Application of a Systems Perspective to Crew Resource Management

Norman MacLeod

Abstract

Historically, Crew Resource Management (CRM) training has focussed on interactions between crew members. Despite being a mandatory requirement in many countries and almost universally recognised as being of benefit, the return on the investment in CRM training is often questioned. This paper sets CRM within a broader systems context. A hierarchical model of aviation is developed and crew performance is situated within that model. By adopting a systems approach, it is suggested that more significant training targets can be identified.

Introduction

The recognition of the significant role played by human actors in aircraft adverse events gave rise to the training domain we now refer to as Crew Resource Management (CRM). Although the original definition of CRM as 'making full use of all available resources' (Lauber) remains unchanged, the manner in which training has been delivered has gone through various iterations (Helmreich. Merritt and Wilhelm). The most significant change in CRM since its inception has been the shift from a set of theoretical concepts to a greater recognition of the need to operationalize theory in terms of observable, effective workplace behaviours. In Europe the assessment of CRM skills is a licensing requirement (JAA). Because CRM is positioned in relation to failure, it can be considered a safety management tool in the social domain. However, CRM still has a number of significant weaknesses. First, it remains divorced from the process of work, being treated instead as an additional skill set. Although facilitators are encouraged to embed CRM concepts in all forms of instruction, the prevailing model remains a discrete classroom event. Second, training is not based on any meaningful model of workplace failure such that the relationship between action and outcome can be made explicit.

This paper will explore the application of systems thinking to aviation in order to, first, reveal the manner in which processes fail and, second, to explore the operator competences associated with the safe and efficient conduct of flight. Systems thinkers (Leveson, Daouk, Dulac. & Marais. (2003), Rasmussen & Svedung (2000)) view organisations as collections of interrelated functional components held in a dynamic equilibrium. Each level in the hierarchy can be described in terms of its specific properties and the influence it exerts on subordinate levels. In this paper a specific incident involving aspects of crew performance will be described which will then be analysed using a hierarchical systems model. The resulting analysis will be used to examine current understanding of CRM skills.

The Event

On 8 August 2003 an ATR 42-300 en route from London Luton Airport to Galway, in the Irish Republic, experienced an in-flight shut down of the right-hand (RH) engine as a result of fuel exhaustion (AAIB 2005). Fog earlier in the day had delayed the departure of the flight from Galway. As a result, the rostered crew had insufficient duty time remaining in which to complete the 4 planned sectors. The aircraft, therefore, made an intermediate landing in Dublin to change crews. In-bound to Dublin the aircraft left-hand (LH) fuel gauge malfunctioned and was reading empty. This was not the first time the aircraft had suffered this particular problem. Given the delay and the fact that the operating crew were confident that the maintenance response would be to sign off the defect without rectification, no technicians were called and the aircraft was handed over to the new crew. Aware of the problem, and having had the same experience himself with this aircraft, the on-coming Captain was comfortable with the situation but decided to refuel in Dublin, incurring yet further delays. The flight to Luton, and then to Waterford, was uneventful and the pilots found that by recycling the fuel panel they could occasionally get the LH gauge to give a fairly accurate reading. Fuel was taken on at Waterford, the process being supervised by the Captain. The departure from Waterford was slightly delayed because the baggage handlers at Luton had incorrectly loaded bags from another flight. These had to be removed. The penultimate sector was back to Luton where the Captain, again, supervised the fuelling. A combination of factors resulted in the Captain inadvertently diverting all of the uplifted fuel into the LH fuel tank. The crew detected a lateral imbalance after take-off and an attempt to rectify the problem was made by feeding both engines from the LH tank for 15 minutes. At the same time, the RH fuel gauge showed lower than expected contents, eventually dropping to empty, but this was dismissed as being symptomatic of a similar failure as had been encountered with the LH tank gauge. At 23:06, 40 miles west of Dublin, the RH engine stopped and a precautionary landing was made at Shannon. This brief description of the key aspects of the flight will be examined in more detail in subsequent sections but, first, a systems model will be used to describe the context of the event.

A Systems Perspective

Rasmussen and Svedlung draw a distinction between describing socio-technical systems either in terms of their structural elements or their dynamic behaviour. Traditionally, systems are decomposed into elements that are then modelled in terms of interactions within elements. However, the authors observe that control of hazardous processes is achieved through nested levels of decision-making and the dynamic nature of systems can be better represented in terms of activities and decisions. A complete description of dynamic behaviour must reflect the fact that work situations present actors with degrees of freedom with respect to possible solutions to problems. Actors make rational choices between courses of action and these sometimes result in error. The relationship between rational choice and risk is important in understanding systems behaviour. Frosch (2006) suggests that all acts have an associated level of risk and that workplace activity can be understood as the selection between risks. He introduces the concept of countervailing risk to describe the situation where attempts to avoid a specific risk (in effect, to act safely) induce other, different risks.

