“You won’t even know we are working on it”. Human factors in airways facilities maintenance.

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Introduction

Air Traffic Management (ATM) relies on an extensive network of ground-based facilities including communication systems, radar, navigation aids and associated infrastructure. Facilities maintenance technicians carry out the preventative and corrective maintenance necessary to ensure that systems operate safely and efficiently. Technological developments are driving rapid change in ATM equipment. Reliability has increased with each new generation of equipment. However the number of maintenance-induced system failures has remained relatively constant (FAA, 1999). As a result, in proportion to other causes of failure, human error presents a growing threat to the integrity of ATM systems.

In this paper we discuss the human challenges of facilities maintenance. We introduce two approaches that Airservices Australia is using to gather information on human error in facilities maintenance; a workplace survey (the Maintenance Environment Questionnaire); and a structured investigation technique (Tool for Investigating Maintenance Error). Preliminary results from their use are presented.

Maintenance outages have featured in several aircraft accidents. In 1997, a Korean Airlines Boeing 747 crashed on approach into Guam. On the night of the accident, the ILS glideslope was out of service for planned maintenance. Although a NOTAM about the glideslope outage had been issued, during the approach, the captain of the aircraft became pre-occupied with whether the glideslope was operational (National Transportation Safety Board, 2000).

On July 1, 2002 a Boeing 757-200 cargo aircraft and a Tupolev Tu-154M passenger aircraft under the control of the Zurich control centre, collided above the town of Überlingen in Germany, resulting in the loss of 71 lives. On the night in question, the air traffic controller in Zurich had been approached by technicians to switch his console into a ‘Fall Back’ mode, for maintenance; effectively removing several critical features, including the visual short term conflict alert. The technical staff later disconnected the primary phone link to neighbouring control centres, unaware that the backup phone system had failed. Shortly before the collision, a German controller attempted to alert Zurich to the developing conflict, but was unable to make contact due to the phone outage (German Federal Bureau of Aircraft Accident Investigation, 2004).

Accidents are thankfully rare, and outages of ATM systems are more likely to result in incidents, disruptions and delays. For example, in 1998, a technician error caused a two-hour outage in an air traffic control system in the United States and reportedly led to 265 flight delays (Ahlstrom & Hartman, 2001). If each two-hour delay cost $US20,000 (Marx & Graeber, 1994) then the total cost for this single error would be in the vicinity of $US5.3 million. In September 2004, air traffic controllers in the Los Angeles area lost voice contact with 400 aircraft when a Voice Switching and Control System (VSCS) failed. The backup system failed seconds later. Controllers resorted to their personal mobile phones to alert other controllers and airlines when aircraft were on conflicting courses. The FAA identified that technicians had not followed procedures for a periodic re-boot of the VSCS to correct a recurring software problem (Geppert, 2004).

Increases in the capabilities of ATM systems, centralisation, networking and a greater reliance on computerised systems may be making systems less forgiving of technician error, and may be amplifying the consequences of system failures. For example, even a brief interruption in the power supply for a computerised system may result in a significant delay while the system re-boots when power is restored.

The maintenance of ATM systems presents a set of human challenges that are subtly different to those experienced by aircraft maintenance technicians. Except on rare occasions aircraft maintenance occurs once the aircraft has landed and been shut down[1]. In contrast, facilities maintenance may affect the operation of live systems, where an error such as an incorrect control movement can have immediate consequences. The scheduling of facilities maintenance requires an awareness of the operational consequences of the loss of the service. For example, shutting down an ILS for maintenance on a CAVOK day is likely to have less impact than maintenance at night or in bad weather. In the case of the Überlingen collision, disruptive maintenance work was scheduled at a time when only one controller was working, with the result that this single controller had to deal with the increased workload alone. In interviews with facilities maintenance personnel, Ahlstrom and Hartman (2001) identified a lack of awareness of the impact of taking a system off-line as a critical problem area. Other human factors identified by Ahlstrom and Hartman included problems with procedures, communication and coordination breakdowns, equipment bumps and trips, and data entry errors.

