DEVELOPING A CONCEPTUAL MODEL OF AIRLINE SAFETY IN NEW ZEALAND: A SYSTEMS THINKING APPROACH

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ABSTRACT

Airline safety tends to result from a combination of many different circumstances that include technical, human, environmental and organizational factors. By using the systems thinking tools of qualitative system dynamics, this paper develops a conceptual causal loop diagram that connects possible influential factors on airline safety. This theoretical investigation constitutes a sound basis for the development of cause-effect relationships associated with accident and incident analysis in the air transport industry. Our findings suggest that causal loop modelling is a very useful tool for producing a comprehensive model of airline safety management that takes into account the multi-dimensional and complex nature of air safety mechanisms. It is hoped that the airline industry, and particularly air safety managers, will become more aware of the importance of this kind of modelling to improve their airline safety management systems.

Keywords: airline safety, system risk factors, air transport accidents, systems thinking, causal loop diagram, qualitative system dynamics

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1. INTRODUCTION

Aviation is nowadays one of the critical modes of transportation. Air traffic has doubled every 15 years in the past, and is expected to continue to grow at an average annual growth rate of 4.9% over the period 2013-2032 (Airbus, 2013). Commercial air transport development is driven by several factors. Some are economic, such as transport costs, global economic growth. Others are linked to social, technological, demographic, environmental and political drivers. As the global air transport traffic volume is expected to continue to rise, and the probability that this will bring with it an increase in the number of accidents, developing a qualitative system dynamics model that conceptualises the complex interactions of causes of air transport accidents could be of interest to managers in the airline industry.

In this paper we present a preliminary analysis of what is thought to be the key factors that exert an influence upon airline safety mechanisms using the systems thinking tools of qualitative system dynamics (e.g. see Forrester (1961), Richardson & Pugh (1981), Senge (1990), Coyle (1996), Sterman (2000) or Maani & Cavana (2007)). The purpose of this systems approach is to create new ways of examining the complex interactions of causes of air transport accidents and to help in their prevention.

The remainder of this paper is outlined as follows. In the next section we provide a brief overview of the current literature on the various system risk factors that could cause air transport accidents. This is followed by a brief overview of the commercial aviation scene in New Zealand, as this provides an illustration of recent historical experience of trends in air transport activities. We then commence developing a conceptual model of airline safety, by adapting relevant aspects of Cooke's (2003) coal mine safety model, Salge and Milling's (2004) airline commercial model and Moizer's (1999) generic occupational safety model. In the rest of this paper, we develop the causal loop diagram (CLD) model for airline safety. This involves developing the causal connections, respectively, in the business operations, safety, and human resources subsystems. These subsystem diagrams are then combined to create a holistic causal loop diagram for airline safety, and a number of important feedback loops are discussed. Finally some concluding comments are provided.

2. LITERATURE REVIEW

Safety is a critical area for airline management. It is not only an obligation for airlines to maintain high safety records, but safety also influences their profitability through brand image and social credibility. Today, airlines are required by law to implement a safety management system for their flight operation as described by the International Civil Aviation Organization (ICAO) document, Safety Management Manual (ICAO, 2013). As part of the safety management system, each airline is required to commit itself to a so-called acceptable level of safety performance (ALoSP). Aviation safety is a complex process, which depends on many interrelated contributing factors; including financial, human, technical and organizational factors. Attempts have been made in the literature to assess aviation safety risks. Nevertheless, much of the research is still partial and unsystematic and there is shortage of analytical frameworks for analysing and interpreting the complex interactions of the various subsystem risk factors.

Scholars such as Borenstein and Zimmerman (1988), Chalk (1987), Rose (1992), Noronha and Singal (2004) and Raghavan and Rhoades (2005) explored the relationship between the financial situation of carriers and airline safety. They examined whether the safety record of airlines is related to their financial health. Not all the studies come to the same conclusion, but they generally favour the notion that there is no convincing evidence of a safety-profitability link.

For instance, Rose (1992) found that for small and mid-sized airlines, a 5 percentage point increase in the operating margin implies about a 5% reduction in the total accident rate. The same profit increase also correlates with more than a 15% reduction in the fatal accident rate. The author argues that more profitable airlines have greater resources to, and actually do, invest more money in safety. Such a link is not apparent in large airlines. Rose (1992) claimed that several factors could make less variable the levels of safety investment of large firms. These airlines have probably greater ability to finance safety programmes, even whilst financially troubled. Other research has been carried out to find the relationship between deregulation and safety performance since the deregulation of airline industry. For instance, Raghavan and Rhoades (2005) examined the relationship between financial performance and air transport safety since the deregulation of the US airline industry in 1978. Using accident rates as a measure of safety, their study shows that total accidents and accident rates, when normalized over departures, have increased over the period 1978-2002, indicating the potential dominance of industry growth over air carrier safety improvements. This study is not without limitations since it relies on limited post-deregulation data. After deregulation occurred in 1978, the US airline industry has experienced several phases of expansion and retrenchment, with significant effects on industry structure, average airfares, patterns of service and profitability. Nevertheless, most scholars agree that it has been a success, particularly in lowering airfares, providing more flights, enhancing airline efficiency, while maintaining a good safety record (Goetz and Vowles, 2009; Papatheodorou and Platis, 2007).