Leveson and her colleagues identify 4 specific properties of systems that have significant importance for safety: Hierarchy, Emergence, Control and Communication. The first property, Hierarchy, relates to the way functional units are arranged such that higher order elements exercise control over lower order elements, typically through constraints on freedom of action or access to resources. Emergence refers to the fact that the properties of a level in a hierarchy are the product of the way that level functions rather than arising from the structural aspects of that level. Control describes the direction of influence between levels in the hierarchy and Communication encompasses the flows of information between levels. The context of the fuel exhaustion event can be captured in a model comprising 5 hierarchical levels:

Level 1 – The Workspace
Level 2 – The Collaborative Workgroup
Level 3 – The Organisation
Level 4 – Constraints
Level 5 – The Environment

A Hierarchical Analysis of the Aviation System

Level 1 – The Workspace. The lowest level in our hierarchical system is that of the individual actor engaged in activity in a workspace. The workspace is the site for skills, tools and procedures to be brought together in order to solve production problems. In the ATR incident pilots and refuellers are specific actors whose workplace performance is open to analysis[1]. In the case of the pilots, the manner in which procedures associated with technical problems were implemented, the conduct of aircraft refuelling and aspects of the control of the aircraft can be identified as specific instantiations of the workspace. Level 1 is concerned with the internalisation of working practices by individuals and their subsequent manifestation as skilled performance. For example, the report contains 3 variations on operator enactment of an element of the refuelling process: the Captain elected to manually operate the fuel valves in order to accomplish refuelling; one of the ground refuellers declined to operate the fuel valves manually because he had never been taught that task, another accepted provided that, first, the Captain demonstrated what to do. Another example was the FO detecting an imbalance in the aircraft after take off and commented on that fact to the Captain. Level 1 activity involves the application of skills to accomplish goal-directed tasks and has traditionally been the focus of job-related training and qualification.

Level 2 – The Collaborative Workgroup. Whereas Level 1 addresses issues of individuals engaged in production, Level 2 deals with the collaborative nature of production in that much activity in the workplace requires the combined inputs of multiple actors. Workgroups can be categorised against at least 4 criteria: constitution, location, tasking and association. Collaboration takes place within formally constituted

---

[1] Although the baggage handlers made errors, no information regarding casual factors was contained in the report.

teams, such as the 2 pilots comprising the technical crew of the aircraft, or between ad hoc teams, such as the Captain and the Refuellers at Luton and Waterford, that come together temporarily to achieve a limited goal. As such, the boundaries of the workgroup are porous and teams are reconfigured as the flight progresses. Location refers to team members' physical proximity to the task. Some actors are actually located in the workspace while others are engaged at a remove from events. The crew of the aircraft are a constant element of the task. Ground staff have a temporary attachment to the workspace. Operational support staff and ATC are removed in space and time from the physical workspace and their efforts are mediated through additional tools and processes. Tasking relates to the fact that differences exist between actors in terms of the numbers of teams they participate in. So, Air Traffic Controllers will deal with several aircraft concurrently but an aircraft will deal with a single ATC agent. This has implications for the attentional resource actors assign to specific tasks. Association refers to the degree of participation actors have in specific elements of the collaborative task. For example, some teams complete activities which they then pass across to other teams, such as the first crew who decided not to report the LH fuel gauge. Some tasks are completed in parallel. So, the baggage handlers at Luton completed their task in parallel with other activities associated with the aircraft turn round. The fact that the job was done incorrectly was not discovered until after the incident aircraft landed at Waterford. The aircraft Captain had a close association with the process of refuelling but his association with loading the bags was restricted to processing the aircraft load sheet.

The discussion between the Captain and the First Officer (FO) about the lateral imbalance after take off from Luton and the interaction between the Captain and the refuellers at Luton and Waterford about the operation of the toggle valves are examples of Level 2 functioning. In the first case, the immediate crew (Captain and FO) are engaged in resolving an anomaly in aircraft performance. In the latter case, members of the extended crew – aircraft and ground personnel – are engaged in creating a solution to the task of refuelling the aircraft. The traditional focus of CRM has been the interaction between crew members, initially restricted to the flight deck but increasingly recognising that cabin-crew and other, off-aircraft, actors are significant. Thus, the focus of CRM has been on Level 2 processes.

