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The relationship between the dynamic model of crew resource management and line operational safety audits

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Abstract: The essential skills underlying crew resource management (CRM) are described in the competency frameworks published by the International Civil Aviation Organization and International Air Transport Association. CRM dynamic model (CRM-DYMO) demonstrated that CRM processes based upon these competency frameworks could be described as a simple input-output-process (IPO) model. This paper illustrates how the major characteristics in the Line Operations Safety Audits (LOSA) threat and error framework relate directly to components in CRM-DYMO. It provides a basis for understanding error within the LOSA framework with respect to a competency-based model of CRM. The approach is illustrated with reference to examples of CRM performance taken from aircraft accident reports. CRM-DYMO forms a practical basis for translating LOSA data into effective CRM training by making explicit the functional linkages between these two constructs.

Keywords: crew resource management; CRM; threat and error management; TEM; evidence-based training; EBT; pilot competencies.

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1 Introduction

In the last four decades crew resource management (CRM) has been the basis of a safety revolution in the aviation industry. It evolved as a result of a series of accidents where aircraft with no, or minor technical faults, crashed as a result of a failure to effectively utilise all the human resources available on the flight deck in an appropriate manner. CRM drew upon the disciplines of social and organisational psychology and management science and applied these to the promotion of safety onto the flight deck. So far, CRM has progressed through six distinct eras (Paries and Amalberti, 2000; Helmreich et al., 1999b). At first CRM was aimed at improving management styles and interpersonal skills with emphasis on improving attitudes, communication and leadership. In third generation CRM it had extended into the airline organisation as a whole and by the fourth generation CRM training per se was being absorbed into all aspects of flight training. Fifth generation CRM assumed that error was pervasive. It accepted that humans are fundamentally fallible, especially under stress, hence emphasis was placed on managing error using a tripartite approach: avoid errors; trap errors; and/or mitigate the consequences of errors (Helmreich et al., 1999b). This was extended further in its following incarnation, where contextual risks to be managed that constituted potential threats to flight safety were incorporated (Wagener and Ison, 2014; Muñoz-Marrón, 2018).

There are many descriptions of the components of CRM (e.g., CAA, 2014; Van Avermaete, 1998) most of which share the majority of elements. However, these definitions and frameworks provide the basis for a CRM syllabus and how it should be evaluated, but do not make any attempt to describe a theory concerning how CRM actually achieves its objective of safe and efficient flight. Foushee (1984) acknowledges that CRM is a process underpinned by communication but does not describe the relationship between the components in the process. However, more recently Mansikka et al. (2019) proposed crew resource management dynamic model (CRM-DYMO) which begins to address this issue.