Until recently, very little information was available on the human factors of facilities maintenance. Investigations tended to focus on the operational consequences of incidents rather than the human behaviour that preceded the incident. Yet, without an understanding of the errors that lead to facilities maintenance incidents, it is virtually impossible to introduce appropriate countermeasures.

Airservices Australia is a government-owned agency providing air traffic management and other services to the aviation industry. Airservices manages airspace covering over 11% of the earth's surface and maintains an extensive network of ground facilities providing data, communication and navigation services. Airservices has recognised the need to introduce a maintenance error management system as part of its overall safety management system.

In 2005, Airservices introduced two initiatives to address human factors in facilities maintenance. A survey of personnel using the Maintenance Environment Questionnaire (MEQ) provided baseline data on human factors issues, and enabled the maintenance environment at Airservices to be compared to norms for other maintenance organisations. The introduction of an investigation system tailored to maintenance incidents is enabling the organisation to identify systemic issues underlying maintenance incidents.

Maintenance Environment Questionnaire

The Maintenance Environment Questionnaire was developed as a rapid method of gathering information on everyday incidents and unsafe acts in maintenance to identify error producing conditions in the workplace and inadequate barriers to human error (Hobbs, 2005; Hobbs & Tada, 2006). Although trained investigators identify such information one case at a time during occurrence investigations, the MEQ rapidly provides a large amount of information on workplace human factors that can be analysed to detect trends over time, or compared with industry norms. (See Hobbs & Tada (2006) for a discussion of the content and structure of the MEQ). Airservices used a modified version of the MEQ comprising 49 questions contributing to ten scales. In addition to questions addressing the strength of defences designed to capture error, and error tolerance, questions relate to

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[1] A notable exception is Gordon Taylor's epic in-flight oil replenishment on the Southern Cross over the Tasman Sea in 1935.

the local factors of system design, procedures, fatigue, coordination, supervision, equipment, time pressure, and knowledge.

In July 2006, a total of 208 maintenance technicians responded to the MEQ. This represents 57% of the technician workforce. The responses from facilities technicians suggested that their work environment generally contained lower levels of error-producing conditions than those found in airline maintenance organisations. For example, compared to facilities technicians, airline mechanics work more night shifts, have more difficulty obtaining specialised equipment, and experience greater time pressures. However the facilities technicians identified a range of issues including spares availability, tool control, system labelling and non-controlled procedures as areas for attention.

Airways systems are complex and tightly coupled with the operational requirements of airlines and general aviation. Despite a strong engineering focus on resilience in system design, technicians indicated that they often worked on live systems where single errors could lead to removing a system (and hence service) without notice. As Figure 1 indicates, there is great potential to increase the robustness of systems to human error.

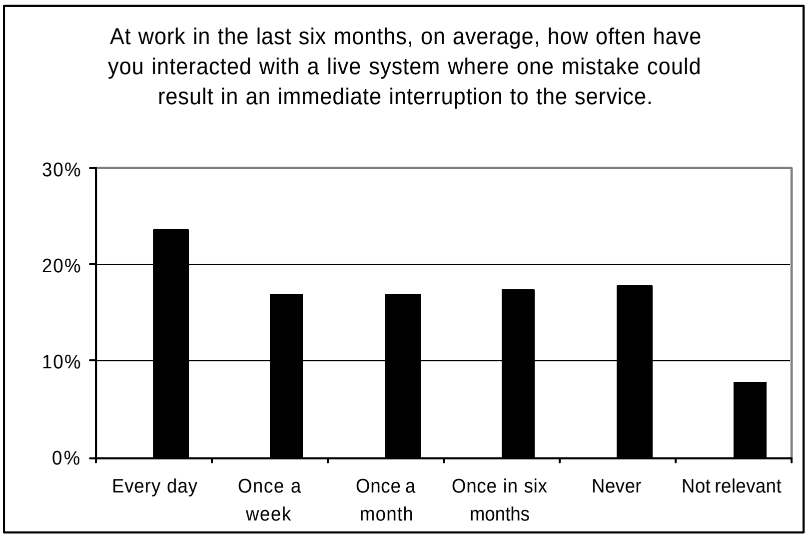

Figure 1. Profile of responses on an item from the Maintenance Environment Questionnaire

