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Original citation & hyperlink:

Mansikka, HP, Harris, D & 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.
https://dx.doi.org/10.1002/hfm.20809

DOI 10.1002/hfm.20809
ISSN 1090-8471
ESSN 1520-6564
Publisher: Wiley

Pilot Competencies as Components of a Dynamic Human-Machine System

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Keywords: crew resource management (CRM); pilot competencies; team performance; dynamic human-machine system; modelling

Running Head: CRM-DYMO

Pilot Competencies as Components of a Dynamic Human-Machine System

Abstract

This paper formulates a theoretical model of flight deck team performance as a dynamic human-machine system, later referred to as CRM-DYMO (Crew Resources Management-DYnamic MOdel). The model identifies human and machine sub-systems. The human sub-system describes the activities taken by the flight crew and the machine sub-system describes the changes in the aircraft's state. The human sub-system's output forms an input for the machine sub-system, and the machine sub-system's output feeds back to the human system creating a closed loop system. Pilots' performance are described as competencies, which form part of the elements in the human sub-system. This paper concentrates only on CRM competencies as defined by the International Civil Aviation Authority and the International Air Transport Association. In addition to the detailed conceptual model of the human sub-system and associated competencies, the approach is illustrated with reference to two accident case studies. These demonstrate how CRM-DYMO can assist in analysing CRM and help in identifying how the different system components interact. While the case studies demonstrate the benefits of CRM-DYMO, they merely serve as a starting point to understand how CRM works and will hopefully encourage supporting quantitative simulation modelling and empirical studies.

Keywords: crew resource management (CRM); pilot competencies; team performance; dynamic human-machine system; modelling

Introduction

In the aviation industry CRM is simply a 'way of life'; although having its origins on the flight deck its concepts and processes permeate every aspect of flight operations in an airline (Harris, 2011). In 1998 the Joint Aviation Authorities defined CRM as 'the effective utilisation of all resources (e.g. crew members, aeroplane systems and supporting facilities) to achieve safe and efficient operation' (JAA, 1998). CRM evolved as an operating concept after a series of accidents in which the principal cause was a failure to effectively utilise all the human resources available on the flight deck in an appropriate manner while there were no major technical failures on the aircraft.

CRM introduced the disciplines of applied social psychology and management onto the flight deck. CRM has progressed through several distinct eras (Paries and Amalberti 2000; Helmreich, Merritt, and Wilhelm 1999). Initially it was simply focussed on improving management styles and interpersonal skills on the flight deck. Emphasis was placed upon improving communication, attitudes and leadership. By the third generation, the concept had extended beyond the flight deck and into the airline organisation as a whole. CRM training per se was beginning to disappear in the fourth instantiation as the concepts were being absorbed into all aspects of flight training and the development of procedures. Fifth generation extended throughout the organisation and started a culture change. Rather than avoiding error, fifth generation CRM assumes that whenever human beings are involved, error is pervasive. It recognises that humans are fundamentally fallible, especially under stress. Emphasis is therefore placed on using the error management troika: avoid errors; trap errors; and/or mitigate the consequences of errors. While CRM originates from aviation industry, CRM-type practices are now commonplace in other high-risk industries which require teamwork, such as medicine (Yule and Paterson-Brown 2012; Flin et al. 2010; Flin and Maran 2004), nuclear power plant operations (O'Connor et al. 2008; Crichton and Flin 2004) and shipping (Hetherington, Flin, and Mearns 2006; Barnett 2005).

UK CAA Civil Aviation Publication 737 (CAA 2014) defines various requirements for CRM. There are also many frameworks for the evaluation of CRM skills, e.g. the NOTECHS (NOnTECHnicalSkills) framework by Van Avermaete (1998). However, these definitions and frameworks of CRM describe *what* it contains and *how* it should be evaluated, but not how CRM actually works to promote safe and efficient flight. Early seminal works describing CRM (Foushee 1984) acknowledge CRM is a process underpinned by communication but does not describe the relationship between the components in the process. What still remains to be answered is how do the components of CRM inter-relate and combine to promote flight safety and what are the mechanisms at work? This paper addresses these issues.

Proficient performance is often described as a group of competencies, which support behaviours required for an effective task accomplishment. Whereas performance is always situated in the surrounding world, competencies, or the desired set of skills, knowledge and attitudes, are considered independent of the situation and thus support performance even in novel situations (Gilson et al. 1994). Competencies refer to measurable descriptions of behaviours of successful job performance. In the commercial air transport, these are statements of human attributes required for safe, effective and efficient operation of the aircraft (Helmreich, Klinect, and Wilhelm 1999).

The development of commercial pilot competencies was motivated by the realisation that it was practically impossible to train pilots for all possible events that could occur during flying (Cooper, White, and Lauber 1979). It was rationalised that there is a finite number of behavioural traits that, if mastered, would serve to facilitate flight safety – even if the encountered situations were unforeseen and unexpected. Data from accidents, incidents, operations and training were analysed to identify these behavioural traits. The International Civil Aviation Authority (ICAO) and the International Air Transport Association (IATA) used these traits as supporting evidence when they formalised the commercial pilot competencies (ICAO 2013; IATA 2013). These describe the prerequisites for overall satisfactory performance, encompassing both technical and non-technical behaviours.