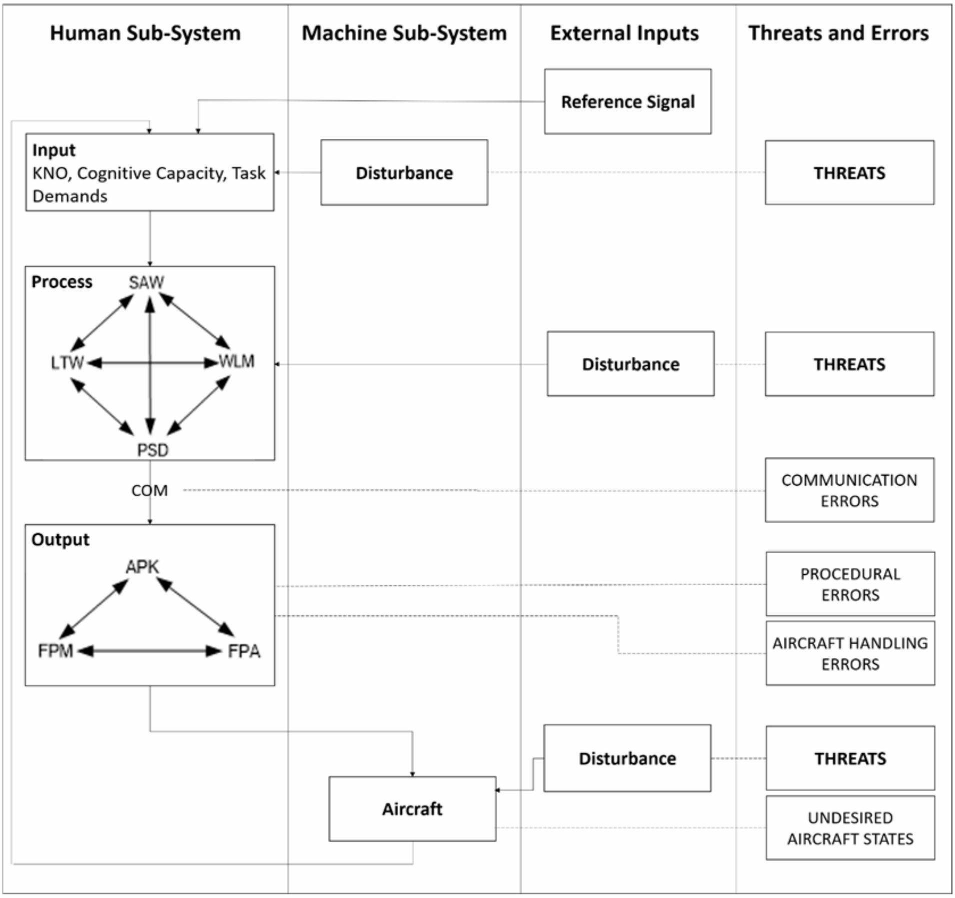
CRM-DYMO explicitly addresses crew actions in the aircraft, however the operation of a modern airliner resides in a wider organisational context, a major component of which is concerned with safety management. One of the functions of an airline safety management system (SMS) is to identify and remedy organisational and contextual hazards and risk (Gerede, 2015). Threat and error management (TEM) programs are one mechanism by which this is accomplished. This work describes the functional links between the CRM-DYMO model described by Mansikka et al. (2019) and the errors prescribed in the Line Operations Safety Audit (LOSA) threat and error model from Helmreich et al. (1999b). By doing so it explicitly links CRM competencies [as specified by ICAO (2013) and IATA (2013)] with risks in the SMS. These contingencies are illustrated with reference to a number of accidents and incidents. By describing the functional linkages between CRM-DYMO and LOSA, this paper helps to translate material collected during LOSA findings into targeted evidence-based CRM training.

2 Crew resource management dynamic model

CRM-DYMO is based on the competency frameworks described by the ICAO (2013) and the IATA (2013). These comprise the following knowledge, skills and attitudes: application of procedures (APK), communication (COM), aircraft flight path management, automation (FPA), aircraft flight path management, manual (FPM), knowledge (KNO), leadership and teamwork (LTW), problem solving and decision making (PSD), situation awareness (SAW), and workload management (WLM) (ICAO, 2013; IATA, 2013). Of these, APK, FPA and FPM represent the technical competencies required by pilots and are aircraft type-specific (to some degree). PSD, SAW, LTW, WLM and COM cover the social (LTW, COM) and cognitive (PSD, SAW, WLM) non-technical components generally referred to as CRM.

Analysis of these competencies enabled Mansikka et al. (2017) to describe CRM as an input-process-output (IPO) model (McGrath, 1984). CRM-DYMO (Mansikka et al., 2019) developed this model further, suggesting that team performance on the flight deck can be characterised as a dynamic human-machine system comprising human and machine sub-systems. The human sub-system describes the activities undertaken by members of flight crew: the machine sub-system describes the aircraft's state (position, attitude, aircraft system status, etc.). The human sub-system's output forms the input for the machine sub-system. The machine sub-system's output feeds back to the human system in the form of a closed loop, human-machine (cybernetic) system. The inputs for the human sub-system's process phase are two-fold. On the one hand KNO feeds the human sub-system. On the other the input is comprised of the pilot's cognitive capacity, skills and experience held in long term memory, which determine the cognitive resources available given the demands of the task. Within the process phase LTW, PSD, SAW and WLM are used to convert the available resources into outputs, i.e., APK, FPM and FPA (Brannick et al., 1993). COM is the competence that allows for data and information to circulate in the IPO model. The basic CRM-DYMO model is described diagrammatically in the left-hand column of Figure 1. Helmreich and Foushee (1993, 2010) have also suggested that CRM is predicated upon an IPO model, however in their conception the inputs and outputs extend beyond the flight deck (e.g., in the case of input factors, these include the organisational environment and regulatory factors: in the case of outputs, these can include attitudes and morale). Ginette in his team leadership model (TLM) adopts a similar perspective (Hughes et al., 2015). CRM-DYMO is better aligned with the 'crew and mission performance functions' (the process component) in the models proposed by Helmreich, Foushee and Ginnett. It specifically addresses crew actions relating to the safe and efficient control of the aircraft. CRM-DYMO can be conceptualised as an inner-loop CRM model, nested within the outer-loop IPO model proposed by Helmreich and Foushee (1993, 2010). In common with this earlier model, COM is the method by which information flows between pilots, crew, air traffic control and the non-human components in the system (Kanki, 2010).