Aviation insurance might have also played an important risk management tool since the deregulation of the industry. Aviation risks are very complex and costly and are usually shared by several insurers with a specific aviation insurance market. Each insurer is accountable for that part of the risk that it agrees to cover. By insuring their fleet, airlines transfer the cost of their potentially daily operating risks. Although insurance does not eliminate the risk of accident, it does assist the airlines avoid the financial difficulty occasioned by airline accidents (Lane, 2005).Consequently, airlines become free to minimize their safety investment given that their risks are transferred to the insurance companies.

Other authors, such as Rhoades and Waguespack (2000) looked at the relationship between service quality and safety quality in US national and regional airlines over the period 1991-1997. Their findings suggest that for four of these seven years, service quality and safety quality were positively correlated, indicating that service quality is a good indicator of overall safety quality.

The influence of different kinds of flight operations on air crews' fatigue has also been identified as one of the factors that could cause commercial aviation accidents. Yen et al (2005) conducted an econometric study to identity the key factors affecting flight fatigue factors faced by air crews. The paper looked at responses from crew members of six Taiwanese air carriers who reported on their levels of fatigue before take-off and after landing. With their survey data, Yen et al (2005) used ordinal probit models to estimate three models for different flight operations – domestic, regional and long-haul. These serve as vehicles to investigate flight fatigue factors and identify their relative significance. The factors for long haul flights (with flight times exceeding 6 hours) are found to be problems with sleep-loss and circadian rhythm disruption. Sleep quality both at home and on board the aircraft has also been recognized as a significant factor affecting the fatigue level of long-haul crews. Air crews serving short haul flights (with flight times of less than 2 hours) tend to suffer from fatigue due to early departures, late finishes, and intensive take-off and landing procedures that are workload demanding. The age of the pilots and the relatively poor cockpit environment are among the most significant negative fatigue factors. For regional flights (between 2 and 6 hours) the factors that cause fatigue tend to vary with the individual. For example, age, extra non-flying tasks on the ground, and experiences of fatigue during flight operations seem to be significant factors.

Maintenance quality is also a key contributing factor of airline safety. Rhoades et al (2005) argue that airline deregulation could tempt financially troubled carriers to lower line maintenance spending. This would lead to lowering maintenance quality and decreasing the overall safety of the carrier. This paper examines the quality of airline line maintenance activity and examines the impact of maintenance spending on maintenance quality and overall safety. Rhoades et al (2005) correlated the maintenance spending of 10 major airlines in the US with their "incident" reporting rates. The results show only a modest level of correlation. Curiously the authors appear not to have tried lagging the maintenance spend and the rates of incident reporting. One would have expected a lagged effect taking place. Nevertheless, this contribution is interesting for two reasons. First, it gives a very detailed account of how airlines schedule their fleet maintenance. Second, the paper explicitly says where future research should head towards: the influence of the fleet mix and the age of the aircraft on maintenance spending, the effect of aircraft utilization and maintenance training, and extend the study to national and regional carriers.

McDonald et al (2000) investigated four aircraft maintenance firms to examine how each organisation manages safety. The emphasis was on the human and organisational aspects. Their investigation shows that, as a group, aircraft technicians have a strong culture of professionalism. However, the authors detected differences in safety attitudes between other occupational groups. The authors suggested that these differences are related to the organisational structure of these companies.

Taking into account the complexity of measuring safety management in the aviation sector, Gill and Shergill (2004) conducted a study to assess employees' perceptions of safety management and safety culture in the aviation sector in New Zealand. The findings show that aircraft maintenance engineers seem to be committed to standards and operating procedures and effective organizational processes in making the maintenance system work. Furthermore, the findings suggest that pilots perceive luck to be a significant contributing factor in safety. Another interesting finding from this study is that employers are not perceived to be giving much importance to safety management systems, and safety culture in the aviation industry. As a consequence, the complex and dynamic environment of this industry requires that aviation regulators, airlines and service providers cooperate to maintain a safe air transport system.

Van Fenema (2002) pointed out another contributing factor likely to have influenced the safety outcome was the nature of ownership. The author believes that state ownership of the national airline is justified because of the lack of certainty that the new owner would abide by existing safety standards. Such views are probably changing, as evidenced by ICAO's statistics on the gradual decline of state ownership. Chang et al (2004) asserted that the primary global concern today is safety. And that, irrespective of who owns the airline, governments and the public will continue to insist on appropriate airline safety standards.

While the above studies provide key feedback mechanisms that help to understand the causes of aviation accident across the world, there is still a lack of an analytical framework that allows those responsible for regulation and safety management to understand the multi-dimensional context of air safety mechanisms. The causal loop modelling framework that we are suggesting in this paper combines many of the contributing factors that we discussed above. The next section briefly outlines the commercial airline safety situation in New Zealand, as the context for developing the conceptual airline safety model.