ICAO and IATA agreed on the following competencies: Application of Procedures (APK), Communication (COM), Aircraft Flight Path Management, automation (FPA), Aircraft Flight Path Management, manual (FPM), Leadership and Teamwork (LTW), Problem Solving and Decision Making (PSD), Situation Awareness (SA), and Workload Management (WLM) (ICAO 2013; IATA 2013). In addition to the listed competencies, Knowledge (KNO) is viewed as an additional competency (IATA

2013). Table 1 summarises the competencies and their definitions. Of these competencies, APK, FPA and FPM represent the technical skills required for pilots' job performance. In contrast, PSD, SA, LTW, WLM and COM cover the non-technical behaviours with social (LTW, COM) and cognitive (PSD, SA, WLM) components. These competencies are generally referred to as CRM, which is the effective utilisation of all available resources, i.e., people, equipment and information (Helmreich, Merritt, and Wilhelm 1999; Adams and Driskell 1992; Lauber 1984). While APK, FPA and FPM are domain specific, CRM related competencies are domain-independent (Salas, Bowers, and Edens 2001).

When ICAO/IATA competencies are used all competencies are considered as processes. As a result, SA is considered to cover both SA (a state) and situation assessment (the process of gaining SA) (Endsley 1995). WLM represents the activities and behaviours required for achieving and maintaining a balanced mental workload. It is therefore possible for a pilot to demonstrate a satisfactory WLM, while still having such unbalanced mental workload that the task performance is negatively affected – or vice versa. Finally, it is somewhat artificial to isolate COM as a separate competency as many of CRM activities involve COM. Therefore, in this paper, COM is considered as an integral component of number of competencies and a mechanism for the delivery of their outputs.

To implement the concept of pilot competencies to training, IATA and ICAO introduced Evidence Based Training (EBT). The basic philosophy of EBT is that during recurrent training pilots are exposed to challenging and novel situations in the simulator. They are expected to develop and demonstrate their resilience by effectively using competencies to maintain a satisfactory safety margin or to quickly recover from any unsafe events. The instructors' and examiners' task is to evaluate the pilots' ability to utilise the competencies and to identify issues with the potential to lead to an unacceptable reduction in safety margin (IATA 2013). Each competency is associated with performance indicators, which are observable manifestations of competency-related behaviours.

An analysis of over 2,500 airline EBT simulator sessions demonstrated that CRM competencies can be described using an 'Input-Process-Output' model (Mansikka, Harris, and Virtanen 2017). Performance in some competencies facilitates better (or worse) performance in others; they cannot be viewed as isolated or disconnected activities. While the different human and team performance models each have their unique characteristics, most of them recognise input, process and output as fundamental phases (Kozlowski et al. 1999; Hackman 1987; McGrath 1984; Steiner 1972). These CRM competencies, together with the aircraft, form a dynamic human-machine system where interconnections and feedback have the potential to generate dynamic complexity (Sterman 2001). By modelling flight deck performance as a dynamic human-machine system incorporating these competencies, the mechanisms by which CRM achieves its goal of safe and efficient flight can be better understood. CRM-DYMO (Crew Resources Management-DYnamic MOdel) describes flight deck team performance where the input, process and output phases are clearly identified. The model further develops the Input-Process-Output model described by Mansikka, Harris, and Virtanen (2017) demonstrating how the different system components interact. This is illustrated with reference to two case studies illustrating instances of how the model can be used to describe instances of questionable CRM performance and good CRM performance.

Flight deck as a human-machine system: Introducing CRM-DYMO

Pilots and aircraft form a dynamic system. CRM performance within such a system is described using competencies which are evaluated using observable behaviours. In CRM-

DYMO, competencies are described as elements of a dynamic feedback system, hence CRM performance is considered to be a result of *all* the interacting components. Observed behaviours in one competency may be affected by performance in another competency, hence performance in one area cannot be considered in isolation. The dynamics of the system over time need to be taken into account when CRM performance is being assessed. CRM-DYMO models CRM behaviours using principles adopted from the fields of systems thinking and system dynamics (Bala, Arshad and Noh 2017).

The combination of CRM competencies and aircraft makes a complex, dynamic human-machine system with two distinct sub-systems; the pilots and the aircraft (Billings 2009; Parasuraman, Sheridan, and Wickens 2000). The human sub-system describes the activities undertaken by the flight crew and the machine sub-system describes the changes in the aircraft's state. The human sub-system's output (responses and control activities) form an input for the machine sub-system. These drive the machine sub-system's internal dynamics, which eventually determine the machine sub-system's output, i.e., the state of the aircraft. The output feeds back to the human system creating a closed loop system. The flight plan and the air traffic controller's clearance form a requirement, or a reference signal, for the actual state of the aircraft. A difference between the machine sub-system's output and the reference signal form part of the crew's task demand (see Figures 1 and 2). Rest of the task demand is constituted by the complexity of the activities required to null this difference. The crew utilises CRM processes to achieve safe and efficient operation. The system is affected by external disturbances and the crews' goal is to manipulate the input of the machine sub-system such that the difference between the system output and the reference signal is minimised.

CRM-DYMO describes the competencies as components of such a system. It is constructed in the spirit of systems thinking and system dynamics, however it does not attempt to strictly follow a system dynamics formalism. Rather, it serves as a starting point to represent the underlying mechanisms of CRM behaviours. The principles of system dynamics are used in a qualitative manner for representing feedback processes and elements of CRM competencies its dynamics. The CRM-DYMO model constructed in this paper concentrates on the ICAO/IATA approved pilot competencies (see Table 1). As this model focuses only on CRM, the system elements not required to understand the dynamics of CRM are discussed just briefly or are excluded completely. For example, while the aircraft, is an essential element of the CRM-DYMO, the internal machine sub-system feedback loops are not considered.