Figure 1 Extended CRM-DYMO model (Mansikka et al., 2019) combined with components of the LOSA threat and error model (Helmreich et al., 1999b)



Notes: Solid lines with arrows indicate paths of causality. Dotted lines illustrate the nature of the threat/error and its relationship with a component in the CRM-DYMO model.

One essential goal of the crew is to manipulate inputs to the machine sub-system such that the difference between the output and the reference signal (which is essentially the flight plan) is minimised. The system is affected by disturbances (see column 3 in Figure 1). Disturbance comprises of all the factors affecting CRM and the machine sub-system (the aircraft: see column 2, Figure 1) that originate externally [cf. Adkinsa et al. (2015) who linked internal and external disturbances to the aircraft to CRM-related errors]. However, despite the ability of CRM-DYMO to describe how CRM enhances safety on the flight deck, its initial incarnation contains no link to the root causes of pilot error, nor does it explicitly describe the relationship between pilot competencies and other common CRM practices found in airlines, such as TEM.

As noted earlier, the management of error on the flight deck is prescribed by the error troika (Helmreich et al., 1999b). This approach forms the basis of one of the other fundamental underlying principles of CRM: TEM. LOSA have become an essential component in the TEM process. FAA (2006, p.2) describes LOSA in a similar manner to an annual 'health check' which provides "a diagnostic snapshot of strengths and weaknesses that an airline can use to bolster the 'health' of its safety margins and prevent degradation." Audits are undertaken on a non-jeopardy basis by trained observers on scheduled flights to collect data on issues which may represent a threat to safe operations, such as operational complexity, environmental conditions and crew performance. These data are then used to produce evidence to inform crew training and revise flight deck practices (Thomas, 2003). The basic philosophy underlying evidence-based training (EBT) is that pilots should be exposed to challenging and novel situations in the simulator based upon an analysis of operational needs (e.g., those derived from LOSA data).

In LOSA, such challenging situations (threats) fall into two major categories:

- environmental threats (mainly weather and terrain-related)
- airline threats, which may be related to aircraft malfunctions, operational pressures, ground handling, maintenance, etc.

Furthermore, threats may either be predicable, and can thus be anticipated (e.g., some types of weather) or unpredictable, so need to be reacted to and managed as they occur. In the threat and error model, which was developed to help observers analyse flight deck activity when collecting LOSA data, a threat not managed properly is potentially related to an error (Helmreich et al., 1999a; FAA, 2006). In CRM-DYMO threats are characterised as either being internal to the machine sub-system (the aircraft) or external to the aircraft, resulting from the environment or other human errors which result in a disturbance input into the system (see Figure 1).

Fight crew errors (which may be actions of commission or omission) fall into three main categories:

- Aircraft handling errors (which may be related to incorrect use of automation, poor manual flying skills, or incorrect use of other secondary controls).
- Procedural errors [which encompass issues such as missed briefing items; missed callouts or omitted checklist items, failure to cross-check, deviations from standard operating procedures (SOPs), etc.]. These procedures form a second line of defence to guard against aircraft handling errors and may not result in an undesired aircraft state unless proceeded by an associated handling error.

- Communication errors (which may be external communications, such as missed calls or incorrect readback, or within aircraft/flight deck communication errors).

Within the LOSA framework, a failure to manage threats and errors may result in an undesired aircraft state, defined in terms of a reduction of safety margins. Such undesired aircraft states may relate to issues such as vertical and/or lateral flight path deviations; speed deviations or incorrect aircraft configurations (e.g., autoflight systems or incorrect weight and balance). CRM-DYMO takes this one step further clarifying the relationship between the threat/error and the undesired aircraft state. Errors are related to specific competencies and stages in the IPO model. Furthermore, in the CRM-DYMO model errors only manifest themselves at the output stage but may be a product of competencies in the process phase or of communications (Figure 1).