3. THE NEW ZEALAND COMMERCIAL AVIATION SAFETY SCENE

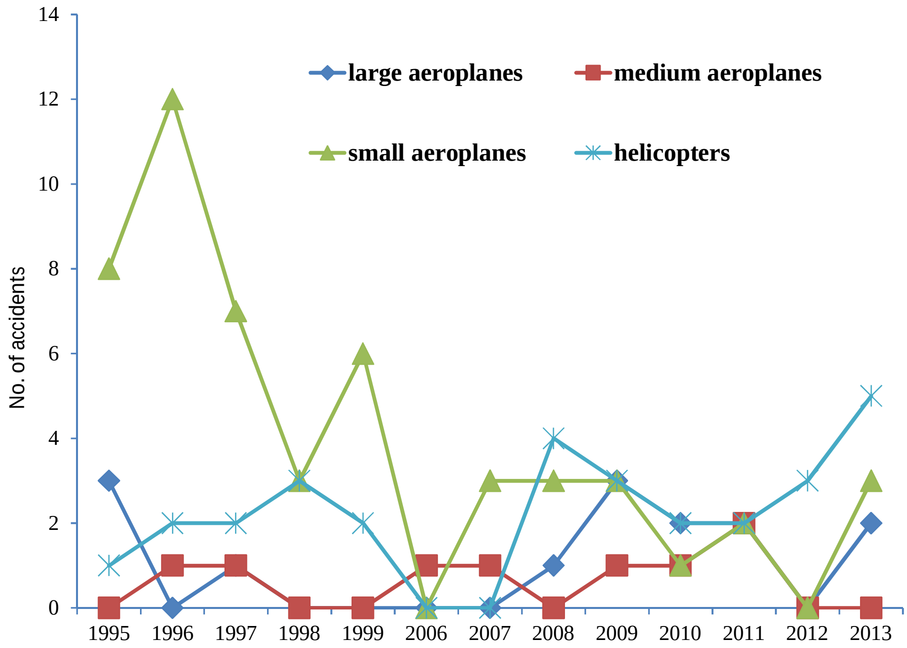
As at 17 November 2012, the New Zealand safety regulator, the Civil Aviation Authority (CAA) had 1982 fixed wing and 792 helicopters on its registry (CAA, 2012a). There were 180 organisations licensed to carry fee-paying passengers or freight, called Part 119 operators. There were also 30 "adventure aviation operators" and 102 agricultural aircraft operators.

Many of the 180 "Air Operators" probably do not perform many passenger carrying flights. For the calendar year 2004, four operators only flew one such flight. At the other end of the scale, three operators each flew over 50,000 passenger flights each.

The CAA keeps counts of two measures that are directly safety-related. The first is a count of accidents. These are aircraft-related occurrences where the aircraft was damaged, gone missing or humans were seriously injured. The second is a count of 'incidents'. These are occurrences where safety was, or could have been, affected.

The reporting of both accidents and incidents is mandatory in New Zealand. The definition of accidents is very clear, so there is little leeway for not reporting an accident. However, the definition of an incident is relatively loose and open to interpretation. It is possible that the database does not capture the vast majority of incidents. Figure 1 shows the number of commercial flight accidents between 1995 and 2013 (Large aeroplanes greater than 13,608 kg; medium aeroplanes between 5,670 and 13,608 kg; small aeroplanes less than 5,670 kg).

Figure 1: New Zealand commercial flight accidents, 1995-2013

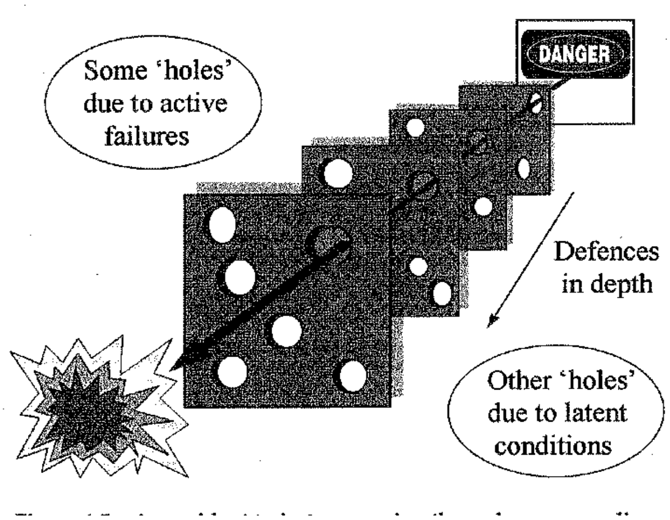


Source: From New Zealand CAA website, 21 Aug 2014

4. DEVELOPING A CONCEPTUAL MODEL OF AIRLINE SAFETY

At an organisational level, safety is a dynamic issue with a tension between profitability and safety. The temptation to increase profitability by reducing spending on safety is an avenue many firms have taken. Such reductions could, though not always, lead to accidents and crashes. Reason (1997) illustrates the problem with his famous "Swiss cheese" model of organisational safety. See Figure 2 below. According to Reason (1997), an incident or accident happens when various 'holes' in the defence barrier line-up. If any of the holes were smaller, or the organisation re-oriented, the accident may have been prevented.

Figure 2: Reason's "Swiss Cheese Model" of Accidents



Source: Reason, 1997, Fig 1.5, p12

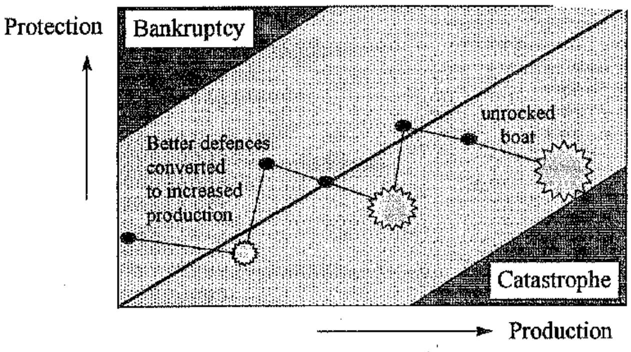
In the aviation context, each slice might represent a different component of the aviation matrix: the airplane manufacturer, the airline, pilots and their training, air traffic control and so on. Each acts in a defensive way to prevent incidents, yet each of these have vulnerabilities where things can go wrong.