[FIGURES 1 and 2 NEAR HERE]

CRM-DYMO is an extension of the 'Input-Process-Output' model described in Mansikka, Harris and Virtanen (2017). CRM related competencies (KNO, LTW, WLM, SA and PSD) were originally formulated to capture the essential behaviours affecting the pilot performance on a flight deck. The other factors affecting pilot performance include task demand, pilots' cognitive capacity and disturbance. Disturbance comprises of all factors affecting CRM (and machine sub-system) that originate outside of the system. Figure 2 represents a top-level view of the competencies as elements of an open loop human sub-system consisting of input, process and output phases. COM is not included in the human sub-system as a separate competency as it crosses and overlaps the boundaries of other competencies.

Figure 3 illustrates the CRM-DYMO with reference to the human and machine sub-systems. The human sub-system's inputs (i.e., task demand, KNO and cognitive capacity) feed individually to the process phase without affecting each other at the input phase. Task demand is comprised of the sum effect of the reference signal, the machine sub-system output and task complexity. In other words, “task demand = task complexity + (reference signal – state of the aircraft)”. As the inputs effect the system’s state, the rest of the competencies are interacting behaviours used to maintain the system’s state at the prescribed performance standard (ICAO 2013).

[FIGURE 3 NEAR HERE]

In Figure 3, the process phase of the human sub-system includes CRM related competencies (SA, WLM, LTW and PSD), which are competencies required to manage team performance, especially to promote shared and distributed cognition. Hutchins (1995) argued that cognition must be studied within the wider context in which it takes place. CRM on its own also has no utility without being situated on a flight deck (or similar application domain). The main control loop described in Figure 3 emphasises the situated nature of CRM within the wider human-machine system. Data on the modern flight deck is held, transformed and transmitted by number of individuals using highly automated systems, determining the progress of the flight (FPM, FPA) and the management of aircraft systems (APK). The crew uses the devices on the flight deck to enhance their cognitive abilities. To achieve a common understanding (SA, PSD) and KNO of the high-level goals, the crew requires COM, the fundamental process that promotes CRM (Foushee 1984).

When the combination of the human and machine sub-systems are considered, the interactions and feedback-loops related to aviating and navigating tasks between the output phase (or responses: APK, FPA, FPM) and response selection in the process phase (PSD) form a fast paced, inner loop (see the dash lined rectangle and two-headed arrows in Figure 3). PSD, LTW, SA and WLM, on the other hand, form an outer loop (in Figure 3 the interactions of the competencies within the outer loop are illustrated by two-headed arrows) which functions outside the immediate control responses and aims to set the high-level goals and objectives for the flight. For the practical application of the CRM-DYMO, the input and output phases shown in Figure 3 are separated between the crew members as this helps in identifying the individual factors affecting performance. This is also necessary when the crew members have different roles, i.e., pilot flying and pilot monitoring. The process phase, however, by its very nature is common between crew members. The competencies as elements of the human sub-system are described in the following sub-sections.

Input phase - KNO

The input phase includes the individual and contextual input components (Stowers et al. 2017). The individual component is considered to comprise of KNO and the pilot's cognitive capacity – both remaining relatively stable for the duration that the flight deck crew is committed to a task. KNO represents the mental models and scripts stored in each crew member's long-term memory (Endsley and Jones 1997; Gilson et al. 1994), whereas each pilot's cognitive capacity determines their overall cognitive resources available to meet the task demands (Wickens 2008, 1991; Norman and Bobrow 1975). COM is required to integrate the individual crew members' shared and unshared information (Wittenbaum and Stasser 1995) into team knowledge and shared cognition (Cooke et al. 2004). Without necessary KNO, and supporting COM, it will be difficult to perform the shared information processing activities required by the crew to arrive at an effective response selection (PSD) and execution (APK, FPM, FPA). The contextual component in the input phase consists of the task demands imposed by the external flight environment.

Process phase – LTW

Flight crew is a social entity. On the modern flight deck, it typically comprises two pilots but larger crews were common in the past). However, the number of personnel interacting may be considerably larger in other applications where CRM principles are utilised). They have task interdependency, shared common goals, and has a finite life span or performance episode (Dyer 1984). Flight crew's effectiveness is an evaluation of its performance output (APK, FPM, FPA) against some predefined criteria (Hackman 1987; Fitts and Posner 1967). The overall task demands have the potential to exceed the cognitive capacity of an individual pilot. To overcome this potential shortage of cognitive capacity and to produce a synchronised performance output (including error checking) the flight crew engages in team processes to coordinate and manage individual crew members' performance.

Based on the taxonomy by Marks et al. (2001), the team processes include mission analysis, goal specification, strategy formulation, backup, affect management, coordination, conflict management, motivation, confidence building and monitoring of progress, systems and team. According to EBT taxonomy, LTW is a combination of leadership and team processes, while at the same time, team processes such as PSD, COM, WLM and (shared/distributed) SA are categorised as separate competencies (IATA 2013). |It is evident that the competencies related to team processes are overlapping and intertwined.

Process phase - SA

Although ICAO and IATA do not make a distinction between the individual and distributed/shared SA (Stanton et al. 2006; Endsley and Jones 2001), these are separated in CRM-DYMO. Distributed/shared SA is closely linked to distributed cognition. When the Joint Aviation Authorities defined CRM as ‘the effective utilisation of all resources (e.g. crew members, aeroplane systems and supporting facilities) to achieve safe and efficient operation’ (JAA 1998) it effectively, but inadvertently, defined CRM as an application of distributed cognition. Distributed cognition proposes that KNO and cognition (SA, PSD) are not confined to an individual but are distributed across people interacting in teams, using tools and/or artefacts. The distributed cognition concept takes a holistic, system-wide based view of people interacting with artefacts within an environment.

