ABSTRACT: McLucas, Alan

When to use qualitative or quantitative system dynamics techniques: guidelines derived from analysis of recent man-made catastrophes

Events found by Boards of Inquiry, Royal Commissions and Inquests to have caused, or contributed to, a number of recent man-made catastrophes were analysed. The basic premise for this research was … 'if, by studying historical events we can better equip ourselves to recognise symptoms and circumstances that were precursors to past catastrophes, we might learn to avert tragedy in the future'. Concept mapping techniques were used to analyse events and their complex interrelationships.

This research not only provided valuable insights into how and why systemic failures occur, it revealed much about the nature of problems, problems comprising both detail complexity and dynamic complexity. Detail complexity describes myriad, interrelated factors or forces, just too many to be considered at any one time. Dynamic complexity describes something insidious and self-organising. The research reinforced the need to be able to identify and understand what underlies and produces spontaneous self-organisation, and the relationship between systemic structure and dynamic behaviour.

The research also revealed recurring systemic structures. Except that in the catastrophes studied the sequences of events resulted in death, the precursor situations identified are strikingly similar to those characterising complex dynamic problems we face daily.

Systems thinking and system dynamics modelling can help: this is widely acknowledged. Not so is when it is most appropriate to use qualitative versus quantitative techniques to aid our understanding and strategy development. This is addressed. Analysing what might have been reasonably known before each of these catastrophes occurred provided insights guiding the choice between qualitative and quantitative system dynamics techniques.

About the Author

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Introduction
A BHP-owned coal mine at Moura in central Queensland in 1994 was the scene of an explosion in which 11 men lost their lives. A build up of heat and methane in the mine had been detected weeks beforehand: seemingly, this was ignored. The consequence of ignoring this and other indicators was disastrous (Hopkins 1999).

On the evening of 12 June 1996, during a routine training exercise near Townsville in Queensland, two Army Black Hawk helicopters collided and crashed to the ground in a massive fireball. 18 soldiers died and 12 were injured (Australian Army 1996). Many similar exercises had been practiced, why did this one go horribly wrong?

One quiet Sunday afternoon in July 1997, a young girl Katie Bender died when she was struck in the head by a fragment of steel having 100 times the energy of a bullet fired at point blank range. She, her family, and thousands of spectators had come to witness a highly publicised spectacle, the demolition of a community hospital in the centre of Canberra (ACT Magistrates Court 1999). The shot-firer who laid the explosives was charged with manslaughter, but was he really responsible? Some wanted the Chief Minister of the Australian Capital Territory to resign, arguing she interfered and was responsible through her unwelcome involvement.

On 5 May 1998, a fire in the engine room of HMAS Westralia resulted in the deaths of four Naval personnel. The fire was caused by diesel fuel from a burst flexible hose spraying onto a hot engine component. Flexible hoses of an unapproved type had been recently fitted to replace rigid metal ones which continually weeped small amounts of fuel (Department of Defence 1998). A minor problem was fixed only to replace it with a much more serious one, with death being the consequence.

At about lunchtime on 25 September 1998, a heat exchanger in Esso's Longford Gas Plant No.1 fractured, releasing hydrocarbon gases and liquid. The resulting explosions and fire killed two workers and injured eight others (Parliament of Victoria 1999). Gas supplies to millions of customers in the State of Victoria were disrupted for months. A safety audit conducted by the parent company Exxon only months before had given the plant a clean bill of health.

The Reports of the Royal Commissions, Boards of Inquiry and Coroner's Inquests each identify a series of factors combining at a single culminating point, with catastrophic results. The naive might argue this was chance. Chance certainly played a critical part, but only in the terminal stages. First, the circumstances had to be created by man: only then could chance play its final tragic role.

Why are these accidents of interest to a seminar on systems thinking and system dynamics? Well, not for the most obvious reasons. Normally such events are analysed to identify who or what was at fault so that penalties can be applied, and procedures or process can be put in place to avoid a repeat. In this paper we are interested in discovering what pre-existed the accident, not immediately before but what was lurking in the weeks, months, or years beforehand.

It should be no surprise that common threads in these cases were:

a. a litany of systemic failures - failures occurred at some or all levels in the organisations involved;
b. failure to learn and to manage risks - these failures were most prevalent; and
c. each accident was avoidable.

The purpose of this paper is to reveal, through case study research, the nature of the complexity surrounding us everyday, how well or poorly we actually manage within it, and how we might grow in our appreciation of detail complexity and dynamism.

Focus on What Existed Well Beforehand

The focus of this research is on what pre-existed these accidents not the final culmination of events. Our primary interest is in what was occurring in those weeks, months or years beforehand, because this was at a time when things might have been perceived as 'normal', but were not. Of course, we now know that in each case the scene was being set for disaster to occur.

The suggestion is that if we are more able to recognise, within what is considered normal, those situations developing and setting the scene for impending disaster (or just undesirable future outcomes), we might routinely manage them. Unfortunately, our track record in recognising systemic structures and dealing with complexity, particularly dynamic complexity where feedback and delay exist, as was the situation in advance of each of these accidents, is not good.

Benefits of Understanding the Preconditions for Disaster

Armed with a deep understanding of the systemic structures, the characteristic preconditions for impending disaster, we would be fore-armed to direct our efforts and limited resources to where they will have best effect. This, then, should greatly reduce the likelihood of undesirable consequences ever developing.

Why This Research Was Necessary

Motivation to undertake this research stemmed partly from witnessing a number of system dynamics modelling activities which produced questionable outcomes. This raised the following questions:

a. To what extent are system dynamics practitioners equipped with a hammer, in the form of system dynamics modelling skills, and looking for nails to drive? Are we intent on plying our modelling skills even when it might be inappropriate to do so?
b. Is system dynamics modelling the most effective, and most appropriate, for the problems our clients face? System dynamics modelling was used recently by the Australian Department of Defence to support analysis and planning activities associated with preparing for conflict. A supplementary aim was to use experience gained to assist in defining requirements for a sophisticated decision support system to be used by the Defence Executive. This was the most ambitious system dynamics modelling task ever undertaken in Australia. Doubt remains about system dynamics modelling being the most appropriate tool (Brunskill and Cox 1999).
c. Does system dynamics practice need a formal requirements engineering 'front-end'? Does current system dynamics practice start with a sound understanding of the problems to be solved? Concerns have been raised about the consultancy approach used and project management of the Defence modelling task (McLucas and Linard 2000).

Preliminary work to define the nature of the problem to be addressed was scant, the scope of the task was unclear, and decision support system's requirements were poorly enunciated by the users.

d. When is it appropriate to build quantitative models? Are qualitative models built using systems thinking principles more likely to be understood and accepted by decision-makers? When are qualitative models sufficient?
e. What is more important, taking hundreds of hours developing system dynamics models intended to build robust understanding, or taking a fraction of that time to galvanise busy senior executives to critically reflect on their own deeply ingrained, and perhaps inappropriate, assumptions and views of the problem?

Before any of these questions can be answered, we need to have a deep appreciation of the nature of the problems we are expected to help solve (Flood 1999, 69-73).

Many 'failures' occur in the analysis of 'messy' problems, the development of strategies, and implementation designed to fix such problems because ambiguity, misunderstanding and conflict about the problems remains unresolved. It is worrying that ambiguity, misunderstanding and conflict exists today amongst practitioners and researchers in the fields of systems thinking and system dynamics. The explanation offered for this is a continuing lack of appreciation of the nature of the complex problems at hand: do we really appreciate what we are dealing with?

The need for this body of research was further emphasised when it was suggested by some that it should be possible to develop a set of heuristics or 'rules of thumb' which would guide the application of:

a. qualitative approaches, and
b. quantitative system dynamics modelling.

Arguments about qualitative versus quantitative modelling have continued unabated for years. Again it is suggested a reason for this is the problems we face are highly complex, both in detail and dynamism: that complexity must be fully appreciated before our problem-solving craft can mature.