Equally, the diagrammatic gaps could be gaps created, knowingly or inadvertently, during maintenance when something is incorrectly performed. Or they could be gaps created by the deliberate disabling of an engineered safety system feature. Or it could be the violation of a safety operating procedure.

Reason (1997) pointedly says that his Swiss cheese model is supposed to represent a dynamic system. Thus the protection and the gaps are never static. Gaps appear when a procedure is mistakenly stopped, disappear when it is reinstated and then appear again when it is 'cut' by order. They could also shrink then expand. They can also represent spatial differences with the holes moving around a layer.

Being a dynamic system, one could try to visualise the 'Swiss cheese' model as a time-series graph, such as Figure 1 above. Reason (1997) presents the graph as a way of illustrating how 'real' companies tend to bounce between levels of safety and commercial aggression. This is shown in Figure 3 below.

Figure 3: How 'catastrophes' occur in companies



Source: Reason, 1997, Fig 1.3, p5

On the vertical axis is increasing safety. On the horizontal axis is increasing production or profit. For all firms including airlines, it is not tenable to be in:

- the top left hand corner (total safety, zero profit – outcome bankruptcy!) or
- the bottom right hand corner (total profit, zero safety – outcome major airline accidents).

Time is represented as the line within the graph i.e. starting at the left 'dot' and ending at the 'explosion'. All airlines will start somewhere near the bottom left hand corner and strive to reach perfection – total profit and total safety. But perfection is usually unreachable, so they 'meander' in some zone in between. The trick is to try to avoid both the 'catastrophe' and 'bankruptcy' zones shown. Although they are portrayed as 'corners', in reality the 'safe' zone outside these danger areas is a band along the diagonal. It is up to an airline's management system to steer the company within this diagonal band.

Although there are a number of published studies dealing with causal models of airline safety (eg see Ale et al (2006, 2009a & b), Chen & Chen (2012), Hsu et al (2010), Roelen et al (2011), and Leveson (2011)), we still believe that there is room for further systems thinking related studies of airline safety. In fact Leveson (2011, p63) reaches the following conclusion:

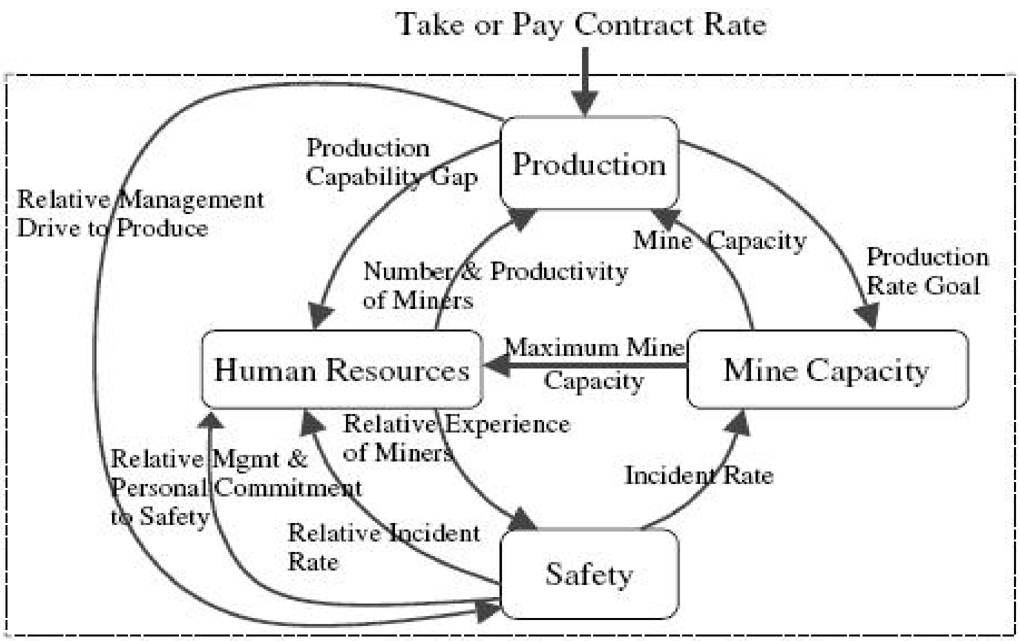
"An argument has been presented that sophisticated models of causality (not more notations for the basic chain-of-events model) based on systems thinking and systems theory presents an opportunity to perform more powerful accident analysis and hence learning from events."

Hence, in this paper, we focus on developing a conceptual 'systems thinking' model of airline safety based on the causal loop diagramming tools of qualitative system dynamics.

4.1 Overview of the Conceptual Model

There have been a numerous papers where system dynamic techniques have been used to consider organisational safety eg Marais et al (2006). However, none of these specifically address the field of airline safety. As there are very limited system dynamics publications involving airline safety, we looked to models involving safety in other fields as examples. Cooke (2003) published a system dynamics coal mine safety model which was based on Sterman's (2000) inventory control and order fulfilment archetype. Cooke's (2003) framework has 4 distinct sub-systems –Human Resources, Production, Mine Capacity, and Safety (see Figure 4). We used this framework as our primary source when building our model. The other main models we used as a source of ideas and inspiration were the ones elaborated by Salge and Milling (2004) and Moizer (1999).

