Leading indicators applied to maintenance in the framework of resilience engineering: A conceptual approach

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Abstract. This paper explores the identification of leading indicators in aviation maintenance. Traditionally, improvements in aviation have been based on incident reporting and analyses and learning from failures. This traditional approach measures safety performance based on lagging indicators. However, there is a growing concern that this information does not provide the requisite information and insight to prevent future accidents. Resilience has been identified as the ability of the system to adjust prior, during and after a major mishap. This implies a need to recognize early signals to be able to anticipate and act properly.

The objective of the paper is to understand leading indicators and the "why" behind the leading indicator as basis to look forward in monitoring safety performance. With regard to the leading indicator definition applied to aviation and maintenance in the context of resilience, we focus on learning from success and failures and propose: Leading indicators are precursors based on a model of safety implying a significant possibility of a subsequent event that has an impact on safety and performance. Leading indicators can therefore provide information about changes in risk before traditional risk analyses are able to capture this change.

1 INTRODUCTION

Measuring safety performance is traditionally based on lagging indicators such as the accident rates. However, there is a growing concern that this information does not provide the required insight for the prevention of future accidents. This paper explores the identification of leading indicators that are of relevance for aviation maintenance. The focus is to understand leading indicators in the framework of resilience engineering (RE) and the "why" behind indicators as basis to look forward in the monitoring of safety. The RE framework emphasises aspects that are difficult to capture in traditional risk analyses. Hence, we discuss indicators that are hard to link to the risk analyses.

Research has shown that risk can exist in a system either because of components in the system or risky interaction between components (Perrow, 1984). There are several examples where maintenance activities were relevant to major accidents and extensive losses. These include the DC9 accident over Florida (1996), the Alaska Airline accident in 2000 and most recently, the Texas BP refinery explosion in USA (Baker, 2007). In many settings, the likelihood of an accident is low and preventing accidents requires continuous vigilance. The absence of an accident is not necessarily an indication that everything is going well (Van Steen, 1996). Organizations tend to attend to what is being measured rather to what is not (Hopkins, 2000). In the Longford accident the focus on Loss of Time Injuries (LTI) allowed the management to become complacent about the management of major hazards. The problem as Hopkins (2008) pointed out is that BP relied on lagging personnel indicators as a measure of performance of the process.

The paper starts with a description of the context of a maintenance organization. Then, a focused review of new approaches in the development of leading indicators is presented and discussed in the context of RE and maintenance. Finally, conclusions are presented regarding leading indicators, their characteristics and resilience approach to the identification of indicators in the maintenance management.

2 CHALLENGES AND OPPORTUNITIES IN MAINTENANCE

Maintenance is seen as a set of activities ensuring that the system continuously performs its intended function at its design level of reliability, performance and safety. Aviation maintenance comprises high technology and a group of interactive people concerned with safety and efficiency. The particular situation in aviation maintenance is that it depends on few aircraft manufacturers, prescriptive regulations influencing maintenance in order to follow specific requirements. The industry works together and provides feedback at all levels to improve continuous and safe operation. Recently, the International Civil Aviation Organization recommended establishing an effective Safety Management System (SMS). However, despite the benefit of an SMS, in general the aviation industry is still focused on reactive part of safety management. Learning is mainly based on failures recorded in the system and is a reactive approach to maintenance improvements. These measures are based on after-the-event information providing information of the past status of the system and they provide little information of the current state of performance for day to day decision making (Wreathall, 2006).

We need to analyse failures and successes and how they might be identified. In the case of successes, the literature provides little theoretical guidance. High Reliability Organizations (HRO) theory provides some examples of successes. The observations in the HRO theory imply two components, the high reliability of the organizations and individual excellence (Reason, 2003). The mindset in HRO expects surprises and has the flexibility to cope with them (Weick and Sutcliffe, 2007). Recently, RE has been defined by Hollnagel (2006) as “the ability of the system to adjust its functioning prior to or following changes and disturbances, so it can sustain operations in presence of continuous stress”. This ability is particularly interesting in a maintenance organization as RE implies that the organization is able to respond to threats and opportunities, to monitor risks and to anticipate potential disruptions in order to continue safe operations.