Following the introduction of the MEQ, focus groups were run with technicians and management to examine, in detail, the issues identified through the survey. For example, it was discovered that the scales for procedures and time pressure ranked highest in the MEQ findings; the focus groups were able to identify that certain work procedures could lead to interruptions in maintenance activities such as spare parts not being available when maintenance was scheduled to occur. This situation could lead to technicians having to stop work on one job and move to another, only to return when spares became available. In other cases, it was found that procedures had contained omissions or errors or that some documents were not easily found, and when they were, staff had less time to read them and refresh their memories. The interruptions and delays often led to technical staff experiencing time pressure to complete otherwise routine tasks.

The MEQ results also highlighted the problem of component labelling. In many cases, labels are attached to the front of an electronics cabinet, despite the fact that maintenance activities occur at the rear of the cabinet. A technician whose job may be to disconnect cables, is faced not only with a lack of labels near the cable attachment points, but also with the fact that when standing at the rear of a cabinet, the left-right order of systems is the reverse of the front of the cabinet.

Investigating Facilities Maintenance Incidents with Tool for Investigating Maintenance Error (TIME)

The MEQ provides a snapshot of the maintenance work environment. However there is still a need for in-depth investigations of facilities maintenance incidents to ensure that areas for system improvement are identified. Maintenance error investigations are most effective when guided by a structured approach. Several error investigation systems have been developed for aircraft maintenance, most notably Boeing's Maintenance Error Decision Aid (Rankin & Allen, 1996) and the Human Factors Analysis and Classification System Maintenance Extension developed by the US Navy (Schmidt, Schmorrow & Hardee, 1998). However in early discussions with facilities maintenance personnel, it became clear that the strong aircraft maintenance focus of these systems would not translate easily to facilities maintenance.

Since October 2005, Airservices has been investigating facilities incidents using a structured approach, the Tool for Investigating Maintenance Error (TIME) to help identify the systemic deficiencies that lead to technician errors, and areas where systems are vulnerable to such errors. Essential features of TIME have been drawn from the "Swiss cheese" model (Reason, 1990) but with a greater emphasis on integrating human factors with the timeline of the incident, and a structured focus on barriers to error. Whereas the Swiss cheese model places all barriers in the single category of 'defences', TIME allows for six specific sub-categories of barriers, described later in this paper.

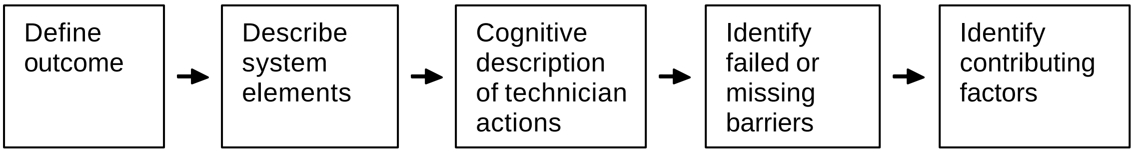

Figure 2. Stages of a TIME investigation.

Analysis of a human error incident using TIME involves five stages, as illustrated in Figure 2. The first step of an incident analysis using TIME is to identify the incident outcome in terms of facilities performance. This will typically fall into one of a small number of categories, such as loss of service, degradation or slowdown of service, or reduced redundancy.

Once the outcome has been clearly defined, the sequence of events that led to it are identified. Where technician actions are involved, these are described in two ways, first using a system elements model, and secondly using a cognitive error model.