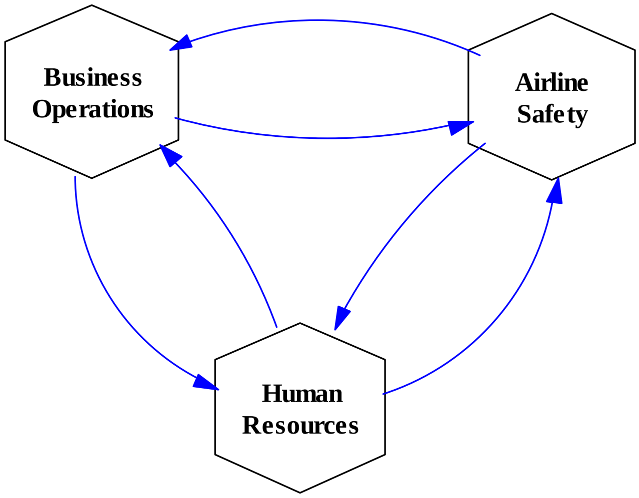
Figure 4: Subsystems of the Westray Mine Safety Model



Source: Cooke, 2003, Fig. 1, p144

We combined the Production and Mine Capacity sub-systems of Cooke's model into a 'Business Operations' sub-system. This would be the part of the model that simulates the commercial operations side of an airline or air operator. The modified subsystem view of the model is shown in Figure 5. We will now build up the causal connections in each subsystem separately: Business operations, human resources and airline safety.

Figure 5: Overview of the Airline Safety model



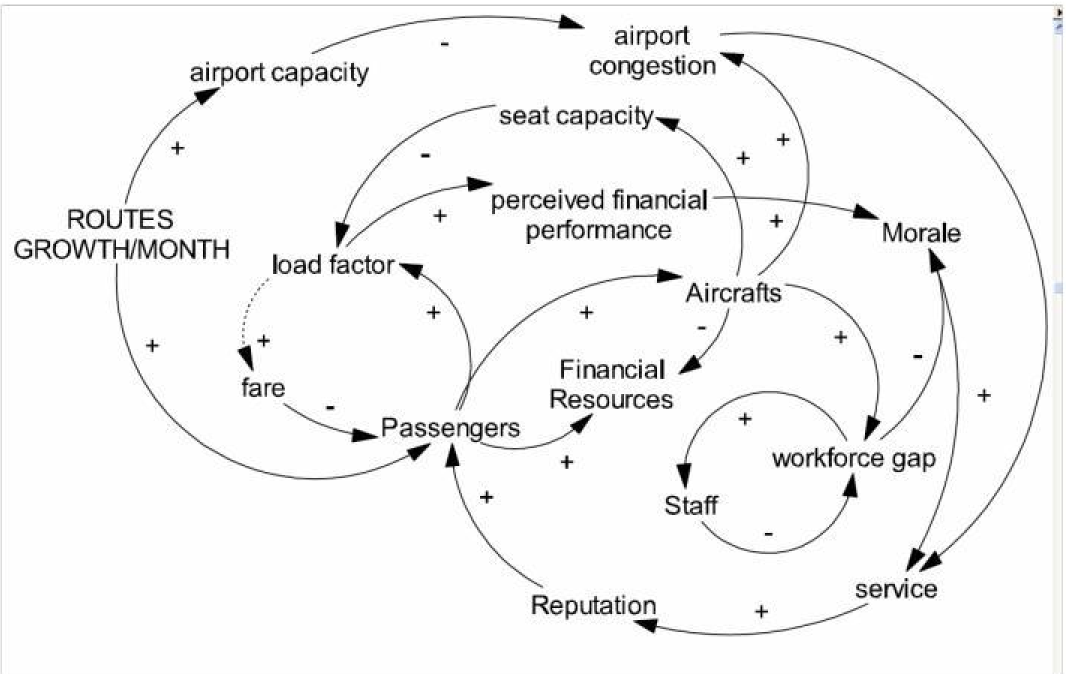
4.2 Causal Connections in the Business Operations subsystem

We began constructing the causal loop diagram (CLD) by starting at the Business Operations subsystem. The causal loop diagram of Salge and Milling's (2004) model of airline business, in Figure 6, has been a good starting point in building our CLD. The connections between the variables are reflected by an arrow with a positive (+) or negative (-) sign. A '+' sign indicates that an increase in a variable at the base of an arrow adds to or changes a variable at the head of the arrow in the same direction. Conversely a '-' sign indicates that the variable at the base of the link causes a reduction in the variable at the head of an arrow or a change in the opposite direction (Sterman, 2000; Maani & Cavana, 2007).

Starting with 'aircrafts', Salge and Milling (2004) show 'aircrafts' affecting 'financial resources'. We retain that idea but introduce 'maintenance expenditure' to highlight how aircraft influence an airline's cash balance (ie their 'financial resources'). Similarly in Figure 6, Salge and Milling (2004) include 'passengers' affecting 'financial resources'. Again we introduce an intermediate variable of 'revenue' as a clarification to increase 'airline cash balance'. We also change 'passengers' to 'customers' to emphasise the business relationship.

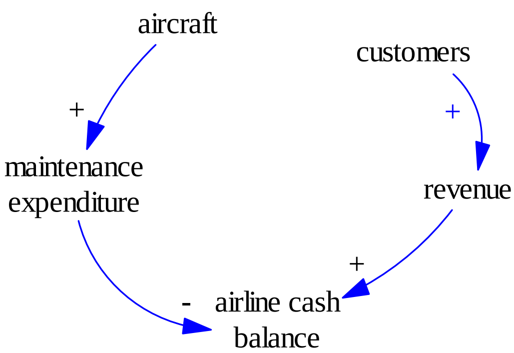
Figure 7 shows these connections, which form the basis of the business operations subsystem.

