going into the "deep learning" stage of the underlying processes. This deep learning, they say, is obtained through systems models. A similar conclusion is drawn by Huber et al. (2009) from their safety audit of a chemical site which identified learning within the organization as a disjointed, local activity. They talk of the need to “close the loop of learning” (p.94), and the employees’ frustration that there was a lack of transparency of the causes of events, as they were not involved in the learning process. Instead failures at other plants were collected by the safety department and posted onto the intranet.

In complex socio-technical systems, especially those prone to high impact, low probability events, safety is as much a construct of its ability to effectively react to new and unique developments as it is its ability to follow existing processes well. Rehearsing emergency plans and ensuring they have been learnt is not sufficient (Lagadec, 1997). Preparing for these unique developments can be achieved through effective deep learning that could be provided by the group model building of causal loop diagrams and system dynamics models for retrospective and external events as well as internal investigations.

Conclusions

The investigation demonstrates the feasibility of the approach and shows its potential to provide additional insights to the current tools by virtue of its Systems Theory, feedback focused process. The conclusions may not be different, but the understanding of the causality can be enhanced, and may lead to the identification of further archetypal structures and patterns of behaviour.

As mentioned previously, any archetypes extracted from these models are not unique, but this is not entirely unsurprising. If the previously identified archetypes are true archetypes then it should be expected that they would be seen in other systems and incidents. It is important to recall though that the participants in the workshop had limited or no prior knowledge of system dynamics. Through discussions and adopting a Systems Theory approach to accident analysis they developed models that recognise and reinforce the existence of these common patterns of behaviour. In a group model building workshop they discovered and elicited, from the prose of the written reports, important issues surrounding the underlying dynamic structure of the causality of the event.

The introduction of system dynamics into the event analysis toolbox, both for internal investigations and the extraction of learning through the exploration of external events could improve the understanding of their underlying causality. This could produce deep learning with a dynamic and contextual appreciation not provided by the current models and tools. Further study is required, but through more group model building workshops it is hoped the knowledge and understanding of the participants and organizations can be improved while further archetypes are discovered, existing ones are verified and related solutions are developed. This learning can then be shared effectively between organizations.

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