The challenges in aviation maintenance include some specific trends regarding the increase of subcontracting, maintenance activities spread over multiple locations, variation in task complexities, introduction of new technologies, decrease in available competence, reduction of available resources and time. The opportunities could include aircraft sensors providing continuous monitoring of aircraft systems, the trend towards openness, structured and detail planned maintenance at in the short and long periods, a dedicated group that follow current aircraft fleet status and operational advantages from early recognition and action with regard to maintenance problems enhancing market recognition for a proactive approach.

3 SEARCHING FOR LEADING INDICATORS

We looked into previous research on leading indicators to understand how they might be identified in the management of maintenance.

3.1 Different concepts

The objective of performance measures is to provide management required information for decision making. The function of a safety performance measure is to reveal the level of safety effectiveness in the organization with respect to the accident control desired (Kjellen, 2000). A safety indicator is an observable characteristic of an operational unit, presumed to bear a positive correlation with the safety of the system (Adapted from Holmberg, 1994).

Different definitions of leading indicators were found: *i)* Type of accident precursors, conditions, events or measures that precede an undesirable event and have some value in predicting the arrival of an event (Construction Owners Association of Alberta, 2004); *ii)* A form of active monitoring focused on few control systems (HSE, 2006); *iii)* “Activity” indicators that show if the organization is taking actions believed to lower risk (OECD, 2003); *iv)* Indicators that measure variables that are believed to be indicators or precursors of safety performance so that safety outcome is achieved (Baker, 2007). In contrast lagging indicators are measurements of a system that are taken after events, which measures outcomes and occurrences.

3.2 The ideal characteristics of indicators

Previous work on indicators reveals the key characteristics. None of the documents reviewed discussed the reasons behind the selection of the characteristics. As a general conclusion the following characteristics seem to be repeated across the literature: objective measure, easy to understand, indicate improvement or deterioration and collected from existing data (Kjellen 2000; Wreathall, 2006). Other characteristics that could be considered are diverse and complementary, interpreted by different groups in the same way, owned by the group whose performance is measured (Sefton, 1997). Specific, Measurable, Achievable, Relevant and Timed (SMART) characteristics are also mentioned for leading indicators including reasons behind indicators and benefit easy to understand, provide information that guide future actions, related to activities that are important for future performance, reinforce willing to intervention and provide clear indication of a means to improve performance (Blackmore, 1997). There is not a single measure that will meet all the characteristics. A combination of measures can provide a reasonable compromise (Kjellen, 2000).

3.4 What can we learn from other studies?

We will give a short introduction to different approaches focus on identification of leading indicators identified in selected studies. Wreathall (2006) identified themes in highly resilient organizations. Leading indicators sets should be based on: Management commitment, Just culture, Learning culture, Opacity, Awareness, Preparedness and Flexibility. Examples of indicators related to preparedness is “crisis training beyond minimum requirements” and to management commitment is “percentage of overtime”. Graboski et al. (2007) identify leading indicators at sharp end (Empowerment, Individual responsibility, Anonymous reporting, Individual feedback, Problem identification, Vessels responsibility) and at organizational level (Organizational structure, Prioritizing for safety, Effective communication).

Another approach based on organizational resilience focuses on Commitment, Competence, and Cognizance (“three C’s” in Reason and Hobbs, 2003). These three C’s’ are combined with “four P’s”: Principles, Policies, Procedures, and Practice. A matrix combines interaction of these concepts to indicate the organization’s position in the safety space from increasing resistance to an accident to increasing vulnerability. The New Zealand Approach proposes organizational resilience as a function of vulnerability (likelihood and criticality of a failure), adaptive capacity (apply existing responses to problems and generate innovative responses to new problems), and situation awareness (understanding interdependencies and complexities within the system, knowing when environment are changing and systems response needs to change) (Seville et al., 2007).

Woods (2006) argues that it is possible to measure potential for resilience rather than resilience itself. Factors identified that contribute to resilience include buffering capacity, flexibility, margin, and tolerance and cross-scale interactions. Mendoça (2008) identifies and measures these factors affecting resilience by triangularization of observation using quantitative and qualitative data.