It is not surprising that building general acceptance of systems thinking and system dynamics as legitimate and powerful techniques for addressing complex, dynamic problems remains an unfinished task. Acceptance will only come about when we can demonstrate that our understanding and our craft, built around that understanding, has fully matured. This paper hopes to enhance that understanding.

Requirements for Selection of Cases for Study

Demands for the selection of case studies were stringent:

a. Cases had to be drawn from real life. They had to be 'messy' problems (Vennix 1996, 13).
b. Cases had to be extensively documented. Surprisingly little in the public domain was found to be documented to the extent sought.
c. Cases needed to be reported with high levels of objectivity and reliability.
d. Cases had to stand scrutiny.

Investigations conducted by the judiciary in the wake of serious accidents involving death were found to fit these requirements. They are frequently subjected to critical review by the legal profession, researchers and litigants alike. This ensures they are robust, objective and reliable.

Of course, the primary purpose for conducting Boards of Inquiry, Royal Commissions and Coronial Inquiries is to determine who or what was the cause of the accident. The aim is to apportion blame and suggest remedies. Whilst those who produced the original reports did not intend them to be used for this type of research, they proved to be most suitable.

Research Methodology - Using Concept Mapping

Concept or cognitive mapping, alternatively known as idiographic causal mapping, was used. This technique exploits Psychology of Personal Constructs (Kelly 1955).

Concept maps were used to graphically depict important elements of the evidence, the relationships between those elements, and thoughts behind legal deliberations contained in the various reports of Boards of Inquiry, Royal Commissions, and Coroner's Inquests. They summarised what the judiciary took months, or in some cases years, of investigation and deliberation to conclude.

At this point, it is necessary to take a slight diversion. Mapping is used to bring various concepts into view, and to understand their interrelationships. When dealing with hard physical problems we seek to define relationships between parameters using algebraic expressions. In concept mapping we are dealing neither with parameters or relationships, which are easily expressed in algebraic terms. Jacobsen and Bronson, 1987, make the following observation about this:

> In their guidelines for causal-loop diagramming, Richardson and Pugh (1981, 28) recommend that one "think of variables in causal-loop diagrams as quantities that can rise or fall, grow or decline, or be up or down. But do not worry if you can not readily think of existing measures for them." This is misusing the term *variable*. A quantity without measurable units is not a variable; it is a concept or a nominal definition of a concept.

These maps will be referred to as concept maps rather than cause maps, influence diagrams, causal-loop diagrams, or directed graphs as are terms found in the literature. Indeed, the term concept map is both appropriate and correct.

Ackermann, Eden, and Williams, 1997, used concept mapping (they prefer 'cognitive mapping') to build compelling arguments to defend a case in litigation over the management of the Channel Tunnel Project. In this research, a similar technique has been used but, rather than building the maps *ab initio*, the maps were developed from source material in the form of the various Reports.

Lane, 1999 and Doyle and Ford, 1999 explain that these maps can be used in different ways:

a. graphically depicting cognitive structure, that is, how people think or have thought (Eden and Ackermann 1998, 193);
b. providing a vehicle for fostering discourse; and
c. validating the meaning expressed during interviews, workshops and similar knowledge elicitation activities.

Whilst concept maps were used here to depict cognitive structure as explained at a., above, in other research and consultancy practice, they have been used for the latter purposes, b. and c.

An important benefit of concept mapping is that all factors relevant to a particular viewpoint can be depicted on a single piece of paper. Concept mapping concentrates information whilst helping to put large numbers of complex interrelationships into context.

Concept Mapping Methodology

Concept mapping methodology follows that of Eden, 1988 and 1994. A concept is an action-oriented statement which makes sense by itself, but makes completes sense when read in conjunction with supporting concepts. It is written as a 'call to action' and is intended to suggest an option for changing the nature of the situation in a positive way. Each action in turn is supported by actions that support them (explanations) placing the former action *as an outcome* (Eden and Ackermann, 1998, 160). Concepts were identified first. Then, the logic of the links between them was determined. A tutorial on concept mapping can be down-loaded from the Banxia© *Decision Explorer* website.

Fuzzy Logic

Unlike digital computers which are programmed to operate using classical logic, human brains operate on 'fuzzy logic'. In many domains people do not have all-or-none convictions about whether something is true (Pinker, 1997, 101) (Kosko, 1993). Fuzzy logic is ubiquitous in the application of the law. Even in the face of seemingly incontrovertible evidence, there is doubt. Guilt or innocence can never proven absolutely: it can only be proven but beyond 'reasonable doubt'.

Similarly, in a complex, dynamic world we deal with strategies that satisfice: they are imperfect, neither black nor white, zero or one. Even Newton's Laws which existed without challenge for around 250 years were shown by Albert Einstein not to be immutable. Fuzziness is an essential characteristic our being and our thinking. If it was not, our systems of meaning would remain unaffected by experiences and views of others. They would be black and white, clinical and totally controlled by classical logic: this is clearly not so.

Fuzzy Logic Links Between Concepts

Only three types of 'fuzzy logic' links were needed:

a. Causal. Causal relationships are represented by arrows, where each arrow means 'leads to …, such as is expressed in the statement 'smoking *leads to* heart disease. This does not mean all smokers will suffer from heart disease but suggests there is strong evidence to this effect, noting all people who smoke will be affected, at least, to some extent. 'Fuzzy logic' underlies the 'leads to' causality. A delayed effect on a causal link may be marked by a 'T' signifying a temporal qualification.
b. Connotative. Connotative relationships are depicted by lines without arrowheads. Here causality may act in either direction at different times or under varying circumstances. This type of link suggests causality is ill defined, open to interpretation, or requires further investigation.
c. Conflict. Conflicting relationships are a special case of a connotative relationship, but where the concepts at the ends of the arrow cannot co-exist without conflict or a state of stress being created.

How maps were developed and interpreted is explained below in the context of the Black Hawk Helicopter Crash case study.

Black Hawk Helicopter Crash - Case Study Overview

On that fateful day in June 1996, at the High Range Training Area near Townsville in Queensland during training to build individual and team skills required for Counter Terrorist (CT) and Special Recovery Operations (SRO), there was a catastrophic training accident. It occurred on the second day of a series of training activities designed to develop and retain high readiness on the part of the Special Air Service Regiment and the 5th Aviation Regiment. These soldiers were training to undertake operations to recover Australian citizens should they become the victims of a hostage situation, such as has occurred in many parts of the World.

After the accident, an extensive and thorough Inquiry was conducted. It lasted three months. The Board of Inquiry Report and related proceedings comprise 17 volumes. The following explanation focuses on the Executive Summary of the Board's Report and the Chief of Army's Report to the Minister for Defence. Analysis of the key findings is demonstrated below.

Mapping of Factors Contributing to the Accident

Individual concepts are numbered for identification purposes only. Numbering is not intended to suggest importance or priority. Where a choice exists for placement of concepts on a map, more important ones are placed towards the top. Placement of concepts is balanced against the need for overall compactness of the map. The latter requires concepts to be positioned adjacent. Maps are easier to understand when read from the bottom up.

Pairs of concepts linked by unambiguous causality can be progressively built into chains. In the first pass, these do not have to be complete. However, the critical requirement is to check that every link can withstand scrutiny of validation that one concept 'leads to …' the connected concept as shown by the direction of the arrow.

As the map develops it might appear as depicted at Figure 1, noting that the diagram may have to be re-drawn several times to tidy it. An alternative is to write concepts on individual Post-it® Notes. These can be placed on a whiteboard, firstly in clusters, then connected by arrows to depict causality. This technique works well in a group setting, or workshop. Eden and Ackermann, 1998, use a variation on this they call the Oval Mapping Technique.

Concept maps serve to present concepts graphically and to facilitate detailed step-by-step analysis. Individual maps accommodate differing points of view. Used carefully and consistently they are also very useful in highlighting omissions and errors in logic.

Analysis of Chief of Army's Report to the Minister of Defence

See Figure 1, below. This summarises Chief of Army's Report to the Minister for Defence on the findings of the Board of Inquiry.

It should be noted that this Figure depicts on a single sheet of paper, months of detailed investigation and deliberation. It warrants close scrutiny.