System elements model

Technicians interact with five elements of the work system, illustrated in Figure 3. These are; 1. Other people (face to face, over the phone, or via email etc); 2. Computer systems, including software and computer-controlled or monitored systems; 3. Documents, particularly procedures, but also tags, labels etc.; 4. Hard switches and controls including circuit breakers; 5. Hardware, such as cables, cabinets and physical components. The system elements model is an extension of the familiar SHEL model developed by Edwards (International Civil Aviation Organisation, 1992).

Errors can generally be described as a failure to interact appropriately with one of these five elements. At this point of analysis, the investigator describes the physical activity being engaged in by the technician at the moment they made the error, as though the investigator was watching a video replay of the person's observable activities at the moment the task began to deviate from the desired sequence. Describing the event in this way enables the investigator to specifically identify what element of the system was involved in the event, without delving into *why* the event occurred. Examples of errors are shown next to each system element in Figure 3.

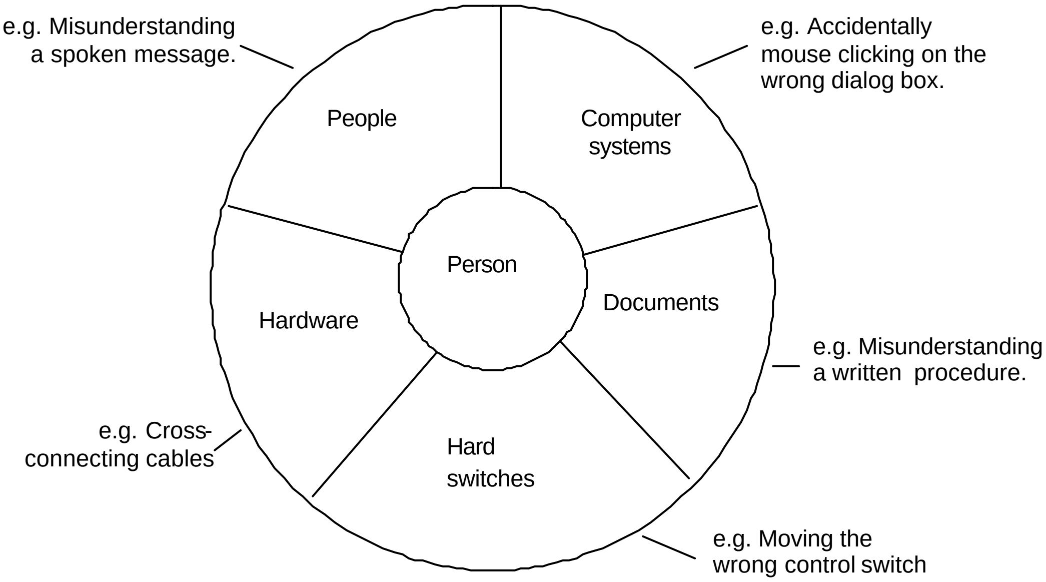

Figure 3. The system elements model of work interactions.

Example: Person-Hardware interaction

A technical officer was attaching an earthing point to an ILS cabinet. This required a hole to be drilled in the cabinet and an earthing lead attached. The technical officer, realising that there may be supply cables behind the cabinet, felt for the presence of cables, as he was unable to get visual access to the rear of the cabinet. As he could not feel any cables, he assumed it was satisfactory to commence drilling. During the drilling, a DC supply cable was damaged resulting in the service failure of the ILS. The investigation identified a range of local factors and failed barriers that contributed to the incident. These included system knowledge, and the non-use of isolation procedures and works plans.