Level 3 – The Organisation. Actors at Level 3 organise work to the extent that they enable work while actual production is delegated to lower levels. They exploit resources to achieve goals defined in commercial terms. Activity at this level is concerned with provision and organisation through initiating, supporting and sustaining production. In this example, the operator of the ATR 42 provided an aircraft, a crew and sufficient ground-based infrastructure to support revenue generation activity based on moving passengers between pairs of locations. Within the context of the report, activity at Level 3 was directed at resolving the disruption caused by the fog. The airline was trying to restore normal scheduled operations as fast as possible within the constraints of crew and aircraft availability and this was manifested by the crew change at Dublin and the revised departure times. Level 3 activity was also reflected in the arrangements for ground handling at the various destinations.

Level 4 – Constraints. This level comprises entities that reach across the production process. They provide the tools of production that are used by lower order actors. They also provide the regulatory framework within which operations are conducted. Actors at Level 4 facilitate operations at lower levels but, importantly, they also constrain action in that they set boundaries within which operations at lower levels must be conducted. In effect, this level functions by granting permissions to the levels below. These permissions typically take the form of certificate and licenses.

In the example, crew duty time limitations imposed by the Irish Aviation Authority meant that the assigned crew could not complete the 4 sectors that comprised their duty. This required the crew change that took place during the intermediate stop at Dublin. This act represents the operational solution, created at Level 3 within the constraints imposed at Level 4.

The aircraft manufacturer is also a Level 4 actor in that, through its design of the tool of production, it has configured the workspace for Level 1 and 2 actors. In the example, the design of different elements of the aircraft fuel system shaped the performance of the Captain, specifically, and the crew subsequently. In particular, the Fuel Gauges, the Drip Sticks, the Manual Fuel Valves and the Fuel Panel all have properties that form part of the construction of the task. Constraints are designed into the system by virtue of the fact that the manufacturer has a view of how systems will be operated. In some cases, constraints are codified through procedures and declared limitations. Some constraints are absolutes: the aircraft will not fly below a defined airspeed or above a defined weight. Some constraints are implicit. For example, the fuel gauge indications represent the remaining aircraft endurance.

Activity at Level 4 is removed in space and time from the scene of the action and is often the site of activity that can be described as fallible, resulting in the creation of latent error (Reason). For example, the aviation authority specifies the airworthiness requirements that must be met by aircraft manufacturers function before an aircraft can be released for operational service. The manufacturer must develop engineering solutions that fulfil those requirements but remain within economic and ergonomic bounds. The design of the fuel system on the ATR aircraft is an example of the manner in which airworthiness regulations are embodied in technology. However, the use of the fuel gauge to provide an input to the low fuel indicator, as opposed to an independent source, rendered the warning system invalid should the fuel gauge fail.

Level 5 – The Environment. Level 5 captures the broader environment in which Levels 1-4 function. It borrows from traditional systems thinking in that factors in the environment can influence events at Levels 1-4 but cannot, in turn, be influenced by them. In the example, the fog constitutes a Level 5 actor. It influenced the crew in that it constrained operations but the crew, in turn, had no influence on the fog. The commercial marketplace can also be seen as a Level 5 agent. Aer Arran identified a set of routes that allowed it to extract value from the commercial environment. As such, it was concerned to minimise the impact on customer satisfaction of the delays developing as the flight progressed. Competition from alternative forms of transport and other airlines operating on the same routes are factors that are addressed by Level 3 actors but the economic climate within which air transport operates is an environmental factor. The economic climate will determine the viability of an air route but providing capacity is unlikely to influence the economic climate. This is reflected in a UK CAA report that suggests that the growth of low-cost carriers has done little to generate increased air travel but, rather, has simply led to a segmenting of the market (CAA 2006)

Properties of Systems

The first property of a system is its hierarchical nature. In the previous section the components of the aviation hierarchy were outlined. However, it is important to remember that the levels in the hierarchy are not primarily structural in nature. Instead, each level exhibits characteristic behaviour associated with its role in the system. This aspect is also reflected in the second characteristic of systems identified by Leveson *et al.* Each level in the hierarchy has characteristic properties not shared by other levels that can be described in structural and functional terms. However, each level also possesses dynamic properties and it is the manner in which levels in the hierarchy behave that is captured in the concept of emergence. Thus, Level 1 in the analysis can be characterised by individual actors doing acts of work. Level 2 requires behaviours of collaboration between individuals but here action is in terms of configuration of social groups in order to allow individuals – Level 1 – to complete their tasks. Leveson argues that safety is an emergent property rather than a structural component. Safety is not designed into systems but is a dynamic function of the way systems work. Of course, safety is designed into components through barriers, interlocks, warnings and indications etc but these structural elements are only effective to the extent that they form part of the dynamic response to situations. Gherardi and Nicolini (2000) similarly propose that safety is a property of the way operators function within systems. In short, organizations are not safe; people act safely within organizations.