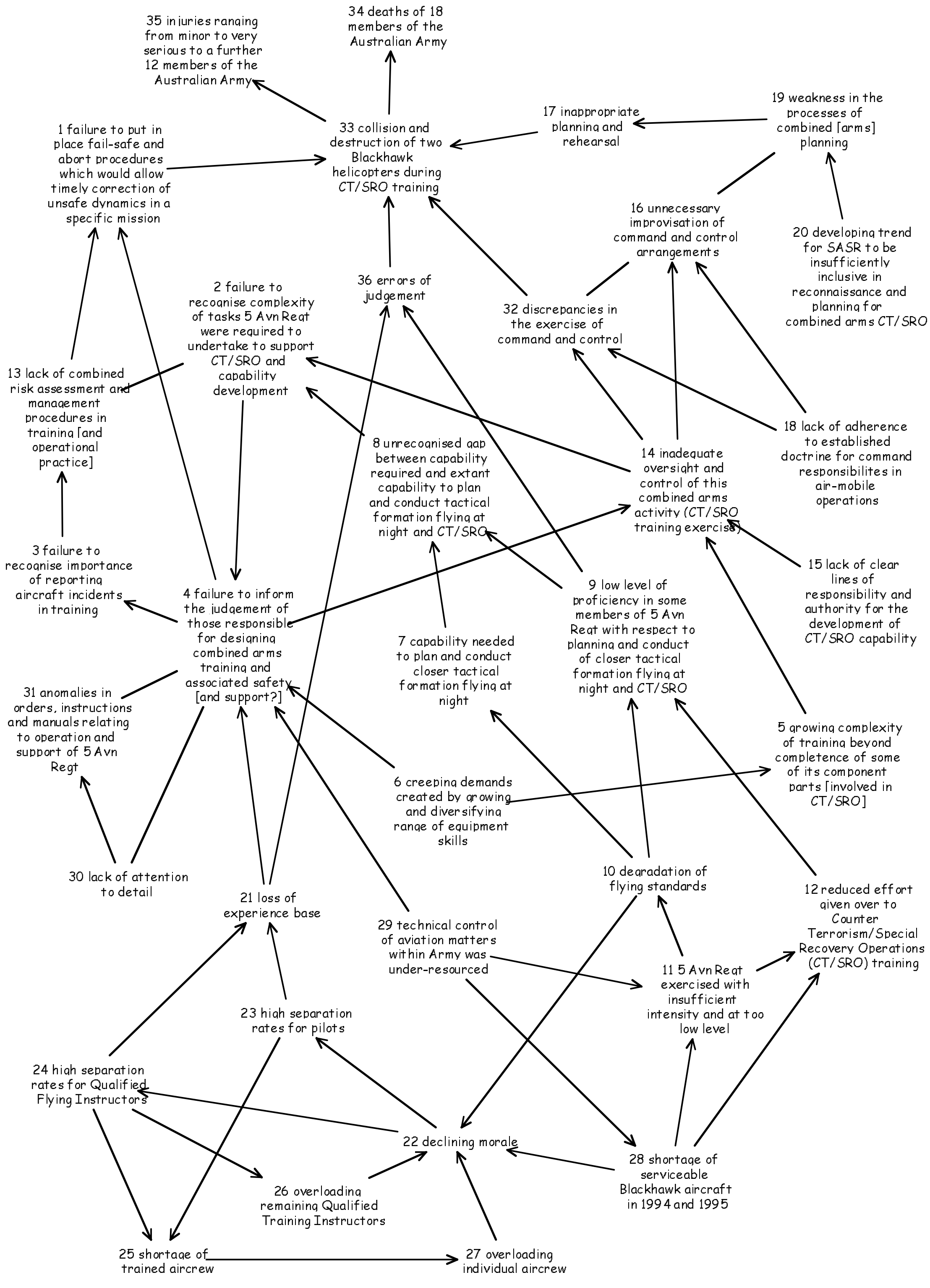

Figure 1. Concepts Included in Chief of Army's Report to the Minister for Defence

Reading the map can start at any point, although starting from the bottom is recommended. Causal links should be read first. Follow each series of links through until each has been read and understood.

The next step involves considering the relevance of individual concepts. Whilst, for example, it may be readily accepted that Concept No 23, *high pilot separation rates for pilots* led to *loss of experience base*, there is little information about the extent of the problem.

When the whole map has been read and understood, the overall structure should be viewed by standing back from the detail, taking a world view or weltanschauung (Checkland 1990) (Checkland and Scholes 1999). To facilitate the remote viewing, consider the map as numbers linked by arrows and lines, without any text, as shown at Figure 2.

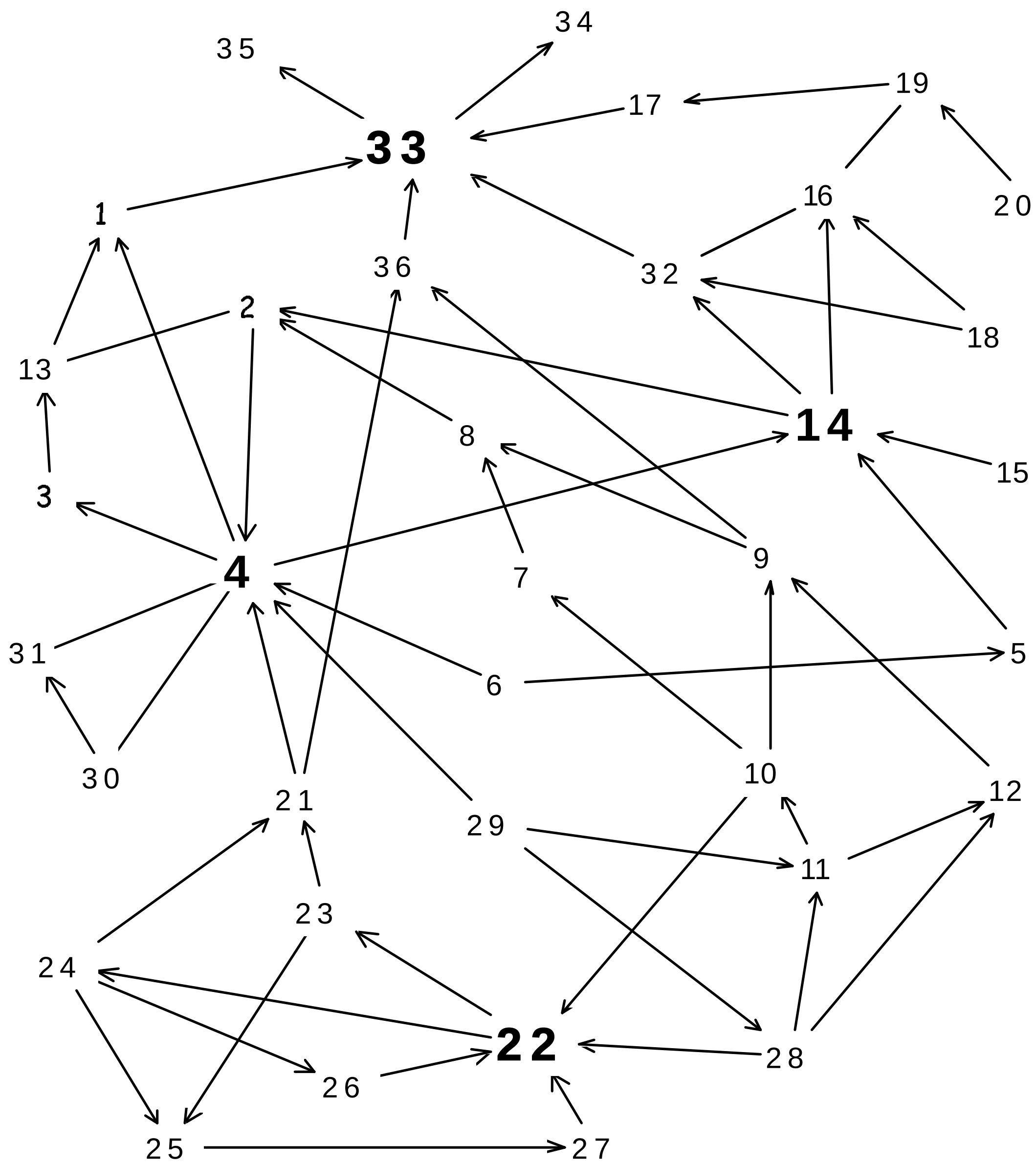

Figure 2. Structural Overview of Chief of Army's Report to Minister

This facilitates thinking about:

a. concepts connected in causal loops, such as 22 – 23 – 25 – 27 – 22, 22 – 24 – 25 – 27 – 22 , and 22 – 24 – 26 – 22;
b. nodes where several arrows enter or leave, such as 4, 33, 22, 14 with nine, six, six and six link arrows or lines respectively; and
c. concepts connected in loops involving a mix of causal and connotative links, where the latter are considered as bi-directional causal links following direction of the loop at least some of the time, such as 4 – 3 – 13 – 2 – 4 and 4 – 30 – 31 – 4.