The following sections illustrate the operation of CRM-DYMO with reference to several well-documented aircraft accidents. In some cases, threats and errors from the operational environment were mis-managed, however in other cases, through the appropriate actions of the crew, threats were managed effectively using good CRM practices and the eventual outcome was a great deal more positive than may initially have been expected in the circumstances.

3 CRM-DYMO meets LOSA: illustrated examples

3.1 Threats and disturbances

The FAA (2006, Appendix 1, p.3) specifically stated that, “TEM [threat and error management] is not CRM and should not be considered a replacement for it. TEM and CRM refer to overlapping but not equivalent activities.” However, there have been calls to link error management directly to CRM (Wagener and Ison, 2014; İnan, 2018). Threats are not errors *per se*, but they amplify the potential for error. CRM-DYMO is a flight deck oriented, ‘inner loop’ IPO model of CRM [in contrast to the ‘outer loop’ IPO model described originally by Helmreich and Foushee (1993, 2010)] which means that the relationship between error types and competencies is described explicitly. The major characteristics in the LOSA threat and error model relate directly to components in CRM-DYMO (see right-hand column in Figure 1). Within CRM-DYMO the aircraft is potentially affected by disturbances. These may originate either internally to the aircraft or from sources external to it. They correspond directly to threats in the LOSA framework; threats provide unwanted disturbances to the conduct of safe and efficient flight which demand the crew’s attention. In the crash of the Empire Airlines ATR 42 (Avions de Transport Régional Aerospatiale Alenia ATR 42-320) in Lubbock, Texas, the key initiating event was the presence of freezing drizzle which resulted in aircraft icing, leading to a flap asymmetry (NTSB, 2011). This external threat was subsequently mis-managed by the crew (poor CRM processes) as was the ultimate output of their efforts. In the accident involving a Boeing 747-400 in Taipei [Singapore Airline SQ006 (Aviation Safety Council, 2002)] the significant external disturbance factor was again deteriorating weather (strong winds and heavy rain from an approaching typhoon) which provoked a series of errors on the part of the pilots. In both the mishaps involving Qantas flight QF32, an Airbus A380 departing Singapore Changi Airport (Australian Transport Safety Bureau, 2013) and British Midland Flight BM92, a Boeing 737-400 which crashed at Kegworth in the UK (Air Accidents Investigation Branch of the Department of Transport, 1990) catastrophic engine malfunctions were internal disturbances or threats (in threat and error parlance) which initiated a subsequent chain of events. However, in the former case the flight crew was complemented on their CRM processes, managing the engine failure (and subsequently resulted in a safe emergency landing). In the latter case, the CRM processes were not so well conducted resulting in a major accident and loss of life.

LOSA proposes that a failure to address threats and errors encountered during operations has the potential to result in an undesired (unsafe) aircraft state. CRM-DYMO goes slightly further and proposes that if threats (disturbances) and errors are not addressed *using appropriate CRM practices*, then this may result in an undesired aircraft state. Furthermore, CRM-DYMO also explicitly proposes that the corollary of this is that adopting appropriate CRM processes to address disturbances should mitigate the risk, minimising the likelihood of the situation developing into an unsafe state. In the Empire Airlines accident in Lubbock TX, the CRM process failed to address the icing issue (an external disturbance/threat) resulting in the aircraft becoming slow and unstable during the approach; a similar argument can be made about the Air France 447 icing encounter (BEA, 2012) which also resulted in the aircraft becoming dangerously slow and stalling; in the Singapore Airlines SQ006 accident in Taipei poor CRM resulted in the crew attempting to take off on a closed runway, subsequently hitting construction equipment; the crew of the 737-400 at Kegworth failed to follow good CRM practice when diagnosing and addressing an engine issue (internal disturbance), ultimately shutting down the wrong, undamaged engine and eventually executing a rushed approach prior to the major failure of the other engine. However, good CRM in the cases of the major engine malfunction in both the Qantas QF32 incident and in the Sioux City McDonnell-Douglas DC-10 accident (NTSB, 1990) resulted in minimising the consequences of the failures and helping to avoid (as far as possible) an unsafe aircraft state. Somewhat unfortunately, in contrast to accidents resulting from poor CRM, well-documented instances of good CRM are difficult to find, but good CRM practices are applied thousands of times every day. Thoroman et al. (2019) make an attempt to address this issue by analysing the effective pilot interventions in serious near misses, however even this is predicated upon the system having first slipped into a hazardous state, something that CRM attempts to avoid if the root of the safety threat lies within the flight deck. Other authors have undertaken *in vivo* studies of CRM to identify successful practices, however these are not located within a theoretical, explanatory framework (e.g., Thomas, 2003; Bennett, 2019, 2020).