Levels in the hierarchy impose control, the third property of systems, on subordinate levels. The aviation authority issues permits for airlines to operate. The airline assigns duties to crews. The roles and responsibilities within crews shape the actions of individuals. These controls typically constrain the freedom of operation of the lower-level units in order to keep activities within expected bounds. Some controls carry the weight of compulsion. For example, an aircraft must have a certificate of airworthiness. This is a permission granted by the authority to the operator to use the aircraft in service. Without that permission, an operator faces legal sanction if it chooses to fly the aircraft. However, the roles of the members of a crew are often vaguely defined and can be interpreted in idiosyncratic ways. The concept of a 'role' is a social control but carries less force as a way of compelling individuals to act in a prescribed manner.

The fourth property of a system is communication. Communication is, in effect, the force that holds the disparate components in the system in a dynamic equilibrium. Communication can be explicit and implicit, formal and informal. The process for dealing with aircraft technical malfunctions is explicitly communicated through instructions. The lack of reported malfunctions is implicit feedback that aircraft are serviceable. Aircraft manufacturers provide technical and procedural information to operators. Operators reconfigure this information in order to comply with regulatory requirements covering the publication of flight crew documents. Flight crew interpret information in the light of operational experience and often annotate manuals and checklists to elaborate procedures to clarify the purpose of actions (Wright, Pocock and Fields). The act of elaboration is an attempt to reveal the implicit meanings in explicit communications.

	Formal	Informal
Explicit	Instructions to refuel Fuel figures recorded in log Fuel quantity input to ERCP	Captain's knowledge of toggle valves
Implicit	Valve Blue light Fuel gauge readings Interpolation of fuel quantity Drip stick indication	Aircraft lateral trim FO's understanding of fuel distribution Spoiler operation light

Formal communication comprises tasking, work rosters, procedures, limitations, order and instructions. Procedural descriptions of work can never encompass all possible workplace problems and so represent a constrained set of contingencies. Actors are required to implement procedures and this may entail adapting to circumstance or creating new solutions to problems that do not map onto the existing procedure. Where non-standard solutions result in successful outcomes, this can act as an informal communication loop that can support future rule breaking.

The behaviour of the system is directed by communication acts and equilibrium is maintained through the operation of feedback loops. The complex nature of communication within a system is exemplified in the case study by the management of the aircraft fuelling process and is summarized in table..

Failure in Dynamic Systems - Solving Operational Problems

Aviation is a socio-technical system of production in which actors engage in work intended to generate returns on invested capital. Production is facilitated by the use of devices. In this particular case, capacity constraints (airspace, runway availability etc) also imposed scheduling requirements on production that required synchronized, collaborative action on the part of disparate actors. Aviation is also a hazardous industry and the consequence of failure can be catastrophic. Therefore, work is organized to meet 2 goals: productivity and safety. Processes are designed to achieve planned goals. However, workplace contingencies require actors to adapt or modify procedures or create new solutions within the general bounds of the published process and within specific regulatory constraints. Although the individual functioning at Level 1 is focussed on the immediate task, all work involves processes that cross the interfaces between levels in the system. It is in these transactions across boundaries, or interfaces, that the dynamic properties of the whole system are manifested. The mechanics of failure are explored in the following 3 instances from the case study.

Hierarchical Failure - Technical Log Management. During the flight from Galway to Dublin the LH fuel gauge began to malfunction. The Company had put in place a process for dealing with such events, which was described in the Operations Manual. The malfunction was to be written up in the aircraft Technical Log. This then rendered the aircraft unserviceable on landing until a maintenance technician either rectified the problem or, if permissible within the Minimum Equipment List, deferred the rectification until a later date. Where an aircraft lands at an outstation with no maintenance support, the relevant page from the Tech Log was to be faxed to Maintenance. If deferred action is acceptable, the faxed page was countersigned and faxed back to the Captain for inclusion in the Log until the aircraft was back at main base.

The first operating crew, taking into consideration the already considerably delayed departure, the probable time required for the maintenance technician to attend the aircraft and the most likely action, which would be to release the aircraft for immediate service with a deferred rectification, elected to create an informal condition. The action of the crew may have been the same as if the procedures had been followed but they created a solution that was parallel to, but outside of, the formal process. The crew was able to do this because of their knowledge of the processes involved.