Accommodating Different Perspectives

Figure 1 depicts Chief of Army's perspective. This perspective was different, in several respects, to that expressed by the Chairman of the Board of Inquiry in the Executive Summary of the Report. This does mean there is conflict between Chief of Army and Board of Inquiry, but the map serves to outline Chief of Army's concerns and reflects his responsibilities to the Minister.

Checkland 1990, Vennix 1996, Coyle 1996, Eden and Ackermann 1998, McLucas 1998; and others have noted the significance of differing perspectives. In human systems, there can be many valid perspectives of the same problem. Different perspectives need to be accommodated both during the analysis of the problem and in the development of strategies.

Insights Derived from Feedback Loops

Contemplation of Figure 2 structure reveals several circular feedback loops. One is shown at Figure 3, below.

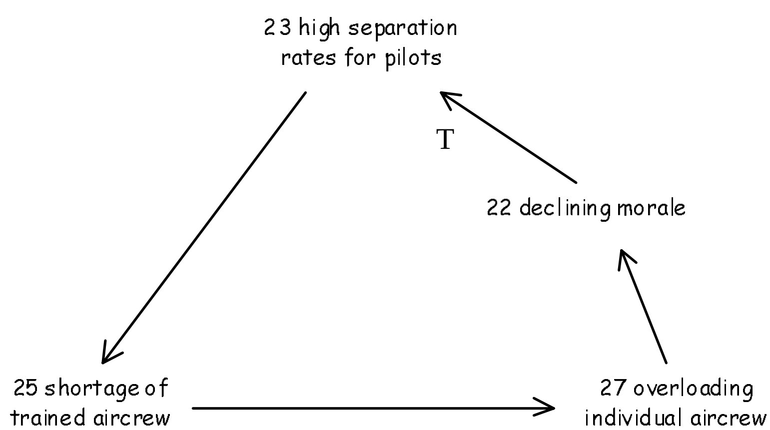

Figure 3. High Pilot Separation Rates and Declining Morale

Interrelationships might be interpreted as follows … *high separation rate for pilots* led to, or resulted in, *a shortage of trained aircrew* which, in turn, led to *overloading of the remaining individual aircrew*, and this led to *declining morale*, which after a delay led to *high separation rates for pilots*. In a feedback loop such as this, there is no start point and no end point. We might summarise the loop as:

> Concepts No 22 – 23 – 25 – 27 – 22: *declining morale –> high separation rates for pilots –> shortage of trained aircrew –> overloading individual aircrew –> declining morale.*

Figure 4 builds on Figure 1-7 to include the following loops:

Concepts No 22 – 24 – 26 – 22: *declining morale –> high separation rates for Qualified Flying Instructors –> overloading remaining Qualified Training Instructors –> declining morale*, and

Concepts 22 – 24 – 25 – 27 – 22: *declining morale –> high separation rates for Qualified Flying Instructors –> shortage of trained aircrew –> overloading individual aircrew–> declining morale.*

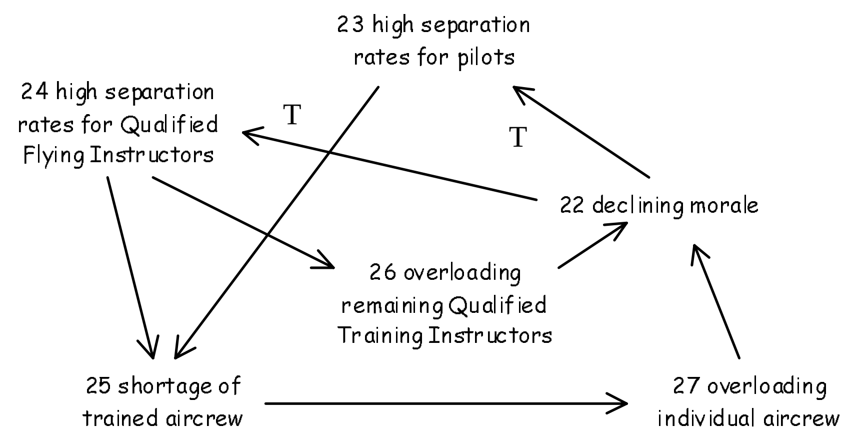

Figure 4. Loops Involving Declining Morale

This serves to highlight that there are several factors impacting upon morale. These feed upon themselves making morale worse unless some action is taken to correct the decline. These three loops are known as positive feedback loops. That is, they reinforce the effect. As morale declines, pilots are more inclined to leave and when they do they create a greater shortage of trained aircrew and that increases the overloading of individual aircrew who become increasingly despondent with their plight, become more inclined to seek alternate employment, and leave. A similar situation existed for Qualified Flying Instructors.

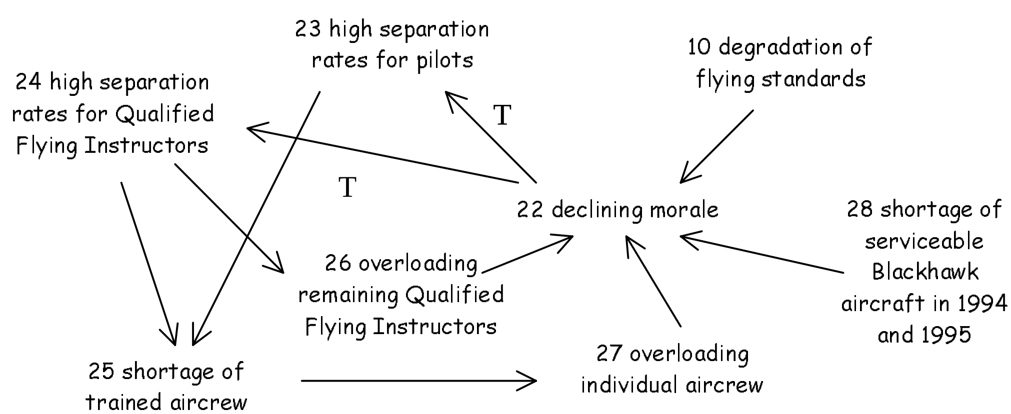

Figure 5. Expanding Consideration of Contribution to Declining Morale

As the picture grows, we consider other links to declining morale, from Concepts No 10 and 28, as depicted in Figure 5.

We now see that *a shortage in serviceable aircraft in 1994 and 1995*, noting that the crash occurred in June 1996, contributed to *declining morale*, as did *a degradation of flying standards*. Logic suggests there should be a link between *available numbers of Qualified Flying Instructors*, not shown, and *degradation of flying standards*. A concept, *available numbers of Qualified Flying Instructors* is not shown because the detail was not contained in the Chief of Army's Report, but the nature of that interrelationship would be discovered had further, and more detailed analysis been undertaken. A logical omission from the Executive Summary has been discovered?

This brings us to the main purpose of presenting concepts and their interrelationships in these maps; to help us identify where to direct our efforts in order to understand and manage extant problems.