CRM-DYMO characterises CRM processes as a cybernetic IPO system, hence a disturbance, if not handled appropriately, can result in exacerbating the initial disturbance, or confounding the problem with further disturbances arising from its mismanagement.

3.2 Garbage-in: errors in the input phase

The phrase ‘garbage-in, garbage-out’ is often used to express the notion that incorrect or poor-quality input will result in an incorrect output. CRM-DYMO is predicated upon a similar assumption. The threat and error model within LOSA only addresses errors made by flight crew related to the final ‘output’ phase in CRM-DYMO (which is where all errors ultimately manifest themselves irrespective of their roots). Procedural errors are related to the ICAO (2013) competence relating to the application of procedures (APK): this is defined as identifying and applying procedures in accordance with published operating instructions and applicable regulations using the appropriate knowledge. Aircraft handling errors in LOSA are described by the ICAO competencies of FPM (controlling the aircraft flight path through manual flight) and FPA (controlling the aircraft flight path through automation, including the appropriate use of flight management systems and guidance). However, CRM-DYMO goes further, suggesting that these output errors are observable products of the 'Input' and 'Process' factors of CRM (see column 1, Figure 1) or result from communication (COM) errors. In the accidents discussed, errors in these output LOSA/CRM-DYMO categories are evident, as the decisions made earlier are ultimately expressed as an 'observable' manifestation resulting in an unsafe aircraft state. For example, AF447 crews' ultimate error was inappropriate manual flight path control inputs (FPM) to low airspeed (constantly pulling up resulting in a stall) partly attributable to misleading airspeed indications and confusing alerts. In the Lubbock ATR 42 accident there was a failure to go around when responding to flap asymmetry as a result of icing and in direct conflict with SOPs resulting in further problems with the manual control of the flight as a result of inadequate flap extension for the airspeed.

3.3 Garbage-out: errors in the output phase

In CRM-DYMO, errors at the output stage are most often based upon poor performance at earlier stages in the IPO model. Problem-solving processes and decisions made (PSD) are themselves predicated upon crews' SAW and the appropriate distribution of tasks (WLM) on the flight deck (itself a product of leadership – LTW). In the Boeing 737 accident at Kegworth the wrong (non-malfunctioning) engine was shut down as a result of the captain's incorrect knowledge concerning system configurations (KNO) and a failure to collect and verify the information available, resulting in poor SAW and an incorrect decision. High workload and poor leadership resulting from a desire to depart before the airport was closed due to approaching poor weather resulted in the crew of Singapore Airlines SQ006 failing to review the taxi route appropriately. As a result, they mistakenly entered a runway closed owing to re-construction and then ignored contrary indications on the para visual display which would have indicated that they were lined up on the wrong runway.

3.4 Communication

Within CRM-DYMO communication is considered as a competency that enables or impedes a number of other competencies. Communication is the manner by which LTW is exercised on the flight deck and workload is managed (the 'process' phase in CRM-DYMO). Within the CRM-DYMO model it is specifically concerned with the transmission of data/information. Effective communication has been identified as a protective factor for the safe and efficient conduct of a flight (Thoroman et al., 2019). Good team working also promotes SAW and hence decision making (see Kanki, 2010). One characteristic of both the Kegworth Boeing 737 accident and the ATR42 crash at Lubbock was that the captain elected to undertake a great deal of the diagnosis, decision-making and control of the aircraft himself taking over from relatively junior first officers. As a result, this increased their own workload and they failed to evaluate all the information available, hence crew SAW was poor. This resulted in ill-informed decisions being made, in one case relating to the fundamental nature of the engine problem and in the other instance relating to the implications of the flap asymmetry issue and a failure to follow SOPs.