The procedure described in the Operations Manual is a Level 3 response to a Level 4 requirement. Notwithstanding the mandatory requirement, company manuals also serve to aggregate knowledge about aircraft operations within the local context. They serve to standardize crew performance and ensure the operation functions to a minimum standard of safety and efficiency. The Operations Manual is intended to direct behaviour at Levels 1 and 2. It prescribes a course of action while also defining constraints on action. The operator was aware that crews were accepting aircraft with open technical defects and had issued an instruction just prior to the incident reminding crews of the formal process.

According to the systems model, Level 3 is exercising control over the subordinate levels and is directing action through the issuance of instructions. Upward communication takes the form of either the successful completion of the task or through enacting specified responses to variations in aircraft status. However, it is clear that line crews were not complying with the intended action and that this was a common occurrence. In this particular case the rationale for not following the procedure was the desire to minimise further disruption to the schedule.[2]. In order to understand failure it is necessary to identify those factors that initiate and sustain discrepant behaviour.

In terms of initiating discrepant behaviour the report notes that the aircraft in question had experienced the same gauge problem for at least 5 weeks prior to the incident flight. It is important to understand the crews' construction of 'failure' in the maintenance sense. The fuel gauge problem was intermittent in that, on occasions, it was possible to obtain a plausible reading from the instrument. Therefore, it might be construed that crews did not see the need for reporting action as the gauge had not failed completely. The Operations Manual states that defects are to be written up *after flight* (authors italics). The landing at Dublin was an intermediate stop and might not have been understood by the first crew as the end of the flight, which was destined for Luton. The Flight Crew Instruction circulated to remind crews of the appropriate action in the event of a defect simply talks about accepting an aircraft with open entries in the Tech Log but makes no reference to aircraft with known defects that are not entered in the Log. From

---

[2] This explanation cannot be applied to all previous instances of breaching maintenance protocols.

this discussion it seems that departures from planned performance stem from ambiguity in the interpretation of procedures. Organizations attempt to control activities by including marker events in procedures that will then initiate remedial activity. Unfortunately, these markers are, themselves, open to interpretation. Dekker (2005), discussing the 1994 crash of a DC-9 off the coast of California, observes that the measured wear on the offending elevator crew-jack was exactly on limits. This prompted a debate as to whether this required a replacement or if maintenance action should wait until wear *exceeded* the limit.

The conditions that sustain discrepant behaviour are equally complex. The incident report notes that, where aircraft are at outstations, it can be difficult to find a fax machine and so crews operate with open maintenance items rather than incur the delays typically associated with compliance with the instruction in the Operations Manual. In aviation, generally, it is not uncommon for crews to report defects that are not then rectified, often because Maintenance are unable to replicate the reported fault. Having taken reporting action that does not then result in a positive outcome crews are often less inclined to report the same fault a second time. Where maintenance assets are limited (either in terms of manpower or spares) there have been instances where airlines have developed a practice of writing faults on notepaper and only those that can be easily remedied during turn round are, in consultation with Maintenance, written up in the Tech Log[3]. Inadequate resource allocation or infrastructure configuration will sustain discrepant behaviour.

This section explored the interaction between the definition of policy and the subsequent enactment of that policy. The manner in which policies are translated into line behaviour illustrates the manner in which levels in the hierarchical model interact. It also casts light on the way safety as an emergent property of the way operators act within systems. The definition of a maintenance policy might be considered a structural component of safety but that policy is only effective to the extent that it guides behaviour in a predictable and desired manner.

Level 1 Failure - Aircraft Refuelling. The first crew briefed the second Captain about the faulty fuel gauge. He was, in any case, aware of the fault having previously encountered it with the same aircraft. He was also aware of the high probability that further delays would be incurred during the day as the air traffic system tried to catch up with the disruption caused by the fog. Therefore, he was conscious of the need to have additional fuel to accommodate any airborne or ground holding. Accordingly, 962 Kg of fuel was taken at Dublin although the quantity was not recorded in the Technical Log.

The next refuelling was undertaken at Waterford. Fuelling is controlled through the Electrical Refuelling Control Panel (ERCP) located on the right-hand wheel fairing. The panel allows the operator to insert the desired final fuel total into a selector. Fuel is then distributed in such a way that both tanks contain equal quantities. A blue lamp on the ERCP indicates that the valve to the respective tank is open. The Captain had inserted 500 kg into the ERCP intending that to be the quantity to be put into each tank. The ERCP will distribute fuel based on the quantity in the tank at the start of fuelling, as measured by the fuel gauge, and the planned total quantity at the end of fuelling.

---

[3] Author's personal observation during airline visits.