Most of the approaches identified for indicators within resilience framework have focus on organizational factors and human performance. The challenge is to integrate a systemic approach taking into account the interactions between human, organizations and technology. The Functional Resonance Accident Model (FRAM, Hollnagel, 2004) explains failures and successes as result of adaptations to cope with complexity. Two forms of monitoring have been identified the monitoring of performance variability at function level and the utilization of the “FRAModel” to understand systems status in relation to resilient characteristics at system level. Functions are defined by six aspects time, control, preconditions, resources, input and output. A change in one these aspects will have impact in the performance of the functions. At sharp end indicators could be related to time to execute a maintenance task, this aspect could be essential in case of maintenance of safety critical systems.

3.5 Lessons from the Ecology perspective

We would like to make an analogy to the ecology perspective on resilience. Figure 1 illustrates the potential ability for change and the resilience of the systems in respect to vulnerability to regular, irregular and unexpected events. Changes in the system are influenced by external and internal processes. Performance conditions are conditions that influence socio-technical system responses i.e. competence, team collaboration, quality of maintenance procedures, communication and system's complexity. Four possible states are illustrated "*K, conservation*"; "*Ω release*"; "*α, reorganization*" and "*r, growth or exploitation*". In aviation maintenance, we have a multiplicity of stable states dealing with scheduled and unscheduled activities.

In state "*Ω release*" tightly coupled and fragile, this state could be related to unscheduled maintenance and the possibility to disrupt operations. This state is followed by α reorganization including innovation and leading to a new stable state. This case represents the gathering of expertise, analyse and act including reorganization of maintenance. The next phase is r restructuring/exploitation and then K conservation characterized by slow changes. This could be related to maintenance solving a specific situation and returning back to a new stable state.

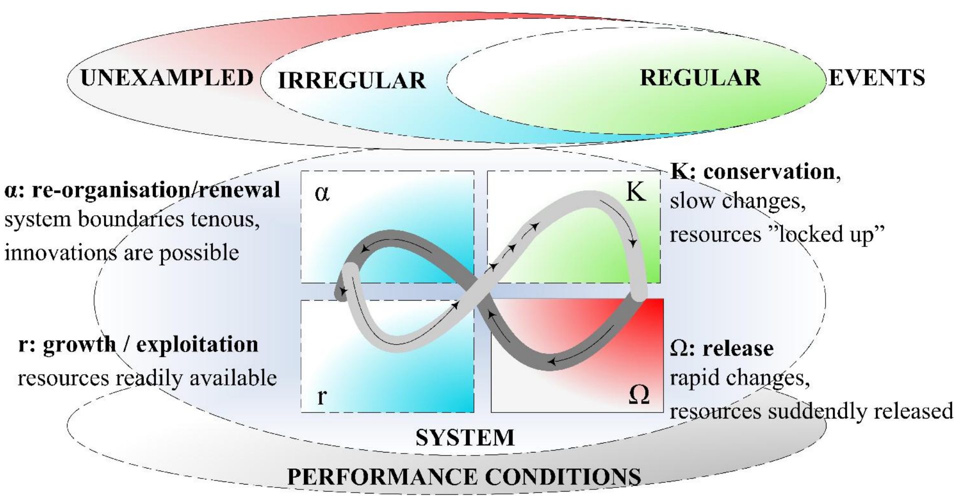

Fig. 1. Possible states in the adaptive cycle adapted from Gunderson (2002)

We argue that RE should provide alternative ways to cope with irregular and unexampled events in maintenance organizations. The model in the figure 1 introduces two dimensions potential and connectedness that influence transitions between the states. "Potential" is related to available resources; whereas "connectedness" is related to the influence of performance conditions and variability. Low connectedness is associated with variables that are dominated by outside factors and external variability.

High connectedness represents those variables that are dominated by inside factors and influence the external variability. In relation to the management of maintenance, it would be convenient to identify which maintenance functions are more sensitive to external stresses and which maintenance functions are dominated by internal variability. An example of maintenance activities dominated by internal variability is reporting of trechnical failures. Some maintenance records contain more detailed information than other maintenance records and this fact influences the quality of the organizational response. Performance conditions in this example are having the time available to write the record, reporting system, experience of the reporter. An example of maintenance activities influenced by outside factors is the airline's execution of maintenance influenced by the variability of the manufacture's recommendations and regulators oversight. In relation, to the development of leading indicators, it is necessary to understand how internal and external factors affect the variability of the system.