In contrast, in the accidents involving the Qantas Airbus A380 departing Changi Airport and the McDonnell-Douglas DC10 over Sioux City there was very effective teamwork, with data gathering, diagnosis and control elements being delegated across all available personnel. United Airlines (UAL) Flight 232 was a McDonnell-Douglas DC10-10 which experienced a catastrophic uncontained engine failure which disabled all the flying controls (NTSB, 1990). The captain and flight engineer worked as a coordinated team to diagnose and re-gain control of the aircraft using differential throttle. The captain discussed options with ATC and United Airlines dispatch while the flight engineer reviewed the situation with the airline maintenance facility. A check airman on board collected further information from a visual inspection of the flying surfaces prior to assuming a position behind the thrust lever quadrant where he took control of heading and descent rate by using differential throttle from directions from the captain. ATC assisted in the navigation of the aircraft, communicating via the first officer. As a result of the crew acting in a coordinated manner a successful crash landing was made, saving many lives. The Qantas A380 also experienced an uncontained engine failure which resulted in a cascade of warnings and alerts on the flight deck, some real, some spurious. Over 100 checklists were generated by the Electronic Centralised Aircraft Monitor (ECAM). Luckily on the day of the flight there were two additional senior pilots on the flight deck (one of whom was a senior check captain) both type-rated on the Airbus A380. The captain distributed tasks (hence workload) across all personnel: The captain flew the aircraft and the First Officer prioritised the checklists, with the other pilots on the flight deck helping to action the checklist items. After holding for 50 minutes, the aircraft made a safe, 50 tonne overweight landing back at Changi Airport. Communication and coordination of the members of crew was essential for facilitating the outcomes of both flights.

4 Future work

The main limitation in this discussion of CRM-DYMO results from its reliance on case studies resulting from accidents and incidents. While these are well-documented and in the public domain they only represent one side of the equation. CRM as a concept is about promoting safe operations, minimising risk and managing error. Even though two case studies have been included in this paper as exemplars of good CRM performance they are still in an accident/incident context. All day, every day there are thousands of flights taking place where CRM is being applied to good effect. Ethnographic studies of CRM on the flight deck using CRM-DYMO as an observational framework would be of great benefit in demonstrating the operation of the model – what happens when CRM works as it is intended. Accidents can be a failure of Human Factors, but it is important to understand that safe operations are not the opposite of accidents: simply doing the opposite of what happened in the sequence of events underlying an accident will not guarantee safety (Harris, 2011). This is why case studies of good performance (CRM successes) are important to document.

CRM originated in civil aviation, but related practices are now commonplace in many other high-risk industries where personnel to work in coordinated teams (for example, nuclear power plant operations, shipping, air traffic control and medicine). Furthermore, these industries typically also collect extensive human performance data. The CRM-DYMO approach used along with data from incidents could easily be extended into these other application areas to support evidence-based team-training.

5 Conclusions

Characterising CRM as an inner-loop process model focussed on the activities on the flight deck provides a greater level of explanation than simply describing it as a set of component parts. This extension of CRM-DYMO provides an all-encompassing approach which combines the development and assessment of pilot CRM competencies with the collection and analysis of safety data, two of the main functions of the human factors departments an airline. It supports directly EBT objectives and processes (ICAO, 2013). CRM-DYMO not only provides an account of accidents and incidents resulting from poor crew coordination, it also provides an explanation for good team performance on the flight deck. It makes it clear that there is a relationship between the ICAO (2013) and IATA (2013) CRM competencies, and that performance in one area can directly affect performance in another. As noted earlier, TEM is not CRM (FAA, 2006) but is a highly related. The CRM-DYMO model makes explicit the relationship between the competencies and the observable manifestations of error in the LOSA/threat and error model, hence provides an explanation of the relationship between CRM and aircraft states (both desirable and undesirable). CRM processes are portrayed as ‘causes’, with errors and aircraft states characterised as ‘effects’ which is important as it is not possible to manage ‘effects’, only ‘causes’: the direction of this dependency is explicit in the model described. The approach introduced in this paper explains how LOSA and CRM are associated and how LOSA data can support evidence-based CRM training.

References

Adkinsa, J.Y., Adams, K.M. and Hester, P.T. (2015) ‘How system errors affect aircrew resource management (CRM)’, *Procedia Computer Science*, Vol. 61, pp.281–286 [online] https://doi.org/10.1016/j.procs.2015.09.216.

Air Accidents Investigation Branch of the Department of Transport (1990) *Report on the Accident to Boeing 737–400*, Report No. 4/1990, HMSO, G-OBME, Near Kegworth, Leicestershire, 8 January 1989 [online] https://assets.publishing.service.gov.uk/media/5422fefeed915d13710009ed/4-1990_G-OBME.pdf (accessed 1 June 2021).