Candidate for Quantitative Modelling

Available numbers of Qualified Flying Instructors, would be a stock, level or accumulator in quantitative models intended to inform strategies about achieving and maintaining appropriate numbers of pilots and instructors. This would be linked to other stocks such as levels of operational competence.

A closer study of aircrew shortages suggests that:

a. more detailed analysis into aspects such as recruiting, training, employment and separation rates should have been conducted years before and should have been the focus of continued intensive management;
b. another map drawn at a lower level of aggregation would provide a more detailed representation, including aspects listed in a., above;
c. recruiting, training, employment, conditions of service and separation are linked through a set of 'business rules' not enunciated here, for example:
    (1) a change in recruiting rates will affect achievable training rates, and
    (2) a change in separation rates might be made by a change in conditions or service or a change in the attractiveness of continued Service employment.

Aircrew shortages is clearly a candidate for system dynamics modelling. It involves stocks and flows in a series of feedback loops and delays. This suggests *Aircrew Shortages* should have been the subject of detailed quantitative analysis (Linard and McLucas, 1999), using disciplines such as system dynamics modelling to inform recruiting policies and other management strategies.

Indeed it was. A system dynamics modelling study was undertaken but the findings of the modelling were not supported for a variety of organisational political reasons.

Further, those responsible for managing *declining morale* did not have a holistic view. In addition to aircrew matters, such a view might have included factors impacting on pilot training and aircraft availability, for example. If they had, they would have realised that the problem was more complex and highly by organisational politics, resource availability and funding issues. As an exercise, it is suggested the reader use a sheet of paper to hide all detail above Concepts No 21 and 10 in Figure 1. This helps identification of issues requiring management and support by a sponsor, mentor or project champion, a person with the necessary executive power to influence what is contained in that view or partial view.

Declining morale was an issue in itself. It was symptomatic of more deeply rooted problems, some going back several years. It was a critical indicator of a set of highly interconnected problems. *Declining morale* could not be rectified overnight. For example, it would take several years to recruit and train pilots and a longer time for qualified flying instructors. This was a complex, dynamic problem exhibiting classical counter-intuitive response to strategies designed to fix it. It was never addressed effectively. Figure 5 provides the initial framework upon which a system dynamics modelling effort might be built.

Focus on Critical Nodes

Further to analysis of feedback loops, analysis of nodes brings further valuable insight. Nodes are points of influence. Nodes have influence over concepts to which they are linked, or are influenced by linked concepts, depending on the direction of causality shown by arrows. In the case where the link is connotative, causality may change in direction: concepts appear to influence each other. With few exceptions, links may change in strength and causality over time and may depend on initial conditions. Singular, direct, linear causal relationships are the exception rather than the norm (Meadows, 1989).

Some nodes are much more important than others. We need to be able to identify which ones are more important and why. We might go about this by counting the number of arrows in, or out, of selected concepts. This might suggest the importance of a node. Whilst this count is an excellent guide but cannot be used alone. The nature of each link needs to be considered.

Further, when a node is common to a number of circular feedback loops, it has extraordinary influence or is influenced to a greater extent. It is to such nodes we should direct development of our management strategies.

See Figure 5, which depicts the situation that existed in the months, weeks and days leading up to the accident. Those loops linking *declining morale* which have already been discussed have been omitted for the time being, only to minimise distraction. In their absence, read Concept No. 21: *loss of experience base.* It is worthwhile to contemplate the nature of Figure 5 if we were to replace *loss of experience base* with *high levels of competence (among pilots and QFIs).*

In order to inform development of management strategies, consider selected concepts and those concepts linked to it, especially those comprising feedback structures. In the case of Concept 4:

a. Concepts 4 – 14 – 2 – 4: *failure to inform the judgement of those responsible for designing combined arms training and associated safety* –> *inadequate oversight and control of this combined arms activity (CT/SRO training exercise)* –> *failure to recognise complexity of tasks 5 Avn Regt were required to undertake to support CT/SRO and capability development* –> *failure to inform the judgement of those responsible for designing combined arms training and associated safety.*
b. Concepts 4 – 3 – 13 – 2 – 4: *failure to inform the judgement of those responsible for designing combined arms training and associated safety* –> *failure to recognise importance of reporting aircraft incidents in training* –> *lack of combined risk assessment and management procedures in training* –> *failure to inform the judgement of those responsible for designing combined arms training and associated safety,* and
c. Concepts 4 – 30 – 31 – 4: *failure to inform the judgement of those responsible for designing combined arms training and associated safety* –> *lack of attention to detail*

– > *anomalies in orders, instructions and manuals relating to operation and support of 5 Avn Regt* **–** > *failure to inform the judgement of those responsible for designing combined arms training and associated safety*.

Note should be taken of the connotative links 4 – 30, 31 – 4, and 13 – 2 in the latter two feedback loops. These links are open to interpretation. They are considered to be pseudo-feedback loops because for at least part of the time their influence is in the same direction as the causal links. When this occurs, the loop is complete.

Concept No 4 has nine links. It is a critical node. Intuitive reasoning also suggests that failure to inform the judgement of those responsible for designing combined arms training and associated safety, is critical, even when considered in isolation.

Further, the concepts to which it is linked are important in their own right. Consider, for example, the following:

a. Concept No 2: *failure to recognise complexity of tasks 5 Avn Regt were required to undertake to support CT/SRO and capability development*;

b. Concept No 14: *inadequate oversight and control of this combined arms activity (CT/SRO training exercise)*; and

c. Concept No 1: *failure to put in place fail-safe and abort procedures which would allow timely correction of unsafe dynamics in a specific mission.*

There should be no doubt that Concept 4 is critically important. It is what Coyle (1996, 222) calls a 'pressure point' and Senge (1990, 64) calls a 'leverage point'. Changing Concept No 4 or the nature of the links to or from it, that is the extent to which it affects other concepts or the influence it has, may have significant influence on the likelihood or consequence of possible outcomes. Managing Concept No 4 is very likely to produce enduring improvements. Both Senge and Coyle agree that tackling a difficult problem is often a matter of seeing the where leverage lies.

In addition to our consideration so far, we might view concepts that are sources or sinks. Those that are sources have influence on several concepts, whilst those that are sinks are influenced by several concepts. In most cases, concepts are sources and sinks at the same time.