Cognitive model of error

The technician's action is then described using a simple cognitive model of error, the Operational Oversight Performance System model (Hobbs, 2006). While categorising error may sound like a dry academic exercise, attempting to understand the person's mental frame of reference at the time of the error is crucial to identifying appropriate system interventions. A memory lapse such as forgetting to move switch A to position B, calls for different corrective recommendations than a knowledge-based error such as being unaware that switch A needed to be moved. Applying cognitive error models to operational errors is a notoriously difficult undertaking, and for this reason the cognitive model used in TIME has been made as simple as possible, and the analysis process is guided by a diagnosis chart in plain English. Rather than being expected to apply psychological terms, the investigator is prompted to consider what the error-maker might have said had they become aware of the error at the moment that it occurred. So for example, if a technician erroneously moved a power supply control to the "off" position, his/her immediate response might take one of the following forms: 'I didn't mean to touch that control'; 'Everybody does it that way'; or 'I thought I was supposed to move that control to "off"'. The responses suggest, respectively, either a skill-based action slip, a routine violation, or a knowledge-based error. The sole purpose of categorising error in this way is to identify how the system may be improved to reduce the incidence of this event in future, and/or withstand it better.

By applying the cognitive error model in conjunction with the system elements model, technician errors can be seen in their ecological context. For example, forgetting to verbally coordinate with a tower controller before taking a navigation aid off-line is a memory lapse in the context of person-

person interactions. Forgetting to place a tag on a system under maintenance is a memory lapse in the context of person-documentation use.

In aircraft maintenance, skill-based slips are less likely to be involved in airworthiness incidents than in worker injuries. Hobbs & Williamson (2002) found that slips were involved in 27% of health and safety incidents involving maintenance personnel, but only 12% of maintenance quality incidents. This is possibly because slips made in the hangar are often detected and corrected before an aircraft is returned to service. In accord with the findings of Ahlstrom and Hartman (2001), our preliminary results are suggesting that slips may play a significant role in facilities maintenance quality incidents, because a single action such as an incorrectly disconnected cable or a mis-selected control may have an immediate impact on a "live" system.

Example: Skill-based slip involving a hard switch.

At a major metropolitan airport, runway and taxiway lighting receive power from two identical UPS (Uninterruptible Power Supply) systems. At the end of a maintenance check, UPS 1 was in the "off" position, while UPS 2 was in the "on" position. The technician intended to move UPS 1 to the "on" position, but inadvertently reached for UPS 2 and moved it to the "off" position. Airport runway and taxiway lighting failed for approximately 10 minutes. At the time of the error the technician had been awake for approximately 21 hours.

Identifying barriers.

Once the sequence of events has been established, TIME prompts the investigator to identify barriers that were inadequate or missing. Error barriers are system features that have been put in place specifically to manage hazards associated with unwanted human behaviour. Barriers aimed at maintenance error can take the form of engineered features (such as warning lights, switch covers and interlocks) or administrative controls (such as procedures, work practices or warning signs). Barriers fulfil one of three functions, error prevention, error capture, or error tolerance (see Table 1).

Table 1.

Examples of forms and functions of barriers.

Function of Barrier	**Form of Barrier**	
	Engineered	Administrative
Error prevention	Interlock	Warning sign
Error capture	"Undo" feature on software	Functional check
Error tolerance	Redundant systems	Scheduling maintenance to reduce operational impact

Error prevention barriers are intended to make it difficult for a person to perform an unwanted action and are particularly important in environments where maintenance activities can affect a 'live' system. Examples are locks or passwords that limit access to a system, or interlocks that prevent an action from being carried out unless certain conditions are met. Error capture barriers are designed to detect and recover from errors before they cause harm. Functional checks and dual inspections are examples of procedures designed to capture errors before they have an opportunity to result in an undesired outcome. Even when an error has occurred, and has not been detected, it may still be possible to manage the risk associated with the error. Error tolerance defences are designed to ensure that the consequences of an error are not catastrophic. This might be achieved by performing maintenance at a time when a system failure would be unlikely to have an adverse impact, or limiting the level of coupling between systems so that the loss of one system does not flow on to other systems.

Example: Lack of engineered barrier to capture error

A reset needed to be accomplished on a console for fault rectification. A trainee was entering the data for the reset under the supervision of a qualified staff member, who was reading aloud the procedure steps from section 7.13 of the technical manual. The qualified staff member was distracted from the procedure by a question from a trainee. When he returned to reading from the manual he read section 7.15, instead of section 7.13, which initiated a total system re-boot of a high frequency control system lasting eight minutes. Calls could still be heard and made during this time, however only on the last selected frequency. There was no feature built in to the software that asked the user to confirm that a total re-boot was required.