The cognitive processes found in individuals also apply to teams (Salas and Fiore 2004), and the flight crew is therefore considered an information processing unit engaged in shared cognition (Hinsz, Tindale, and Vollrath 1997). Shared cognition among the crew is predicated upon shared understanding of the situation (SA), aims and objectives as well as the required method of achieving them (PSD). This shared cognition includes information encoding, storage and retrieval between crew members. Shared cognition is based upon the notion of transactive memory (Wegner 1995) which is a collection of knowledge possessed by each crew member and a collective awareness of who knows what (Austin 2003).

Process phase – PSD

PSD includes problem solving, decision making and response option selection before the response execution (APK, FPM, FPA in the output phase). Flight deck PSD is a form of naturalistic decision making (Klein, Calderwood, and Macgregor 1989) characterised by high temporal demand, conflicting goals and sometimes lack of clear standards of correctness or coupling between event outcome and decision process (Orasanu and Martin 1998). As suggested by Neisser (1976), PSD is based on a cyclical relationship between pilots’ shared mental representations, or shared mental models (Richardson and

Ball 2009), and perceived difference between the machine sub-system's state and the reference signal. This interaction between the flight crew and the task environment forms the foundation of the flight crew's shared SA (Endsley and Jones 2001) and is facilitated by COM. Although transactive memory systems contain more and better information than any individual alone could possess, teams are not necessarily better at PSD than individuals. For the team to be effective, COM needs to be effective to make the group aware of the collective knowledge that is available and where it resides within the distributed human-machine system (Wegner 1987).

Process phase – WLM

WLM describes how the flight crew minimises the process loss (the characteristic of teamworking which prevents a group from reaching its full potential) and a result of inadequate coordination of effort (coordination loss), poor communication, or ineffective leadership (Urban et al. 1996). Mental workload and WLM determine which team processes are required (Kleinman and Serfaty 1989): one crew member with an unbalanced mental workload can negatively impact the performance of the team as a whole (Dyer 1984). WLM is achieved by reallocating crew's cognitive resources (Littlepage and Poole 1993) and by altering the group's performance strategies (Härtel and Härtel 1997). WLM is a management activity – it is not a synonym for mental workload. It is highly related to other CRM competencies such as COM, PSD, SA and LTW activities, all aimed at balancing crew members' mental workload.

Process phase - COM

The conduct of any flight is an exercise in LTW and COM, which extends beyond the flight deck and the aircraft. From the system dynamics perspective, COM is not seen as a separate variable and therefore not included explicitly in the CRM-DYMO. As outlined by McGrath (1984), it crosses and overlaps the boundaries of CRM competencies by enabling team's task performance-oriented behaviours, social relationships, leadership and followership. COM is the central mechanism to promote shared cognition (SA, PSD), team coordination and crew performance (APK, FPM, FPA). The crew, acting as a coordinated team, manages APK, FPA and FPM through a series of nested loops facilitated by COM, exploiting the human and non-human information processing capabilities within the system. Failures in COM derail the shared cognition, lead to poor performance in other competencies and result in poor performance output (Stout et al. 1999).

Output phase - APK, FPM and FPA

From the human information processing perspective, APK, FPM and FPA are responses or performance outputs preceded by team performance and central processing (Mathieu et al. 2008; 2000; Wickens 2002; Wickens and Flach 1988). When the competencies are considered as the elements of the open-loop human sub-system (see Figure 2), APK, FPM and FPA are the immediate behaviours related to aviating, navigating and managing the aircraft during the output phase. The output of the human sub-system also forms the input for the machine sub-system.

CRM-DYMO: Closing comments

CRM-DYMO is based on an input, process, output model of human and team performance. As an addition to previous models, the CRM-DYMO also takes into account the relationships and feedback between the system's elements and the psychological principles underlying the competencies. The premises behind CRM-DYMO are well established and broadly accepted.

Compared to existing models, CRM-DYMO provides insight concerning how the components of CRM inter-relate and describes the causal relationships between the different competencies and other system components. The following sections illustrate the operation of CRM-DYMO using two accident case studies.

Case Study 1: Empire Airlines Flight CFS8284 Accident, Lubbock, TX

Introduction

This chapter describes an accident involving Empire Airlines flight CFS8284, an Avions de Transport Régional Aerospatiale Alenia ATR 42-320, which crashed on approach to Lubbock Preston Smith International Airport in freezing drizzle and mist on 27 January 2009 after encountering icing conditions while en route[1]. First, a brief description of the accident is provided, followed by two alternative conclusions of the probable causes for the accident: one by the National Transportation Safety Board (NTSB 2011) and other based on the analysis utilising the CRM-DYMO.