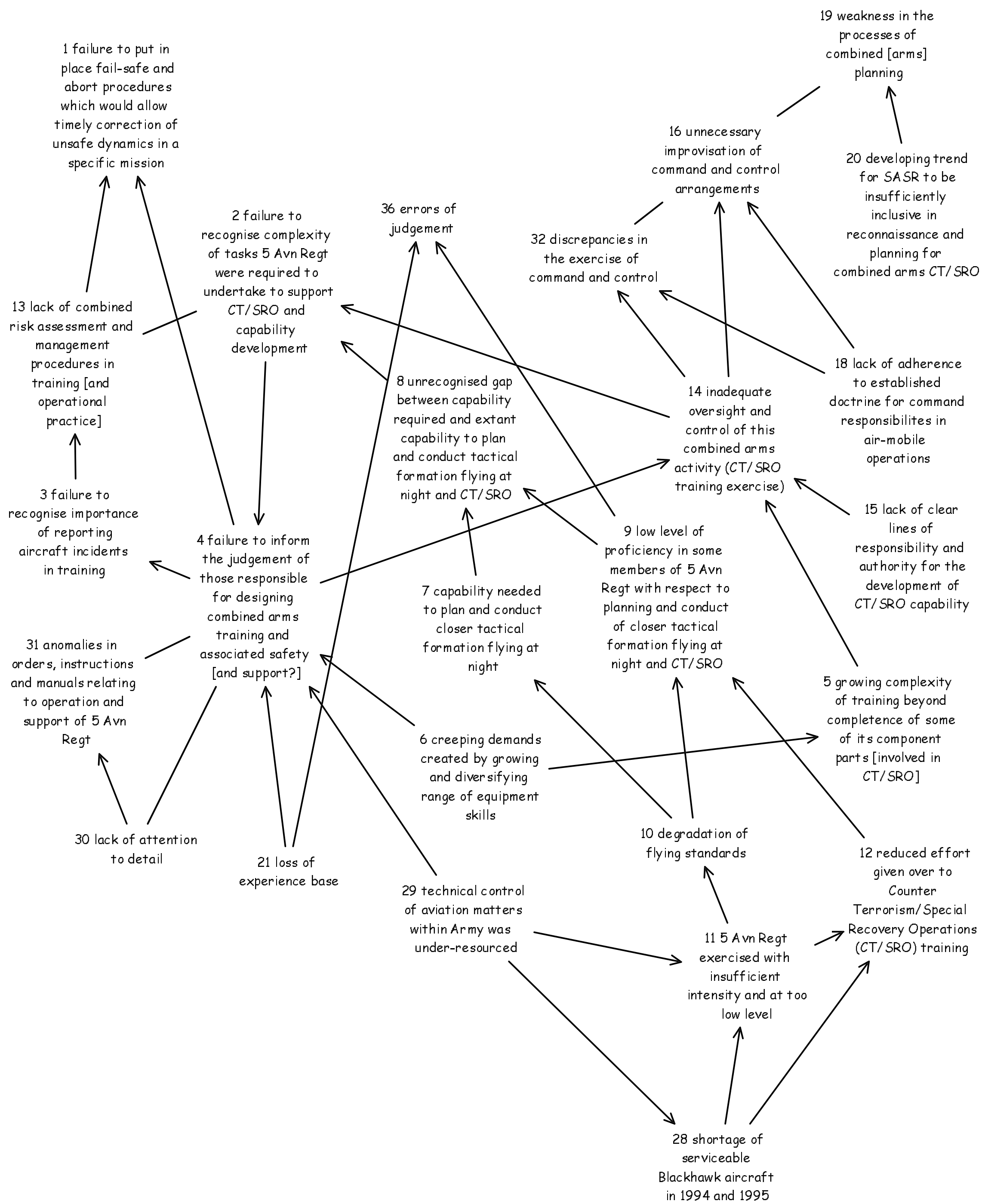

Figure 6 Circumstances Existing Before the Accident
(Less details of 'Aircrew Shortages' leading to concept 21 'loss of experience base')

Concepts at the boundary of the map are either sources or sinks. Sources are more likely to appear lower in the map, and sinks near or at the top. Referring back to Figure 5 and focussing on Concept No 28, we see it is a source with influence on three concepts, Nos 22, 11, and 12 respectively. It is also a sink with influence from Concept No 29. The fact that Concept No 28 *shortage of Blackhawk aircraft in 1994 and 1995* is an influential source is most important in this map. Clearly, another map focussing on aircraft serviceability would give a picture of what influenced the 1994/95 shortage. But, that is outside the boundary set for the extant map. Reiterating, Concept No 28 is an influential source worthy of closer consideration. Much earlier, serviceability of Black Hawk helicopters should have been better managed, but it was not.

In the early 1990s, after considerable inter-Service bickering, Army had taken control the helicopter fleet from the Royal Australian Air Force (RAAF). RAAF had flown troop-carrying helicopters with distinction in Vietnam and was reluctant to lose this capability. RAAF also had extensive expertise maintaining helicopters. Further, the purchase of Black Hawk helicopters had been an embarrassment to the government, Minister for Defence and Chief of Defence Force (CDF). The Black Hawks had proven very expensive both to procure and maintain, much more so than their predecessor the Bell Huey UH-1 series. Their procurement occurred almost concurrently with the hand-over form RAAF to Army. Army was faced with taking over from RAAF and bringing a new and more sophisticated aircraft into service, with all the concomitant training and logistics demands. It was little surprise to many, particularly the RAAF, that a chronic shortage of spares occurred and unserviceability became a serious problem in 1994/95. Many RAAF officers had predicted this years before.

Whilst is might seem obvious after the fact, and after the Board of Inquiry had completed its deliberations, these concepts and relationships should have been understood and managed routinely. It is suggested that had this been so, the accident might have been averted.

Indeed, it is suggested that any strategy to avoid training incidents or accidents in the future would be directed at correcting critical Concepts such as those identified by our analysis here. The Board of Inquiry's observation that *failure to inform the judgement of those responsible for designing combined arms training and associated safety* … suggests the worst failure, the failure to learn. In general, failure to learn leads to a breakdown in the management of risks.

Before leaving this point, it is most important to note that effective approaches designed to fix problems should be multi-pronged. Problems should be attacked simultaneously at strategic, operational, and tactical levels. At the strategic level, those concepts most worthy of attention are:

a. Concept No 4: *failure to inform the judgement of those responsible for designing combined arms training and associated safety*;
b. Concept No 2: *failure to recognise complexity of tasks 5 Avn Regt were required to undertake to support CT/SRO and capability development*;
c. Concept No 14: *inadequate oversight and control of this combined arms activity (CT/SRO training exercise);* and
d. Concept No 1: *failure to put in place fail-safe and abort procedures which would allow timely correction of unsafe dynamics in a specific mission.*

Whether Concepts No 3, 6 and 21 also directly linked, should be included is a matter for risk assessment. As part of this process, weightings are placed on likelihood and consequence of each event occurring. This point will be developed further in later discussion about risk management and quantitative analysis.

At the operational level, Concept No 22, *declining morale*, certainly would be worthy of attention. Figure 1 does not really cover tactical issues. To identify appropriate tactical level issues would require more detailed investigation and analysis.

Identification of critical issues and their continual review are fundamental risk management activities. It is not at all surprising that the Board of Inquiry's first recommendation attends to the matter of risk analysis, and subsequent recommendations relate to treatment of identified risks.

Breakdown in Management of Risks

Before the Black Hawk helicopter crash occurred, there was a breakdown in the understanding of complexity involved, failure to learn, and a breakdown in risk management. This was brought about, at least in part, by:

a. misunderstandings of risks, their likelihood and consequences;
b. a lack of appreciation of mechanisms and systemic structures, feedback and delay, that underlie dynamic complexity, and contribute to dynamically changing risk; and
c. 'systems of knowledge-power' and 'systems of meaning' (Flood, 1999) issues which militated against effective risk management.

Breakdown in Management of Risks - General

It is normally assumed that the desire, the ability, and the scope to manage risks are unimpeded. In a number of case studies, organisational cultural issues proved to be serious impediments. Examples are a 'culture of denial' [an espoused view that there were no problems when, in fact, there were], and a 'can do' mentality. These militated against effective risk management, and exercising of duties at some, or all, organisational levels.

It is important to note that in all accidents studied there was a breakdown of some form, or other, causing a deleterious effect on understanding and managing risks. In one case, that of the death of Katie Bender, incompetence was also found to be a major factor.

Winding the Clock Back

In each of these case studies, the clock was wound back as follows:

a. Once the complete map was developed, concepts that could not have existed before a selected point in time were removed (Banxia© 'Decision Explorer' has the facility to allow concepts to be hidden from view).
b. The resultant map depicting circumstances that existed well before the final tragic events, was analysed. Analysis then took the form of determining what would have been reasonably known at the time. [Note: A concept taken from British Law is that of a 'reasonable man'. A reasonable man confronted with the circumstances suggested in the evidence might be expected to act in a way seen under law to be 'reasonable'. This legal device is designed to facilitate legal argument or judicial rationale.] The resultant map is a revelation of what might be reasonably considered to exist to have existed or to have been known at the chosen point in time.
c. Systemic structures were identified and analysed as in the Black Hawk helicopter case.

What the Concept Maps Revealed in General

Space precludes a similarly detailed review of each of the other cases. However for the Katie Bender case, nearly 400 concepts comprised the concept map. This reflects the complexity contained in of the Coroner's Report. But to depict more than 300 concepts on a map is time consuming. This is overcome by working at a higher level of aggregation. Doing so reduced the numbers of concepts to around 200.

The concept map can be compared to the street map of a large city with arterial roads into the central business district (CBD) clearly discernible, as are the minor industrial districts and suburban shopping centres, the CBD being 'failure to understand, failure to learn and, hence, failure to manage risks'. Indeed in each of the cases studies cited a similar concept or group of concepts formed the CBD. This suggests that any intervention we might design should set out to improve understanding and learning. This is arguably the most important finding of this research.