Australian Transport Safety Bureau (2013) *Aviation Safety Investigation Report 089 – In-Flight Uncontained Engine Failure Airbus A380-842*, VH-OQA, Department of Transport and Regional Services, Government of Australia [online] https://www.atsb.gov.au/media/4173625/ao-2010-089_final.pdf (accessed 1 June 2021).

Aviation Safety Council (2002) *Aircraft Accident Report: Crashed on a Partially Closed Runway During Takeoff. Singapore Airlines Flight 006 (Boeing 747-400, 9V-SPK)*, CKS Airport, Taoyuan, Taiwan, Aviation Safety Council, Republic of China, 31 October 2000 [online] https://reports.aviation-safety.net/2000/20001031-0_B744_9V-SPK.pdf (accessed 1 June 2021).

Bennett, S.A. (2019) 'The training and practice of crew resource management: recommendations from an inductive in vivo study of the flight deck', *Ergonomics*, Vol. 62, No. 2, pp.219–232 [online] https://doi.org/10.1080/00140139.2018.1506159.

Bennett, S.A. (2020) 'Human-factors lessons from a longitudinal, in-vivo study of operations at a low-cost carrier', *International Journal of Human Factors and Ergonomics*, Vol. 7, No. 1, pp.1–25 [online] https://doi.org/10.1504/IJHFE.2020.107284.

Brannick, M.T., Roach, R.M. and Salas, E. (1993) 'Understanding team performance: a multimethod study', *Human Performance*, Vol. 6, No. 4, pp.287–308 [online] https://doi.org/10.1207/s15327043hup0604_1.

Bureau d'Enquêtes et d'Analyses (BEA) (2012) *Final Report on the Accident on 1st June 2009 to the Airbus A330-203 Registered F-GZCP Operated by Air France Flight AF 447 Rio de Janeiro – Paris*, Translated by BEA from French [online] https://www.bea.aero/docspa/2009/f-cp090601.en/pdf/f-cp090601.en.pdf (accessed 10 December 2019).

Civil Aviation Authority (CAA) (2014) *Flight-Crew Human Factors Handbook (CAP 737)*, Civil Aviation Authority, UK [online] https://publicapps.caa.co.uk/docs/33/CAP%20737%20DEC16.pdf (accessed 1 June 2021).

Federal Aviation Administration (FAA) (2006) *Line Operations Safety Audits (Advisory Circular AC 120-90)*, US Federal Aviation Administration [online] https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_120-90.pdf (accessed 1 June 2021).

Foushee, H.C. (1984) 'Dyads and triads at 35,000 feet: factors affecting group process and aircrew performance', *American Psychologist*, Vol. 39, No. 8, pp.885–893 [online] https://doi.org/10.1037/0003-066X.39.8.885.

Gerede, E. (2015) 'A study of challenges to the success of the safety management system in aircraft maintenance organizations in Turkey', *Safety Science*, Vol. 73, No. 1, pp.106–116 [online] https://doi:10.1016/ j.ssci.2014.11.013.

Harris, D. (2011) *Human Performance on the Flight Deck*, Ashgate, Aldershot, UK.

Helmreich, R.L. and Foushee, H.C. (1993) 'Why crew resource management? Empirical and theoretical bases of human factors training in aviation', in Wiener, E.L., Kanki, B.G. and Helmreich, R.L. (Eds.): *Cockpit Resource Management*, pp.3–45, Academic Press, San Diego, CA.

Helmreich, R.L. and Foushee, H.C. (2010) 'Why CRM? Empirical and theoretical bases of human factors training', in Wiener, E.L., Kanki, B.G. and Helmreich, R.L. (Eds.): *Crew Resource Management*, 2nd ed., pp.3–58, Academic Press, San Diego, CA.

Helmreich, R.L., Klinect, J.R. and Wilhelm, J.A. (1999a) 'Models of threat, error, and CRM in flight operations', in Jensen, R.E. (Ed.): *Proceedings of the Tenth International Symposium on Aviation Psychology*, The Ohio State University, pp.677–682.

Helmreich, R.L., Merritt, A.C. and Wilhelm, J.A. (1999b) 'The evolution of crew resource management training in commercial aviation', *International Journal of Aviation Psychology*, Vol. 9, No. 1, pp.19–32 [online] https://doi.org/10.1207/s15327108ijap0901_2.