Figure 6: Salge and Milling's airline operations causal loop diagram



Source: Salge & Milling, 2004, Fig 3, p7

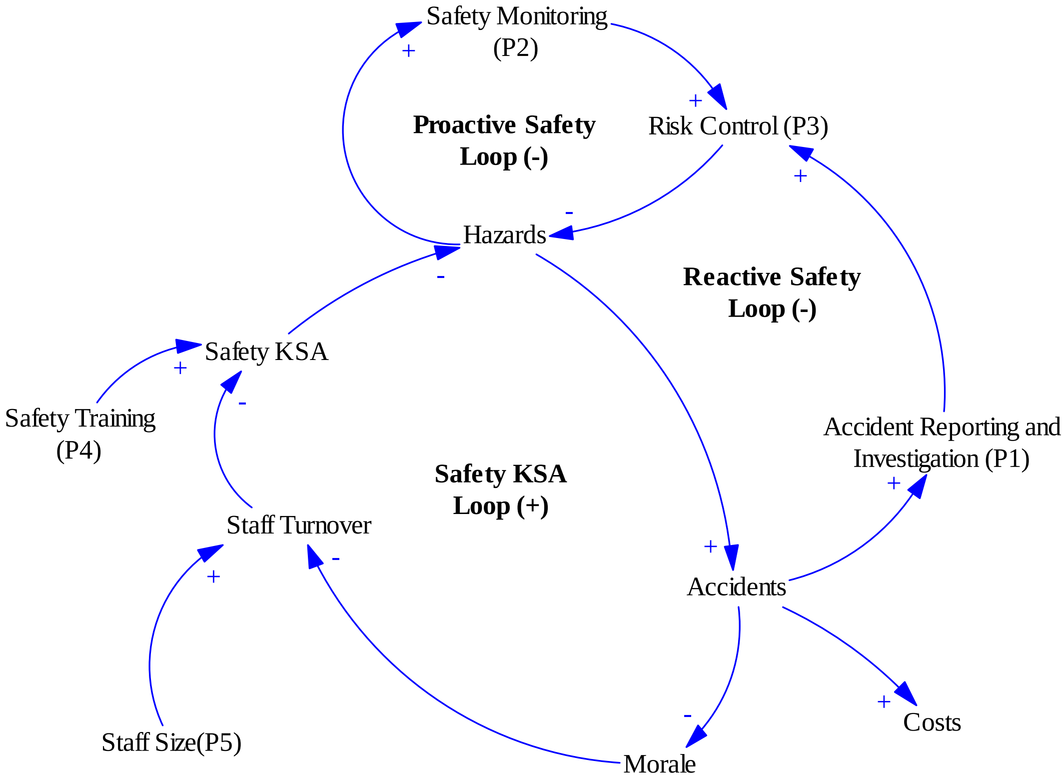
Figure 7: Initial causal connections in Business Operations subsystem



4.3 Causal Connections in the Safety Subsystem

We began by adapting Moizer's (1999) model into an airline safety model (see Figure 8). Moizer (1999) makes a positive connection between 'accidents' and 'costs'. Direct cost of a crash is mostly covered by insurance, according to Reason (1997) and Rose (1992). So we introduced 'insurance' as an intermediate step (in Figure 9).

Figure 8: Mozier's Safety causal loop diagram



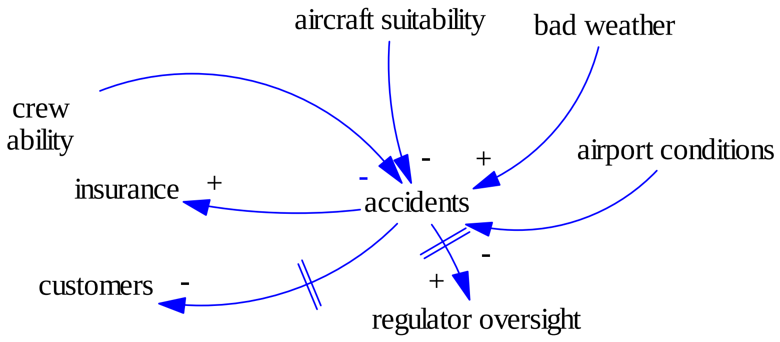
Source: Moizer, 1999, Fig 5.3, p128

Accidents could alter client demand for that airline. Salge and Milling's (2004) model shows that 'service' affects 'reputation' which then affects 'passengers' (see Figure 6). For a safety model, accidents affect 'reputation' which then affects 'customers'. This was confirmed by the research of Castillo-Manzano et al (2012). They demonstrated that an airline involved in a major crash which killed 154 persons sustained a statistically significant reduction in custom after the crash.

What affects 'accidents'? Chen et al (2009) surveyed experts who would prioritize 78 percent of safety resources to their top 2 'causes' of flight crew and maintenance staff errors. Rhoades et al (2005) conjectured that fleet mix, fleet age, aircraft utilisation and maintenance training could have an effect on safety. We used the terms 'aircraft suitability' and 'crew ability' to cover these factors. Phillips and Talley (1992) also include aircraft and crew characteristics and introduce weather and airport conditions, which we also include in Figure 9.

None of the cited articles specifically mentions the role of the safety regulator. However it is obvious that a greater number of accidents would lead to more oversight activity by the regulator. We thus incorporate a positive connection between 'accidents' and 'regulator oversight' after a significant delay (indicated by the parallel lines on the link). Figure 9 shows the connections discussed in the safety sub-system.