Maps for each case study exhibited very similar characteristics:

a. a single central business district, or a small number of highly interconnected business districts;
b. distribution systems linking the business districts; and
c. choke points which might be likened to 'pressure points' (Coyle 1996, 222) or 'leverage points' (Senge 1990, 64).

Once having developed an understanding how these messy problems, viewed as large cities, leads us to search for characteristic topologies in other problems spaces. We begin to notice business districts, distribution systems and choke points. This technique utilises one of the strongest attributes of the human mind, the ability to recognise patterns (Carroll and Johnson 1990).

Discussion - General Observations - Dealing With Complexity In Strategic Decision Making

In his 1999 book 'Rethinking the Fifth Discipline', Bob Flood reminds us of the difficulties of dealing with detail and dynamic complexity acting in concert. Indeed, Flood suggests building models of a highly complex world is nugatory unless such activity is accompanied with building systemic appreciation as an ever expanding exercise (Flood 1999, 69-73) … we might be better served applying our efforts to learning within the unknowable rather than trying to manage detail complexity and dynamism of the world that surrounds us?

Eden and Ackermann,1998, suggest looking more closely at both the nature of the problems we might attempt to solve and forces that militate against achieving their solution. Much current system dynamics practice glosses over the need for comprehensive initial investigation into the problems and advocates proceeding as directly as possible to building models. The latter, of course, is the approach advocated by Jay Forrester. The efficacy of rushing headlong into building system dynamics models without preliminary qualitative analysis is questioned.

Vennix, 1996, attends to this by closely and continually involving client groups in knowledge elicitation and model building. Iterative and Interactive Strategy Development (IISD), McLucas, 1998, and Eden and Ackermann 'JOURNEY', 1998, have similar aims.

It is critical that we spend time and effort to reveal, as completely as possible in the time available, the organisational decision-making or strategy-development environment, the politics, the incompetence, or ignorance which might need to be dealt with before meaningful analysis or problem-solving action can be taken. Otherwise we will find ourselves in an organisational decision-making minefield.

Nature of Complexity - A Review

There are two considerations here that need to be reviewed. Firstly, there is the inherent complexity of the world (Kline 1995) (Flood 1999) (Senge 1990). Secondly, human ability to understand and make predictions regarding behaviour of complex systems, that is to deal with complexity, is limited (Paitch and Sterman 1993).

Kline defines an *Index of Complexity C*, based on numbers of:

a. independent *variables* needed to describe the state of a system;
b. independent *parameters* needed to distinguish the subject system from others; and
c. control *feedback loops* within the system and connecting the system to the surroundings.

Applying the *Index of Complexity* to socio-technical systems, where there are not only numbers of humans but complex hardware and many feedback loops both within the system and to the world, Kline suggests a value of C greater than 10^{13} (Kline 1995, 61). By stark contrast Kline suggests human ability to reliably predict all aspects of behaviour, even with computer assistance, is limited to systems described by $C \approx 4$, not 10^4. (Kline 1995, 61-65). The deduction is frightening: our ability to deal with complexity, to solve complex problems is in considerable doubt, indeed.

Improving Management in Complex Environments - Removing the Disjoint

Through the routine daily exercise of their power, decision-makers, consciously or unconsciously, strive to mould their environment to what is comfortable for them. A 'comfort zone' is created when decision-making ability, ability to resolve problems characterised by $C \approx 4$, accords with the complexity decision-makers are prepared to routinely confront.

Miller, 1956, expressed the notion of human ability to deal with complexity in a somewhat different way. He simply suggests a link to the 'magic number' seven: at any time decision-makers are able to deal with between five and nine (7±2) concepts. We might take a somewhat more sophisticated systems view and read interpret this as follows … a comfort zone exists when the number of critical and highly interrelated issues thought to impact on this instant's decision or policy formulation does not exceed the numerical range 7±2.

Consider what happens when a CEO insists on a single page brief highlighting no more than nine critical issues that he might take into account in formulating strategy. A subordinate manager and supporting staff tasked with preparing the CEO's brief have to deal with considerable complexity before making the appropriate recommendations. The CEO's actions have effect of suppressing the level of complexity that he and other decision-makers at the strategic level are exposed to at any time.

Argyris, 1991, and 1994, suggests that many 'successful' senior decision-makers have poorly developed skills for analysing their own decision-making failures. Similar observations have been made about senior decision-makers ability to deal with complexity, particularly dynamic complexity where feedback and delay occur (Sterman 1989a., 1989b., and 1989c). The result is a disjoint between strategic and lower decision-making levels. Other factors contributing to this disjoint are:

a. Socio-technical organisations are massively complex; even so though we might not accept the extent of socio-technical organisation's complexity suggested by Kline, $C>10^{13}$.
b. Executive decision-makers, who are generally amongst the busiest in the organisation, would prefer to avoid the impositions on their time, and the extensive delays that often accompany the application of analytical techniques: for them, the true nature of complexity remains undiscovered. When this understanding is absent or deficient, over-simplification, of what is really a messy problem, can result. This leads to the practice of

seeking a single 'golden nugget' as the cause current problems. Donella Meadows, 1989, suggests that this is probably the most widespread problematic assumption in the current industrial paradigm: one cause produces one effect, find the cause and fix the problem.

c. Decision support is often untimely. It simply does not fit within the decision cycle, the decision-maker's OODA Loop. This involves cycles of Observing the changing situation, Orienting to what is occurring, Deciding what action to take and Acting. Critical to successful decision making is understanding what is really happening. Integrating decision-support and the OODA Loop of specific decision-makers is a real challenge. How many decision-support systems can provide virtual real-time answers to a wide range of scenarios? Data gathering takes time as does analysis. Unfortunately, decision-support systems are often circumvented and decision-makers rely on their own sources of intelligence and advisers.

d. Executive decision-makers who are often intimidated by the complicated appearance of analytical methods fail to appreciate their value, mistrust them along with the 'witch doctors' in the organisation who advocate their use (Nutt 1989, 32-33).

e. There is a strong aversion by decision-makers to have their deeply ingrained assumptions, their mental models (Senge 1990), psychological constructs (Kelly 1956), schemata and sysreps (Kline 1995, 31), 'systems of meaning' (Flood 1999, 110-115) surfaced and critically analysed (Mason and Mitroff 1981). They are likely to be incomplete, flawed or immature in their development, when compared with the true nature of the detail complexity and dynamism faced or needing to be managed. Kline, 1995, explains that … 'precise representations of systems (sysreps) used for analysis arise only in human brains, as far as we know. These transformations of information into sysreps, and the recordation of the sysreps, carry with them the possibility for many kinds of imperfectly mirroring the systems concerned, including outright errors. This is the reason why such close attention needs to be paid to how we form sysreps, how we use them and how they are influenced by the limitations of the human mind.' (Kline 1995, 55).

f. Strategic decision-makers are also political players frequently more concerned about the impact particular decisions have on their careers in the short-term rather than seeking out underlying systemic structures and cycles, and using that knowledge to inform their decisions, strategies and policies.

g. The structure of organisations and business activities have the natural effect of shifting the management of complexity to lower organisational levels.

h. Information is compartmentalised within organisations. Compartments can be sealed by organisational hierarchies and politics. As a consequence, compartmentalisation militates against the best intentions of the designers of information systems and decision support systems alike.

i. 'Systems of knowledge - power', in which executive decision-makers are central players, militate against the sharing and flow of information (Flood 1999, 116-122). Davenport and Prusak, 1998, explain that … 'understanding that there are knowledge markets and that they operate similarly to other markets is essential to managing knowledge successfully in organisations. Many knowledge initiatives have been based on the Utopian assumption that knowledge moves without friction or motivating force, that people will share knowledge with no concern for what they may gain or lose by doing so … people rarely give away valuable possessions (including knowledge) without expecting something in return.' (Davenport and Prusak 1988, 26).

j. The ‘need to know’ principle also militates against sharing information. Decision-makers who are not granted the need to know are not only denied information but are denied opportunities to be involved in strategy development except in a controlled and limited sense.

k. Reward systems in organisations, particularly in the public sector, are rarely centred on rewarding the sharing of information for long term strategic gains, rather they reward performance measured against short-term political and profit-centric indicators. This suggests that the notion of a public sector learning organisation remains a fantasy.