Accident

The flight departed Fort Worth at 03:13 (local time) from Fort Worth Alliance Airport, Texas. As the aircraft descended from 14,000 to 8,000 feet (ft) towards the Lubbock Preston Smith International Airport the Captain, who was the pilot monitoring, performed the descent and approach checklists. Anti-icing was set. At 04:33 (local time) air traffic control cleared the flight for an approach to runway 17R and instructed them to contact Lubbock Tower. At 04:34 (local time) the flight was cleared to land. Very shortly after this, the First Officer called for flap 15°, deployment of landing gear and the landing checklist. The aircraft accelerated briefly to about 160 knots (kts) and the First Officer decreased engine power to compensate. She noted that this need for power reductions was unusual. At this point the Captain observed that the aircraft ‘had no flaps’. The flight data recorder showed that a flap asymmetry had occurred. As a result of icing, the right-hand flaps did not extend, and the left-hand flaps extended only partially (8° to 10°). The autopilot countered the flap asymmetry by applying aileron deflection. At this point the aircraft was about 1,400 ft AGL (above ground level). Neither crew member discussed a procedure or checklist to address the flap issue. The Captain attempted to troubleshoot the flap problem while the First Officer continued to fly the aircraft using the autopilot. The Captain checked the circuit breakers (none were out) and then moved the flap handle back to the ‘up’ position.

The aircraft’s airspeed began to decay from about 160 to 125 kts and approximately 26 seconds after (at 900 ft AGL) the Captain commented on the flap anomaly, the aural stall warning sounded and the stick shaker activated causing the autopilot to disconnect. The Captain instructed the First Officer to continue flying the aircraft. However, he was unaware that the autopilot had disconnected and there was no aural warning captured on the cockpit voice recorder. The First Officer increased engine power to about 70 percent torque and began flying the approach manually. Airspeed increased. The First Officer then asked if she should go around, in response to which the Captain instructed her to continue the descent. At approximately 700 ft AGL the Captain took over control at the request of the First Officer.

The aircraft was high and to the right of the required approach path. The Captain reduced the engine power to about 10% torque. The stall warning and the stick shaker activated for a second time concurrent with the terrain awareness and warning system (TAWS) warning. Height was about 500 ft AGL and speed was 156 kts. In the ATR 42-320, if a flap asymmetry occurs due to a restriction (such as icing) and it is subsequently removed, hydraulic pressure in the system will automatically move the flaps to a symmetrical position, which is the average of the right and left flap positions when the asymmetry occurred. This occurred automatically at about this point after the Captain's control inputs. The left-hand flaps retracted to approximately 4.5° with the right-hand flaps extending to approximately 4.5°, thereby removing the need for control inputs to counteract the flap asymmetry. Normal landing flap would be 30° (116 kts).

The flight continued to descend, however the airspeed decreased from about 156 to 129 kts. As the Captain called for maximum propeller speed, the aircraft aural stall warning and stick shaker activated again, and the aircraft began to roll right wing down. Height was 150 ft AGL and airspeed 123 kts. During the final seconds of the flight, the aircraft first rolled right 35°, then left to a bank angle of 50° before rolling again right just before it impacted the ground. The aircraft came to rest at the right side of the runway, about 200 ft west of the runway centreline. The Captain sustained serious injuries. The First Officer had only minor injuries.

The aircraft manufacturer calculated that at the time the flap asymmetry occurred, because of icing there was a drag increase corresponding with about 23 percent of total power. Published minimum safe airspeed with flaps retracted in icing conditions was published as 143 kts. Following the autopilot disconnect, the mental workload of the flight crew was high because of the flap asymmetry, a 10 kts tailwind, and ice accretion. Post-accident analysis of the airspeed bugs indicated that they had been incorrectly set. Speeds corresponded more closely to the take-off reference speeds rather than the approach and landing speeds (i.e., they were lower that was required for safe flight). Furthermore, the Captain and the First Officer also had different settings in their airspeed bugs.

Contrary to Standard Operating Procedures (SOPs) the Captain opted to continue the approach when the flap anomaly was detected (pilots are trained to call for a go-around to give them the opportunity to perform the abnormal flap procedures in the aircraft's quick reference handbook). The First Officer did not object. Furthermore, during the approach neither pilot adequately monitored the airspeed, which decayed until the stick shaker activated. Company SOPs for both stick shaker activation and TAWS warning also require immediate application of maximum power and execution of a go-around. Again, the First Officer did not intervene.

NTSB's conclusions

The National Transportation Safety Board (NTSB 2011) concluded that the probable cause was:

> *'…the flight crew's failure to monitor and maintain a minimum safe airspeed while executing an instrument approach in icing conditions, which resulted in an aerodynamic stall at low altitude. Contributing to the accident were 1) the flight crew's failure to follow published standard operating procedures in response to a flap anomaly, 2) the captain's decision to continue with the unstabilized approach, 3) the flight crew's poor crew resource management, and 4) fatigue due to the time of day in which the accident occurred and a cumulative sleep debt, which likely impaired the captain's performance.'*

CRM-DYMO analysis

The accident was analysed using the CRM-DYMO described in Figure 3. The superscripted numbers in the text refer to the system elements of the CRM-DYMO presented in Figure 4. COM as an essential factor is included as a superscript when necessary. In Figure 4, the input and output phases are separated between the Captain and the First Officer.

At the initial stages of the flight, the crew did not correctly operate the aircraft's systems[1], neither did they cross check each other's instrument settings [COM]. As a result, the airspeed bugs were incorrect and different between the crew members, contributing to the development of incorrect mental model and inaccurate shared SA[2] at the later stages of the flight. The aircraft was affected by icing[3]. This resulted in flap anomaly[4] during the final approach. The First Officer did not identify the flap anomaly[5,6], and as a team the crew did not effectively identify, consider and communicate their options or concerns[7,8, COM] – mainly as the mental models (and their shared SA) of the crew were not aligned. Both the Captain and the First Officer were unaware of the state of the aircraft and its systems[9, 10] once the aural stall warning sounded and the stick shared activated. The warnings and flap indicator systems (both on the flight deck and externally) were poorly designed, however it is the flight crews' response and handing of the situation (i.e. CRM issues) that are of primary concern in this discussion.