At the same time the system is exposed to regular, irregular and unexampled events (Westrum, 2006). System response varies. Some systems are not able to cope with regular events. Regular events can be seen as same or known maintenance problems that are experienced. Therefore, unscheduled maintenance and disruption of operation are often experienced. This issue could be related to socio-technical ability of the system to learn. Leading indicators for these systems should therefore provide information towards improvement related to regular events. Other systems that manage responses to regular events will as a consequence be exposed to irregular and unexpected events. Leading indicators for these systems should focus on maintenance changes for unknown situations, sharing the risk picture of current maintenance situation, promoting alternative solutions for different risky situations.

3 DISCUSSION AND CONCLUSION

Most of safety performance indicators are based on after-the-event and provide limited information on current performance. Leading indicators are proposed as a complement to improve current practices for monitoring safety performance. The focus in this discussion is the understanding of the "why" behind leading indicators. The first challenge is to draw the line between the leading and lagging indicators. Hopkins (2007) pointed out that lagging indicators measure failures regardless if the consequences are catastrophic or not. Based on a literature review, there is no consistency between the definition of leading indicators and their application. Regarding the leading indicators definition applied to aviation and maintenance in the context of resilience, we focus on learning from both success and failures, proposing: Leading indicators are precursors based on a model of safety implying a significant possibility of a subsequent event that has an impact on safety and performance of maintenance activities.

Leading indicators are interpreted differently in the various safety models. In domino models leading indicators consist of single elements. Upon failing, these may subsequently lead to catastrophic failures. Leading indicators in the Swiss cheese model monitor performance of safety barriers. Indicators monitor according to defence-in-depth such as status of barriers.

The RE perspective proposes a systemic approach looking into the dynamics of safety. This means that leading indicators should attempt to provide a signal of the unintended system interactions. Successes and failures are the result from the normal performance variability. Instead of looking at failures the focus is changed to the understanding of the normal operation of the system. In this context, leading indicators allow the monitoring of changes which normally are not picked up and reflected in traditional risk assessments. These assessments have been based on decomposition and linearity.

Lessons from RE and resilience in ecology that should be taken into account for the development of leading indicators are: i) consideration of resources for the potential of their future use, ii) shifting balance between internal and external forces and connectedness in the system and iii) resilience is dynamic and must generate and sustain novelty and persistence to survive, iv) awareness of present state and indication regarding transitions between states. Questions for leading indicators: which factors might push the system to critical thresholds, which kind of indicators are worth monitoring if the system follows a particular trajectory? We consider that leading indicators will vary in different states, different events and will also differ depending on whether they are perceived at the sharp end or at management level. In addition to adaptation that it is mainly reactive, another aspect in resilience that is valid for socio-technical systems is recognition, this helps to identify unwanted interactions and provide guidance to creative responses.

Based on a literature review, indicators should contain the following characteristics: an "objective" measure that is easy to understand and will indicate improvement or deterioration that can be collected from existing data. While an "objective" characteristic is very relevant for lagging indicators that can be observed, we argue that leading indicators are characterized by inter-subjectivity: transparency and perceived in the same manner by different people. These are subject to inter-subjectivity with consensus between experts and decision makers. We propose that it is necessary to go further with the single indicators and provide interpretation to differentiate unintended interactions. Core tasks like monitoring and reflecting, carrying out analyses of change or "interpretation of information at hand to reveal what it is believed to be important" (Oedewald and Reiman, 2003) are necessary for interpretation and action.

Indicators in the framework of resilience do not replace other approaches to safety performance monitoring, but increase the understanding of normal performance. Once this new understanding is gained, the model is renewed and the system looks for new indications. Using FRAM to understand normal work in a specified maintenance activity, we propose leading indicators are context specific. Examples of leading indicators for the monitoring the accomplishment of maintenance in other sites are: the resources available, the capacity to identify circumstances beyond the experience, the possibility to reflect-on-action, openness, communication, the current technical state of the aircraft (critical systems monitored by Minimum Equipment List), maintenance oversight, and implementation of preventive maintenance.

Finally, while it is impossible to predict all possible scenarios, it is possible to improve system resilience by making sense of unintended interactions and use creativity to take advantage of system dynamics. This paper summarized the "why" of leading indicators as means to look forward and to lead actions for improvement. Further work on this paper will include development on specific leading indicators at sharp and blunt end.

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