Figure 9: Initial causal connections in the Safety subsystem

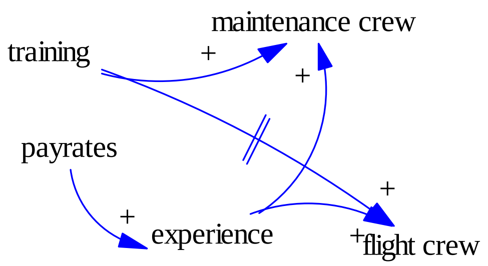


4.4 Causal Connections in the Human Resources Subsystem

Crew characteristics (flight crew and maintenance) of relevance to safety are the experience and the training of the personnel. Training can be provided by the company itself. Experience can only be 'procured' by employing experienced pilots, or retaining pilots long enough to gain sufficient experience. In both cases, pay rates are a major factor in the retention and recruitment of experienced staff (Cavana, et al., 2007).

Wilson (1997) noted that the US regulator was concerned about Valujet's pay rates. Rhoades and Waguespack (2000) go further and directly associate the lower pay of regional carriers compared to major airlines as a reason for the worse safety record of regional carriers. This is shown in Figure 10.

Figure 10: Initial connections in the Human Resources subsystem

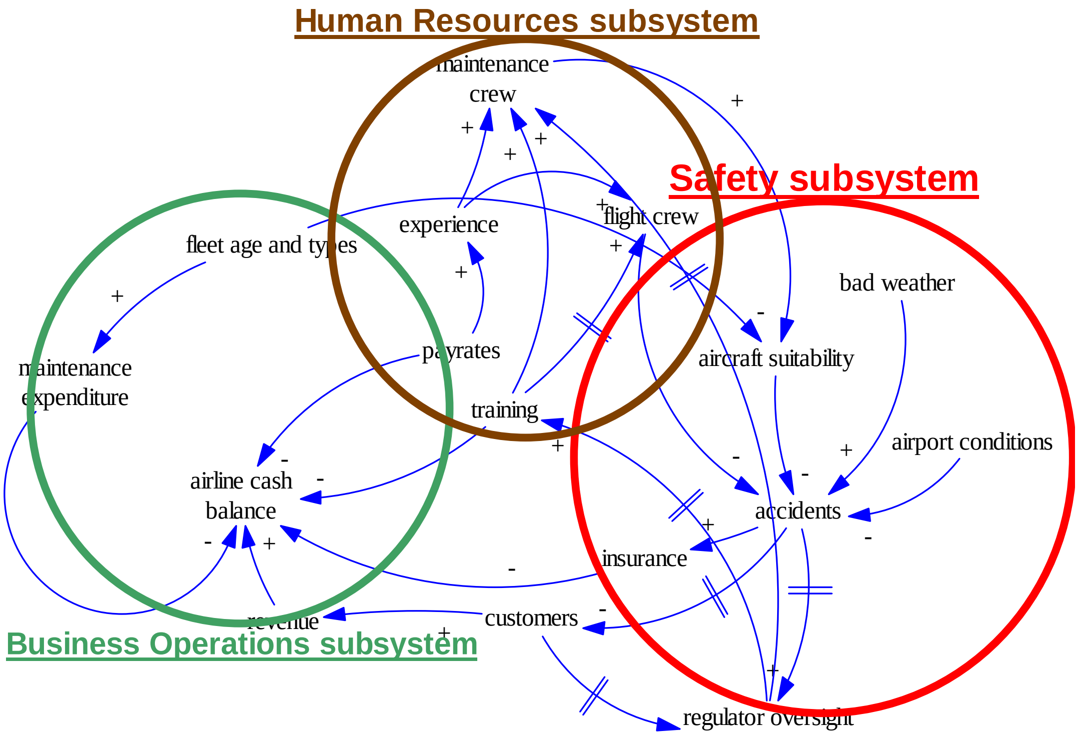


4.5 Connecting the Subsystems in the Airline Safety CLD

The three subsystems are connected via the common variables, as shown in Figure

11. The three overlapping circles reflect the interactions between the separate subsystems of business operations, human resources and airline safety.

Figure 11: Connecting the Business Operations, Safety and Human Resource Subsystems



Other connections are now made in Figure 11:

'Insurance', 'pay rates' and 'training' are connected to the 'airline cash balance' variable. The age of the airline fleet and the number of different aircraft types would have an effect on the cost of maintenance – see Rhoades et al (2005) and Easdown and Wilms (2002).

The Regulator Oversight must extend to the functions that the CAA (2012b) has authority over. This would include the maintenance performed on aircraft and the provision of training. Maintenance – as carried out by the maintenance crew – would affect the condition of the aircraft for flying. This, in turn, would affect how and if accidents occurred.