The Captain arrived at a premature and poorly informed decision[11,12] to continue the approach and instructed the First Officer to continue flying the aircraft – despite the First Officer communicating her concern about the state of the aircraft[13,COM]. The Captain's delayed decision to take over the controls[14] unnecessarily increased the mental workload of the First Officer[15]. By the time the stall warning cues activated again, the Captain had cornered himself in a situation where the task demand had exceeded[16] his cognitive capacity[17] to cope with it. As a result, he had committed to the selected course of action without being capable of reviewing his decision[18]. He was also unable to re-building his situation awareness[19] to support such activity, or to effectively engage the First Officer [20, COM] and help share some of the task load[21]. In combination, the Captain's deficiencies in a number of competencies resulted in a failure to solve the fundamental tracking-stabilisation problem (cf. Figure 1) and it became almost impossible for the crew to null the difference between the state of the aircraft and the reference signal. Eventually, the subsequent output phase [22, 23,24] was almost certain to fail.

[FIGURE 4 NEAR HERE]

Case Study 2: United Airlines Flight 232 Accident; Sioux City Airport, IA.

One of the main issues with analysis of accidents is that while they are well-documented, they tend to be a story of failure. Case studies of CRM successes are rare (hopefully every flight, every day is a CRM success). However, there are instances of accidents and incidents which have been subject to forensic analysis where there have been excellent examples of CRM practice recorded and analysed.

United Airlines (UAL) Flight 232 was a McDonnell-Douglas DC10-10 on scheduled flight from Denver to Chicago (NTSB 1990). It departed Stapleton International airport on July 19, 1989 just after 2 pm. Just over an hour into the flight, the fan disk of No. 2 (centre) engine explosively disintegrated. Debris penetrated all three hydraulic systems leading to complete loss of flying controls. Initially, the Captain and Flight Engineer could not shut down the engine using SOPs (the thrust lever was stuck), however they finally shut it down using the fuel cut off. As a result of damage to the flight control surfaces, the aircraft began to roll to the right, almost in danger of rolling inverted and complete loss of control. However, working as a coordinated team the pilots were able to diagnose the situation and re-gain control of the aircraft using only differential throttle to the two wing-mounted engines: The Captain regained control by closing left-hand engine thrust lever and firewalling the opposite engine. Having recovered control the Captain discussed options with both Air traffic control (ATC) and UAL dispatch: UAL proposed Lincoln, Nebraska (longer runway, lower crosswind) however ATC informed UAL 232 that Sioux City was directly ahead. Simultaneously the Flight Engineer discussed the failure with San Francisco Maintenance facility.

A deadheading check airman who had made himself known to the flight crew and had taken up a position on one of the jump seats was sent back by the Captain into passenger cabin to make a visual inspection of the flying surfaces. On his return he assumed a position behind the throttle quadrant and took control of heading and descent rate by using differential throttle using instructions issued by the Captain. As the check airman was now occupied manipulating the thrust levers, when a Flight Attendant reported damage to the wing the Captain sent back the Flight Engineer to make a visual inspection of the damage.

Prior to attempting a final approach into Sioux City, fuel was jettisoned using the automated system to reduce landing weight and the crew discussed the merits of lowering (or not) the landing gear to act as a shock absorber. The gear was extended. The deadheading check airman continued to control the heading and descent rate of the aircraft using differential throttle as instructed by the Captain. ATC helped to navigate the aircraft away from overflying Sioux City, communicating via the First Officer. As a result of the crew acting in a coordinated manner, they were able to line the aircraft up with runway 22 at Sioux City Airport but with a high sink rate (1,620 ft/min at an airspeed of 215 kts). At about 100 feet the nose pitched downward and the right wing dropped. The DC10 touched down slightly left of the centreline, skidded to the right and rolled inverted. Of the 296 people on board 111 died.

Despite the fatalities, the actions of the pilots were considered to be a prime example of successful CRM because of the manner in which they handled the emergency. No procedures or prior formal training addressed the situation that they found themselves in. The NTSB accident report concluded that "*the UAL flightcrew performance was highly commendable and greatly exceeded reasonable expectations*" (p.76).

Analysis of the accident using CRM-DYMO serves to demonstrate that the approach is generic (not restricted to the failure case) and can be extended to crews of more than just two people.

[FIGURE 5 NEAR HERE]

CRM-DYMO analysis

As previously, the superscripted numbers in the text refer to the system elements of the model presented in Figure 5. COM is included as a superscript when necessary. In Figure 5, the input and output phases are separated between the Captain, First Officer, Flight Engineer and the deadheading Check Airman. The approach to the management of the problem can be divided into three phases: initial reaction to the engine problem; stabilisation of the situation, diagnosis and planning; final approach and landing.

After the initial disintegration of the centre engine and the loss of flying controls[1], the Captain and First Officer had to work to develop a quick solution and to stabilize the problem in the absence of clear information[2] and no relevant SOPs. They needed to reason from first principles, communicate quickly, share knowledge [COM, 3, 4, 5], and act decisively to regain control of the aircraft[6].

Having stabilized the situation, tasks were then distributed between crew members to assess the damage [COM, 7, 12], generate options[8] and develop potential solutions[9], with regards to suitable diversionary airfields. The task of controlling the aircraft itself was distributed between the Captain (issuing directions[10]) and the deadheading airman who was manipulating the thrust levers[11] to execute them. The distribution of tasks[13] in this manner ensured that no one person was subject to higher workload than was required. Constant communication ensured the development of a shared mental model on the flight deck [COM].