Contributing factors

TIME is based on the premise that virtually all errors reveal something about the wider system in which they occur, whether at a local or organisational level. Technician errors generally represent the starting point for a TIME investigation, but only as signposts that point towards opportunities for system improvement. Local factors are conditions present in the immediate workplace that are considered to have increased the probability of an event occurring. The local factors used in TIME are based on the factors used in the MEQ, with some additions, enabling comparisons to be made between issues identified via investigations and those identified via the MEQ. Organisational factors originate in the managerial levels of the organization and are present beyond the immediate time and place of the incident. TIME enables the investigator to identify a range of organisational factors such as training systems, staffing levels, management of risk, and organisational communication.

Example: Inadvertent shut down of system

A technician who was conducting a software upgrade via a monitoring and control system inadvertently bumped the computer mouse. As a result the cursor came to be positioned over an incorrect window on the monitor screen. When he opened a command window it was for a different system controlling a remote tower, rather than the more limited node (single computer) he had intended to select. Without recognising that he had selected the wrong window, he then selected a "STOP SYSTEM" command on the screen, shutting down the system used to control the remote tower rather than the single node he intended to shut down. While a sequence of human actions undoubtedly triggered the incident, the investigation focused on the system issues that had "set up" the technician. Investigation with TIME found that the local factors of poor interface design, fatigue, and time pressure had all played a role in the technicians' performance. Significantly, the TIME investigation highlighted the lack of an engineered barrier to capture errors, in the form of a prompt for verification of system commands.

Conclusions

Until recently, the human challenges of ATM maintenance have received very little attention from the human factors community, despite the safety implications and economic cost of facilities maintenance errors. Advances in ATM technology are resulting in improvements in equipment reliability, yet ironically, modern computerised ATM equipment may be less forgiving of technician error than earlier generations of equipment. Change is also occurring in the technician workforce. The departure of experienced personnel and the worldwide trend away from lifetime employment with a single organisation mean that the ATM technicians of the future may bring less depth of knowledge and experience than current technicians.

The systematic investigation of maintenance incidents with TIME, in conjunction with the MEQ is revealing the systemic issues that underlie many maintenance errors. Preliminary results are highlighting the significance of skill-based slips and the corresponding need for barriers designed to capture such errors. For example, whereas it is impossible to exit a word processing file without being prompted to save the contents, it is in many cases possible to shut down an item of ATM equipment without any need to confirm that this action is intended. Other issues are controls that operate in a counterintuitive manner; the screen design of computerised systems; improved labelling of cables, cabinets and controls; procedure design; and communication. Communication between ATS personnel and technicians is particularly important to ensure that facilities are not removed from service at inappropriate times. In addition, technicians must understand the operational effects that could occur when they interact with a "live" system where there may be little margin for error. Although the TIME system was developed with facilities maintenance in mind, it may also be applied in other settings.

The findings from the MEQ will be compared over time and trend information will be used to detect any significant movements that might not be obvious otherwise. However, the MEQ also provides a compass for more immediate reviews of systemic issues that create the potential for error in the maintenance environment. The 'big picture' provided by the MEQ is assisting managers to capture a range of possible human factor issues rather than directly focusing on one or two. Issues identified through the MEQ may, in future, lead to directed or focused investigations. We also hope to compare the information gathered with the MEQ and TIME with comparable information gathered by air traffic service providers in other parts of the world, when such information becomes available.

In conclusion, it is apparent that human error is an inevitable part of facilities maintenance activities, and even well-engineered systems can be vulnerable to it, often in ways never anticipated by system designers. Examining the human factors of facilities maintenance is already having payoffs in terms of reducing the frequency of error, and increasing the resilience of systems when errors do occur.

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