During fuelling the Captain noticed that the RH valve light went out, indicating that the valve had closed (the RH valve closed because the total quantity in that tank had reached 250 Kg (i.e. half the 500 Kg planned quantity). He tried to open the valve using the electrical switch on the ERCP but this did not work. The Captain then showed the bowser operator how to open the valve using the manual trigger located by the fuelling point on the leading edge of the right wing. The Captain was able to observe that a blue valve light illuminated on the ERCP but, from his position, he was unable to verify which tank the valve related to. A total of 600 Kg of fuel was uplifted.

Once refuelling was finished the Captain estimated the quantity of fuel in each tank by inspection of the dripsticks. The dripstick is a mechanical device installed in each tank that provides a numerical value for the quantity of fuel in the tank. This value is used to enter a table in the aircraft manual and is then converted to actual fuel quantity. The value has to be factored for lateral inclination and to do this the pilot has to take a further reading from an inclinometer installed on the aircraft. Inadequate maintenance of the device meant that the Captain had difficulty getting a reading from the aircraft's inclinometer. However, he estimated that the LH tank contained 600 Kg of fuel and the RH tank contained 720 Kg.

This event further illustrates the manner in which activity occurs in a systems context. The aircraft manufacturer designed a process for placing fuel in the aircraft tanks, which it embodied in technology and in procedural information. The technology possessed some 'intelligence' (i.e. a means to ensure equal lateral distribution of fuel in the 2 wing tanks) such that it was capable of independent action (i.e. valves closing when tanks contents are equivalent). In addition, the manufacturer incorporated 2 alternative methods to open fuel valves (electronic switch and manual trigger) to allow operators to over-ride the automatic system. The manufacturer communicated with the airline through the embodied technology, incorporating controls and indicators, and the associated documentation, which contained system descriptions and operating instructions. The operator, as required by the Authority, provided manuals, checklists and training for its crew through which it promulgated the desired mode of operation of the technology. However, the company only incorporated a sub-set of the available information in its documentation and training. Information relating to the operation of the manual fuel valve triggers was only contained in maintenance documentation and was not accessible to pilots in the company. The Captain was an experienced ATR pilot, having worked in a number of companies. He had never operated the manual triggers before but he 'knew' of their existence and function. Therefore, although the primary mode of communication between Level 3 (company) and Level 1 (individual) is through training and procedures, information is also acquired and disseminated by a variety of informal means.

Level 1 is the domain of workplace performance and is represented by the Captain enacting a task and resolving anomalies as they arise. The task was to configure the fuel system to receive a volume of fuel, initiate the uplift of fuel and monitor progress. The system would terminate fuelling once the quantity had reached the preset value. The Captain's management of the fuelling process was erroneous in that the value he entered into the ERCP was only half the desired uplift. His assumption was that 500 kg would be put in each tank whereas the system was configured to distribute 500 kg between the 2 tanks. The progress of refuelling was indicated by the blue fuel tank valve lights on the ERCP that extinguished once the tank contents reached the desired quantity and the valve closed. Because the ERCP received an indication of tank quantity from the respective tank gauges, the failure of the LH gauge meant that the tank would default to a value of nil contents and, so, the LH tank valve would not close. The RH valve closed when the tank contents reached 250 kg. The Captain interpreted the behaviour of the system, manifested in the lamp extinguishing, as needing his intervention. The report does not say what triggered the Captain's response. Two likely hypotheses might be, first, that the short duration of RH lamp illumination was at odds with the Captain's expectation of the time required to uplift fuel or, second, that he expected both valve lights to extinguish simultaneously. In any event, because the Captain entered an incorrect value into the ERCP he misunderstood the behaviour of the system and subsequently tried to over-ride the process, first with the electronic switch and then with the manual trigger. The electronic switch failed to open the valve because it was acting in accordance with its design principle. The trigger is a manual over-ride but, from its location, the Captain could not clearly see which valve lamp illuminated. One final point to note is that the Captain's intended to put 500 Kg of fuel in each tank (i.e. 1000 Kg total) but the fact that only 600 Kg of fuel was actually taken does not seem to have been noticed. This episode reveals a tripartite structure of activity. The process of refuelling comprises a task as defined, a task as understood and a task as enacted. The extent to which the 3 components are discrepant increases the probability of error.

The next sector was from Waterford to Luton where the aircraft was again refuelled. The Captain made an assumption that the quantity of fuel in each tank was the same (325 Kg) and he planned to uplift 960 Kg of fuel, 480 Kg in each tank. During refuelling the RH valve remained closed. Because of his earlier experience with the electronic valve switch at Waterford, the Captain went directly to the manual triggers. He initially asked the refueller to operate the manual trigger but the request was declined on the grounds that the refueller had not been trained to do the task. The Captain then climbed onto the refuelling vehicle platform and manually operated the trigger. The triggers are located either side of the refuelling point. They are not labelled but their position relates to the tank they operate. The Captain operated the valve on his right-hand side. Again, he observed a blue valve light but could not see which valve it related to. Because there were no steps available, and to find a set would only add to the already considerable delay, the Captain did not use the dripsticks to estimate the contents of the tanks before departure. However, it was noticed that the RH fuel gauge was indicating less than the anticipated value after refuelling.