Prior to final approach, fuel was jettisoned[14] and the crew engaged in a joint decision-making process concerning the merits of lowering the landing gear as a shock absorber. All crew were engaged in this process, pooling knowledge and ideas[COM, 15]. Control remained with the Captain and deadheading airman[16] but with navigational assistance from the First Officer and ATC[17], a distribution of tasks which ensured that situation awareness remained high but workload also remained within reasonable bounds[18].

Concluding comments

The ultimate objective of CRM is safe and efficient flight. This is based upon the inputs and processes in the human and machine sub-systems in response to the requirements of the flight objectives and in response to any disturbances. CRM is predicated upon clear and effective communication between both the pilots, and the aircraft and the pilots. Without this communication the information available in the heads of the people and resident in the aircraft automation cannot result in effective distributed cognition; the 'bigger picture' cannot be formulated amongst all the human and non-human elements to accomplish safely the goals of the flight.

In the case of the accident at Lubbock, TX the NTSB's statement that the '*crew's CRM was poor*' is merely a starting point for an analysis rather than a finding. CRM-DYMO provides a diagnostic framework: it can assist in identifying what was wrong with the CRM and how the different system components interacted and affected the overall state of the system. Similarly, in the Sioux City DC10 accident, it can now be better understood how 'good' CRM resulted in a more positive outcome than would be expected. CRM-DYMO assists in building an in-depth understanding of factors affecting flight deck team performance both in a positive and negative way. This aids in determining the root and contributing factors underlying flight deck team performance compared to analyses where the system elements are taken in isolation. In addition, when the relationships between the different competencies and other system components are properly understood and analysed, crew performance evaluations can be more accurate and detailed, resulting in more efficient training interventions.

It should also be noted that the CRM-DYMO approach is domain independent. It can potentially be utilised in larger teams and other, non-aviation applications where the same competencies underlie effective team performance.

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Table 1 Summary of pilot competencies (IATA, 2013; ICAO, 2013)

Competency	Competency Description
APK	Identifies and applies procedures in accordance with published operating instructions and applicable regulations using the appropriate knowledge.
COM	Demonstrates effective oral, non-verbal and written communications in normal and non-normal situations.
FPA	Controls the aircraft flight path through automation, including appropriate use of flight management system(s) and guidance.
FPM	Controls the aircraft flight path through manual flight, including appropriate use of flight management system(s) and flight guidance systems.
LTW	Demonstrates effective leadership and team working.
PSD	Accurately identifies risks and resolves problems. Uses the appropriate decision-making processes.
SAW	Perceives and comprehends all of the relevant information available and anticipates what could happen that may affect the operation.
WLM	Manages available resources efficiently to prioritize and perform tasks in a timely manner under all circumstances.
KNO	Demonstrates the knowledge required for safe and efficient operations. Demonstrates ability to source the necessary information.

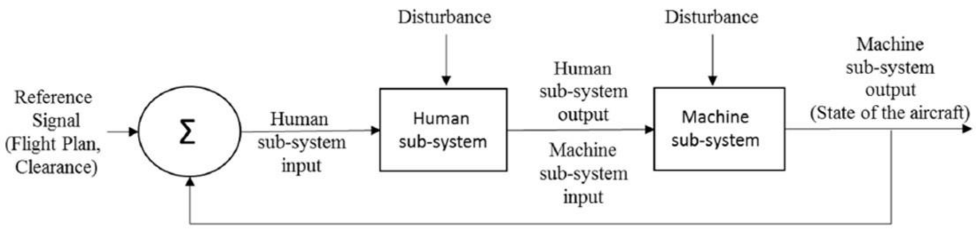

Figure 1. **Top level representation of the conceptual model of a feedback dynamic system consisting of human and machine sub-systems.**

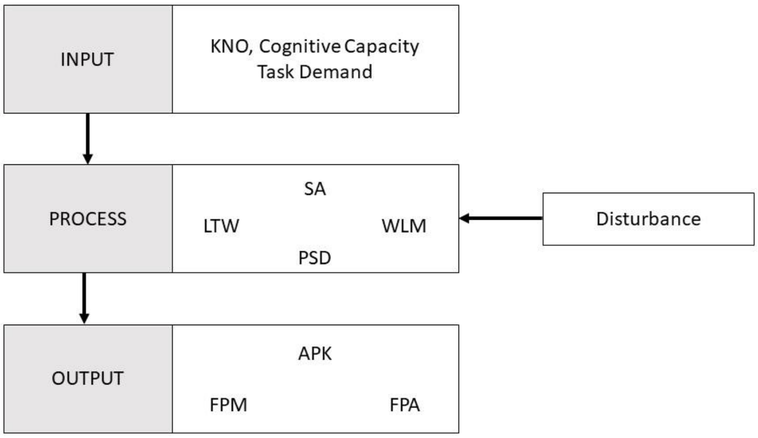

Figure 2. **Top level representation of competencies as elements of an open loop human sub-system.**