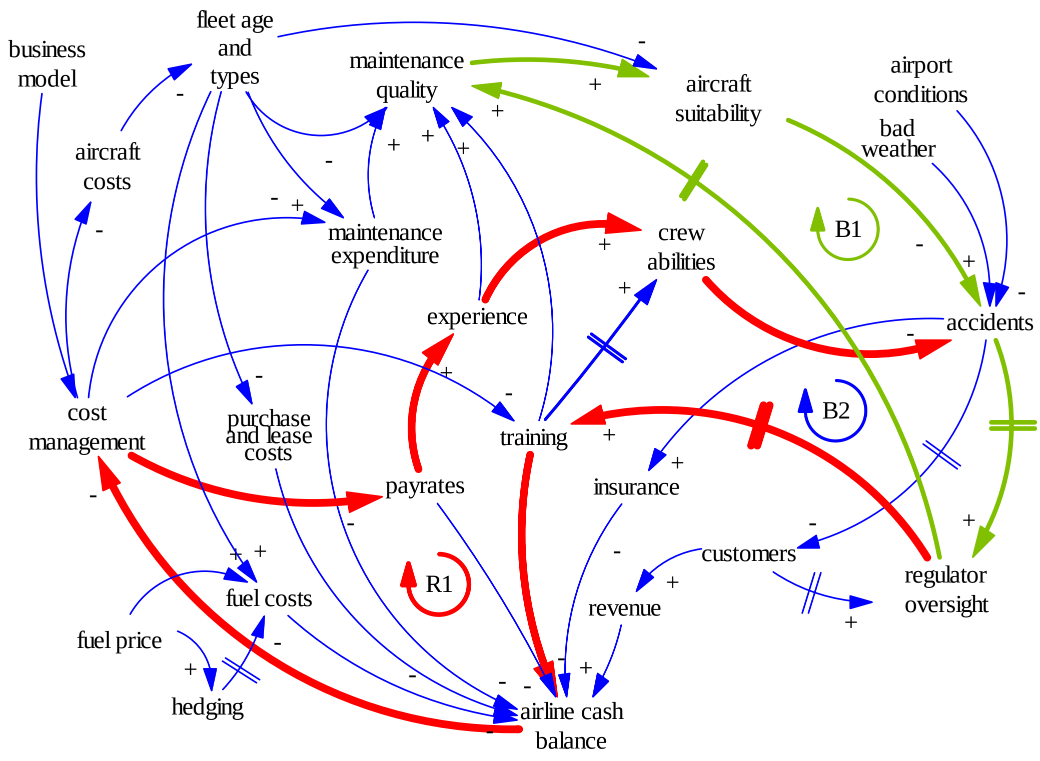
The commercial aspect of the model is incomplete. There must be a feedback loop between the 'airline cash balance' and the various expenditure items – maintenance, training, and pay rates. The capital costs of aircraft procurement or leasing must also be added.

The CAA gets the bulk of its income for aviation safety from levies of airline customers (CAA, 2012b). This is reflected by a delayed connection between 'customers' and 'safety regulator'.

5. FEEDBACK LOOPS IN THE AIRLINE SAFETY CLD

Figure 12 shows the final CLD which contains 40 loops. Three such loops are highlighted. The one coloured green shows a balancing loop (B1) which involves 'accidents' and 'regulator oversight' (ie maintenance quality loop). The one coloured red identifies a reinforcing loop (R1) that involves these 2 variables plus 'training' and 'pay rates' (ie the training cost implications loop). A second balancing loop (B2) operates to reduce accidents after a delay by additional training for airline staff (staff training loop).

Figure 12: Preliminary Airline Safety CLD with Feedback Loops highlighted



In the balancing loop (B1), an increase in accidents leads, after a delay, to an increase in regulator oversight activity. This subsequently results in an increase in maintenance quality and aircraft suitability, which thereby decreasing the future accident rate.

The reinforcing loop (R1) is more elaborate. As in loop B1 above, an increase in accidents leads to an increase in regulator oversight activity. This also leads to an increase in training, which decreases airline cash balances, thus putting additional strain on the airline's cost management. Often the response to this situation is a decrease in pay rates, leading to decreases in the experience of retained and recruited staff, further decreasing crew ability and subsequently leading to an increase in accidents. This reinforcing loop fits the findings of Banks et al (2012) who found that cost pressures led to crew overwork which could reduce safety margins.

Although another balancing loop (B2) evident in this diagram does result in a reduction in accidents due to the additional training airline staff receive, there is evidence of a 'Fix that Fails' systems archetype (Senge, 1990) operating here. This balancing loop would be offset by the adverse effects of reinforcing loop R1, unless other measures are put in place to prevent these adverse unintended consequences occurring.

One policy implication of the loops shown is that there is no "one size fits all" solution. In some situations, extra vigilance by the regulator could have an effect that ultimately reduces accidents. But given a different airline business operating model, it could have the adverse effect of potentially reducing safety.

Thus the response by the regulator must be tailored to the situation. Furthermore the regulator must monitor the situation carefully to ensure any action has the desired effect.

6. CONCLUDING COMMENTS

This paper shows how the causal loop modelling tools of system dynamics can be used to develop a conceptual model of airline safety involving the subsystems of human resources, business operations and airline safety. A preliminary causal loop diagram is developed linking the variables within these subsystems and a number of feedback loops have been identified. However, the preliminary CLD outlined in this paper can be developed in the following ways:

- A more comprehensive literature from the airline safety literature can be included to provide additional links and variables to enable the development of a more comprehensive conceptual model of airline safety.
- Group model building workshops (Vennix, 1996; Andersen et al 1997) can be

undertaken to provide empirical data for the formulation of a conceptual model of airline safety. This can also be combined with the current preliminary conceptual model, and an enhanced CLD can be developed.

- The preliminary model or an enhanced conceptual model can be further developed into a computer simulation model (using system dynamics methods) for policy analysis and scenario testing for airline safety managers or air transport regulators.

Finally, we consider that the preliminary conceptual model developed in this paper does go some way towards developing a theory of airline safety using system dynamics methods as outlined in the 'theory building' special issue of *Systems Research & Behavioral Science* edited by Lane & Schwaninger (2008).

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