This second refuelling event was also erroneous in its conduct. The Captain's estimation of fuel consumption from Waterford to Luton and, hence, the tank contents on landing was incorrect[4]. However, despite his planned fuel uplift, he failed to enter the information on the ERCP which was still set to the 500 Kg entered at Waterford. Therefore, at the start of refuelling, the LH lamp was illuminated (for reasons described above) but the RH lamp failed to illuminate because the actual tank content were greater that 250 Kg, the planned quantity as entered on the ETCP. At this point, the Captain, having already experienced an apparent difficulty using the electronic switch to open a fuel valve, immediately resorted to the manual trigger. The Captain was facing aft when

---

[4] Although this had no bearing on the subsequent outcome it is significant at this particular moment.

he operated the trigger and, although he used his right hand, he was actually using the trigger for the LH valve, which was already open. The triggers are located in relation to the fuelling point and assume that the operator is facing forward. His physical distance from the ERCP again prevented him from clearly observing which valve lamp was illuminated. As a result, the entire fuel uplift was directed to the LH tank. Although the company Minimum Equipment List contained advice on how to estimate fuel tank contents in the event of a gauge failure, there was no formal requirement to do so. Finally, the apparent under-reading of the RH tank content gauge was assumed to be an early indication that the RH gauge was failing in the same way the LH gauge had failed.

Waterford and at Luton represent 2 discrete but interconnected episodes. At Waterford the Captain made an error in setting the ERCP, which required a flawed intervention on his part to remedy the situation. The Captain's actions at Luton were influenced by the Waterford episode in that the Captain had immediate recourse to the manual triggers given his earlier failure to open the RH valve using the electronic switch. The selection of the wrong trigger was a combination of a lack of markings, knowledge acquired through informal means and an inadvertent transposition of axis. There is no evidence that the Captain was feeling the pressure of time but his failure to complete the dripstick test was in part influenced by the desire not to incur additional delays. Although company procedures do require fuel checks to be completed, there are no specific requirements in the event of unreliable or faulty fuel gauges. Therefore, the Captain's failure to check the tank contents at Luton was not a breach of procedure. The incident report refers to 'common sense, prudence and good airmanship' in suggesting that taking a manual reading of tank contents at Luton would have been advisable under the circumstances. In fact, the report's authors have captured the extent to which processes are generally underspecified, relying on operator expertise to elaborate the process should circumstances dictate. The tripartite nature of the task is again apparent but in this case the task was completed in a context in part configured by prior experience.

Creating Reality – Dynamics at Levels 1 and 2. The previous section looked at how work was conducted by an individual in a context influenced by factors present at various levels in the hierarchy. This section will look at how personnel working in collaboration construct situations as part of controlling action.

The FO was the handling pilot on the final sector from Luton to Waterford. Soon after rotation she detected that the aircraft was out of lateral balance, feeling left-wing heavy. She made a comment to the Captain who took the controls to ascertain, for himself, the degree of imbalance. In fact, at take-off the difference in content between the 2 fuel tanks was 889 Kg, 339 Kg above the maximum permissible lateral imbalance[5]. There were 4 aspects of the operational environment relevant at this stage. First, the imbalance was immediately noticeable through the controls. Second, the failure of the LH fuel gauge, the apparent imminent failure of the RH gauge and the failure to estimate tank quantities at Luton meant that crew had no explicit information about the actual distribution of fuel. Any attempt to reconcile the position would require complex manipulation of the available information: the information existed but was opaque.

---

[5] In fact, the imbalance exceeded the limitation for the duration of the final sector.

Third, the imbalance was within the command range of the autopilot, possibly indicating that the problem was not excessive. However, and finally, the starboard spoiler was occasionally being deployed to counter the imbalance, as indicated by a light on the overhead panel. The crew decided to run both engines from the LH tank for 15 minutes to reduce the imbalance. About 30 minutes after take-off the RH tank was indicating empty and both Fuel Low warning lights were illuminated. As was discussed above the lights are triggered by a gauge indication and are not linked to an independent measure of tank contents. The lights, in themselves, were not a reliable warning and, presumably, the LH light had been illuminated for most of the flight. One hour and 21 minutes after leaving Luton the RH engine stopped.