Hughes, R.L., Ginnett, R.C. and Curphy, G.J. (2015) *Leadership: Enhancing the Lessons of Experience*, 8th ed., McGraw-Hill Education, Boston, MA.

İnan, T.T (2018) 'The evaluation [SIC] of crew resource management concept in civil aviation', *Journal of Aviation*, Vol. 2, No. 1, pp.45–55 [online] https://doi.org/10.30518/jav.409931.

International Air Transport Association (IATA) (2013) *Evidence-Based Training Implementation Guide*. International Air Transport Association [online] https://www.iata.org/contentassets/c0f61fc821dc4f62bb6441d7abedb076/ebt-implementation-guide.pdf (accessed 1 June 2021).

International Civil Aviation Organization (ICAO) (2013) *Manual of Evidence Based Training (Doc 9995 AN/497)*, International Civil Aviation Organization [online] https://store.icao.int/en/manual-of-evidence-based-training-doc-9995 (accessed 1 June 2021).

Kanki, B.G. (2010) 'Communication and crew resource management', in Wiener, E.L., Kanki, B.G. and Helmreich, R.L. (Eds.): *Crew Resource Management*, 2nd ed., pp.111–146, Academic Press, San Diego, CA.

Mansikka, H., Harris, D. and Virtanen, K. (2017) ‘An input-process-output model of pilot core competencies’, *Aviation Psychology and Applied Human Factors*, Vol. 7, No. 2, pp.78–85 [online] https://doi.org/10.1027/2192-0923/a000120.

Mansikka, H., Harris, D. and Virtanen, K. (2019) ‘Pilot competencies as components of a dynamic human-machine system’, *Human Factors and Ergonomics in Manufacturing and Service Industries*, Vol. 29, No. 6, pp.466–477 [online] https://doi.org/10.1002/hfm.20809.

McGrath, J.E. (1984) *Groups: Interaction and Performance*, Vol. 14, Prentice-Hall, Englewood Cliffs, NJ.

Muñoz-Marrón, D. (2018) ‘Human factors in aviation: CRM (crew resource management)’, *Psychologist Papers*, Vol. 39, No. 3, pp.191–199 [online] https://doi.org/10.23923/pap.psicol2018.2870.

National Transportation Safety Board (NTSB) (1990) *Aircraft Accident Report United Airlines Flight 232 McDonnell Douglas DC-10-10: Sioux Gateway Airport Sioux City Iowa July 19, 1989 (NTSB/AAR-90/06)*, US National Transportation Safety Board [online] https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR-90-06.pdf (accessed 1 June 2021).

National Transportation Safety Board (NTSB) (2011) *Crash During Approach to Landing. Empire Airlines Flight 8284 Avions de Transport Régional Aerospatiale Alenia ATR 42*-320, Accident Report No. NTSB/AAR-11/02, US National Transportation Safety Board, N902FX Lubbock, Texas, 27 January 2009 [online] https://www.ntsb.gov/investigations/AccidentReports/Pages/AAR1102.aspx (accessed 1 June 2021).

Paries, J. and Amalberti, R. (2000) ‘Aviation safety paradigms and training implications’, in Sarter, N.B. and Amalberti, R. (Eds.): *Cognitive Engineering in the Aviation Domain*, pp.253–286, Lawrence Erlbaum, Mahwah, NJ.

Thomas, M.J.W (2003) ‘Improving organisational safety through the integrated evaluation of operational and training performance: an adaptation of the Line Operations Safety Audit (LOSA) methodology’, *Human Factors and Aerospace Safety*, Vol. 3, No. 1, pp.25–45.

Thoroman, B., Goode, N., Salmon, P. and Wooley, M. (2019) ‘What went right? An analysis of the protective factors in aviation near misses’, *Ergonomics*, Vol. 62, No. 2, pp.192–203 [online] https://doi.org/10.1080/00140139.2018.1472804.

Van Avermaete, J.A.G. (1998) *NOTECHS: Non-Technical Skill Evaluation in JAR-FCL*, Technical Report No. NLR-TP-98518, National Aerospace Laboratory (NLR), The Netherlands.

Wagener, F. and Ison, D.C. (2014) ‘Crew resource management application in commercial aviation’, *Journal of Aviation Technology and Engineering*, Vol. 3, No. 2, pp.2–13 [online] https://doi.org/10.7771/2159-6670.1077.