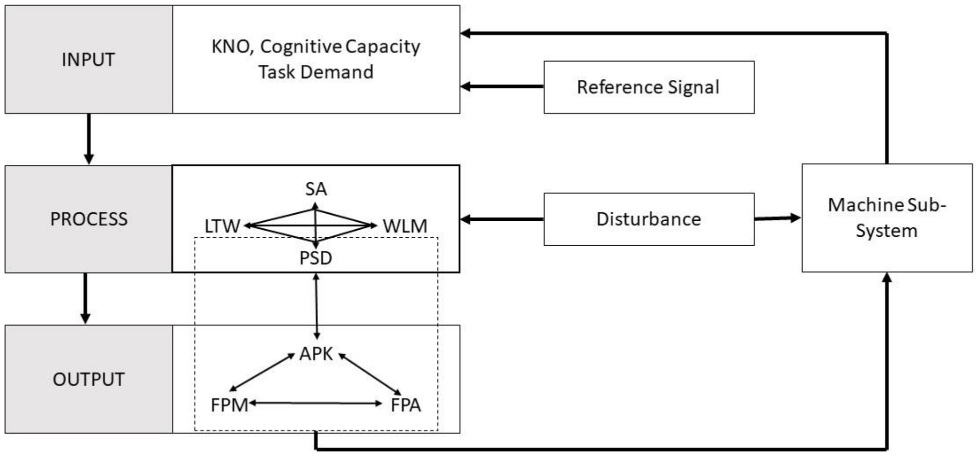

Figure 3. **CRM-DYMO with human and machine sub-systems. The inner loop is located within the dashed rectangle. The two-headed arrows represent the interactions and feedbacks between competencies.**

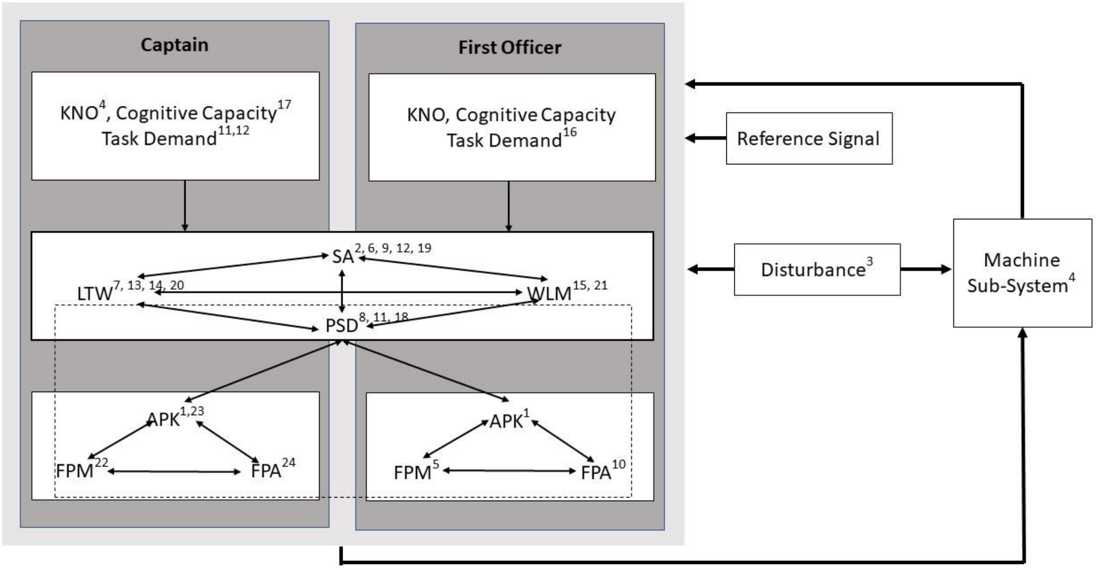

Figure 4. Factors leading to an accident interpreted as elements of a dynamic system (Empire Airlines Flight CFS8284 Accident, Lubbock, TX). To highlight the different roles of the flight crew, the human sub-system has been divided between the Captain and the First Officer.

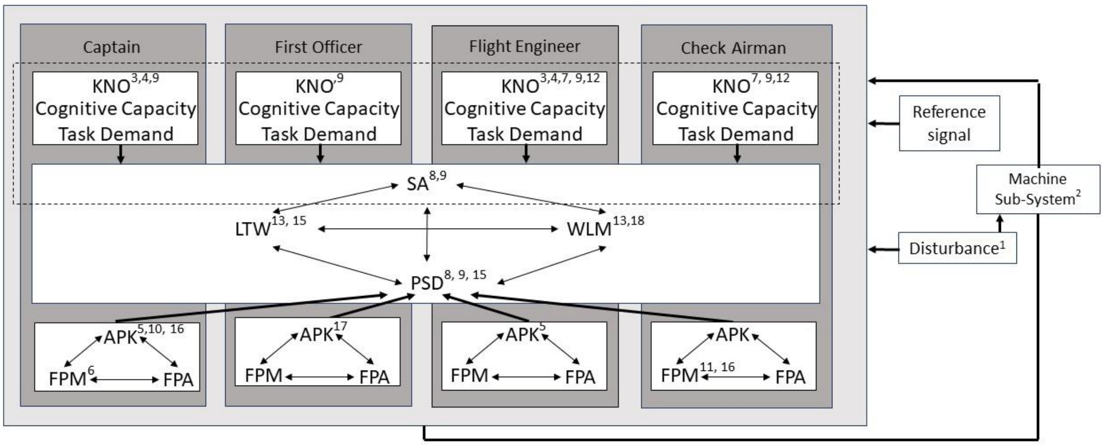

Figure 5. **Factors leading to an accident interpreted as elements of a dynamic system (United Airlines Flight 232, Sioux City Airport, IA). To highlight the different roles of the flight crew, the human sub-system has been divided between the Captain, First Officer, Flight Engineer and Deadheading Airman.**