Consequently, organisational learning, knowledge management, and decision-making practices are adversely affected. The imperative to build those skills needed to deal with complexity is continually displaced downward from the strategic decision-making level. Opportunities to develop skills or to involve new players in strategic decision-making activities are repeatedly and continually removed. This can even lead to groupthink: groupthink amongst the Joint Chiefs of Staff advising US President J.F. Kennedy almost precipitated war between US and USSR during the 'Bay of Pigs' incident in the 1960s (Silverstone 1993) (Argyris 1994). Consultancy practice needs to accommodate the factors that might produce this disjoint and inhibit appreciation of the true nature of complexity, that appreciation considered so important by Flood, 1999.

There can be other undesirable consequences. For example, strategic decision-makers who expect to deal with relative simplicity do not develop an appreciation of the inherent complexity of their organisations and problems with which they have to deal. When problems surface it is hardly surprising that executive decision-makers either argue about the nature of the problem or if, indeed, there is one (Vennix 1996, 12).

In the worst cases there can be a strong sense, or even a culture, of denial that problems exist despite strong evidence that serious problems exist, or are developing (Hopkins 1999). This was common to each of the case studies researched during the preparation of this paper, although the Moura Mine Disaster and the Esso Longford gas explosion and fire are particularly graphic examples.

Some decision-makers develop unrealistic expectations that their staff can keep problems at bay. Others fail to learn and fail to develop skill levels needed to deal with ‘messy’ problems. The result can be institutionalised incompetence. Coroner Madden slated many involved in the demolition project which led to the death of Katie Bender as incompetent.

Both anecdotal evidence and these case studies suggest some decision-makers deal with complexity by avoiding it, or by hiding behind the power of their position to ensure their ignorance is not revealed. In contrast to Bob Flood’s ‘systems of knowledge - power’, we might describe this cynically as ‘systems of position-ignorance’, a form of incompetence through aversion.

The consequence these observations have on the elicitation of the requirements for the design and development of strategic-level decision support systems is quite profound.

Human capacity to predict dynamic behaviour in limited in all but the simplest of systems (Sterman 1989a, b and c) (Kline 1996, 60-62). Paich and Sterman, 1993, showed that learning in situations of dynamic complexity is often poor. It seems there is nothing to suggest executive decision-makers are better at predicting behaviour of dynamic systems than anyone else. Indeed, given the comments above regarding the disjoint between strategic and lower levels in organisations, it is likely that others in the organisation who are more frequently exposed to complexity may well be better equipped to deal with it, if anybody is.

These case studies, observations from Australian Department of Defence case studies (not covered in this paper) and an extensive series of workshops involving public sector decision-makers, leads to the conclusions:

a. decision-makers at any level are only able to reliably solve problems of limited complexity;
b. executive decision-makers are unlikely to be the best equipped in the organisation to deal with complexity; and
c. decision-makers are likely to revert to relying on intuition and judgement unless there is powerful, timely, responsive, and trusted decision support available.

Sterman, 1994, and Morecroft and Sterman, 1994, argue a compelling case for learning and understanding complexity through modelling. This learning does not have to be derived from system dynamics modelling. What is important is that 'double loop' learning is experienced by those involved in decision-making and strategy development in the organisation (Argyris 1982) (Sterman 1994, 318).

Research by Wick and León, 1993, reveals that to achieve successful organisational learning demands strong leadership (Wick and León 1993, 127). CEOs and other executives must be prepared o commit time, resources, and effort to deliberate, planned learning. However, we have to be careful in assuming:

a. senior decision-makers are committed to learning, that is, they have the will to learn and to invest the time and resources necessary (Wick and León 1993, 79-92), and
b. system dynamics modelling is most appropriate for analysis for all problems.

Recent experience in Defence Preparedness Resource Modelling and case studies researched for this paper clearly indicates that a commitment to learning cannot be assumed.

The primary justification for building system dynamics models is to inform the revision of decision-makers' mental models and, in turn, inform the development of strategy in situations where we are otherwise unable to fully comprehend dynamic behaviour (Richardson and Pugh 1981, 17). This is agreed.

To enhance learning, understanding and to build better commitment to implementation of strategy, consultative practice is increasingly involving decision-makers in knowledge elicitation, problem conceptualisation, model building activities and strategy development activities. Group model building work of Vennix, 1996, and his team at Nijmegen, Netherlands is an excellent example of the approach.

Gaps in Understanding Remain

A major concern is that the fundamental nature of the problems found to exist in each of these case studies appears not to be well understood, either by managers or by those professing expertise in systems thinking or system dynamics. If we do not deeply appreciate the nature of the problems we profess to be able to solve, or the environments within which they exist, how can we expect to act as expert advisers.

It is not widely acknowledged that considerable experience is required before systems thinking and system dynamics practitioners, like any professionals, have the skills to recognise where and how to best apply their tools and techniques. In conjunction with applying our skills correctly, we should be further developing our consultancy methods to identifying and eliminating the disjoint described above.

Selecting the Best Problem Solving Approach

The veracity of qualitative system dynamics modelling is not questioned, per se. What is questioned is how we develop the pre-requisite skills and knowledge that leads to the selection and application of the most appropriate problem solving approaches.

For those of us with less extensive exposure to messy problems, deciding which tools and approaches to use is not so clear cut. Indeed, even amongst those who might purport to be highly experienced practitioners there are 'black spots' of misunderstanding of the true nature of messy problems such as described here.

Conclusions

This research involved many months of effort. At times it was painstakingly slow and tedious. Maps typically contained 200-300 concepts and a larger number of links. Dealing with this amount of detail is not recommended as part of the normal consultancy method. The Black Hawk Helicopter Crash case study presented here is one of the least detailed.

The research effort expended has been rewarded by insights otherwise only gained through years of systems thinking and system dynamics modelling experience.

There is still a good deal of work to be done before there is widespread acceptance of systems thinking and system dynamics modelling as legitimate and powerful techniques for addressing complex, dynamic problems. This has little to do with the techniques, rather it is highly dependent on the way we go about helping clients deal with strategy development. It is also due to the way decision-makers think and limited human ability to understand and conceptualise complex, dynamic problems.

There is strong evidence that managers and strategic decision-makers alike have underdeveloped appreciation of the nature of complexity with which they must deal. They also have low levels of skill when it comes to identifying systemic structures. To help overcome this we need to espouse the virtues of *weltanschauung* and educate decision makers in systems thinking and the significance of *systemicity* (Checkland and Scholes 1999)

Politics, systems of knowledge-power, compartmentalisation of information, incompetence, ignorance, resistance to having ingrained and potentially erroneous assumptions surfaced, mistrust of analytical methods, bounded rationality and defensive routines are all part of the organisational decision-making environment. This is a minefield with the potential to render the most rigorous analytical tools ineffective. We need to be able to detect the mines and disarm them before planting new crops in the fields of decision-making and strategy development.

Those executives involved in decision-making and strategy development are amongst the hardest working and most intelligent people we are likely to encounter. We need to capitalise on their motivation, dedication, industry, experience and ability to recognise patterns of behaviour in complex, dynamic systems.

There is little argument about the veracity of system dynamics modelling as a tool for addressing dynamic complexity. But where and how to apply this tool must be based on a deep appreciation of the nature of complexity, and how it is likely to affect organisational decision-making and strategy development. Once we have investigated in detail the nature of the problems at hand, it will become obvious, as demonstrated in this paper, where we should apply our system dynamics modelling efforts.

Our prime objective should be to use systems thinking and system dynamics modelling skills to enhance understanding and learning. This must be the highest priority. This is where the greatest gains are to be made.

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