The failure was attributed to an engine problem and, on final approach, the Captain elected to remain high on the glide path in case the LH engine similarly failed. During the descent, the FO voiced her opinion that perhaps the problem might be linked to the RH fuel tank indicting empty. She attempted to estimate the fuel in each tank, her task made more difficult by the fact that the figures for the initial uplift at Dublin had not been recorded and the tank contents had not been measured at Luton. Even so, engine failure was still the theory in use by the Captain, as evidenced by his management of the final approach in which he attempted to minimise any subsequent loss of the LH engine.

This event illustrates how crews are involved in constructing hypotheses based on information distributed across their workspace and mediated by their own individual understanding of the situation. Individuals engage in mental processing at Level 1 whilst participating on collaborative activity at Level 2. The FO's recognition of the imbalance and her attempt to reconstruct the actual fuel state were both the products of internal processing. Her individual understanding of events was then put into the group domain for additional processing. Constructing reality and using this to drive future action was a shared activity between the 2 crewmembers.

Systems, Failure and CRM

This paper has used a hierarchical systems framework to explore the manner in which work is conducted. Personnel are engaged in a continuous stream of activity that requires the construction of solutions to workplace problems in order to achieve operational goals. These solutions exploit knowledge embodied in tools and procedures but also require adaptive behaviour. Prescribed procedures are typically normative descriptions and represent a 'least-risk-by-design' model. Paradoxically, procedures cannot fully accommodate the variability encountered in routine operations. The problem is aggravated by the fact that observed workplace activity is the result of mediated processes. The process as planned is mediated through an operator's understanding of the components of the process and then enacted in ways that are themselves vulnerable to failure. Furthermore, as crews adapt procedures to situations they induce an increased level of risk in that processes are likely to fail in unexpected ways.

Dekker (2006) points out that most commercial enterprises function in conditions of resource scarcity and competition. In order to generate a sufficient return on investment in the face of competition for customers, organizations exist in highly marginal production environments. Frosch (2006) observes that all organizations adopt a position of ‘Self Organized Criticality’ in which safety is a reflection of the gap between catastrophe and normal operations. The forces outlined by Dekker ensure that margins of safety are minimal in that excessive safety is wasteful of resources. Frosch further observes that all actions are, in effect, choices between levels of risk and that actions to increase safety will generate risks elsewhere in a system. For example, although the ATR 42 is fitted with a manual system for checking fuel tank contents, the system requires the provision of steps. The investigation found that access to the inboard drip sticks is routinely achieved by standing on the undercarriage doors, a purpose for which the doors were not designed. The use of the doors as an observation platform is likely to induce wear which, in turn, may result in door failure at some future time. This progressive degradation of the system of production can be described as safety drift. The implications for CRM training are 3 fold.

First, this paper has shown that workplace performance is delivered within a systems context. Initiatives that target operator skills in the absence of any broader organizational analysis are likely to be ineffective. It is not unknown for airlines to use CRM training to target specific, broader organisational issues. Topics such as ‘Organizational Factors’ and ‘Safety Culture’ feature in published syllabi (JAR-OPS 1) and classroom sessions on these subjects are intended to bring about a broader change within the parent organization. For example, the author is aware of an attempt to address systemic non-adherence to company SOPs within annual CRM training when, in fact, the problem probably reflects a deeper malaise within the organization concerned. The discussion of maintenance issues in the case study reflects the way in which organizational factors shape workplace actions and illustrates the important of addressing the source of a problem rather than discussing the symptoms during a CRM class.

The second implication is that prevailing models that position CRM as a distinct training domain are flawed. Sub-optimal performance is typically the result of a mismatch between operational goals and enacted solutions. The root cause of a problem typically lies in the flawed application of skills in the workplace. Models of competence that integrate ‘action’ and ‘control of action’ (MacLeod 2001) will result in more robust training. Each problem presented to the crews during this incident had associated pay-offs that can be evaluated in terms of various indices of desirability. At each decision point, the ‘most safe’ course of action was usually the least desirable in terms of customer satisfaction. However, the solutions generated did not appear to have, at least in the eyes of the crew, any apparent incremental risk attached to them. With respect to the final sector from Luton, information about the actual status of the aircraft was distributed about the cockpit, but no single stimulus had sufficient salience to cause the crew to question the effectiveness of their solution. It is perhaps salutary to note that, if there had been an additional 150 Kg of fuel in the RH tank, the aircraft would have landed at Galway in an apparently ‘normal’ state but with all of the salient points of the case study unchanged[6]. In effect, what would have seemed no more than a ‘challenging’ day to the crew would, in fact, have been an operation conducted completely outside of the organization’s and the crew’s conception of reality.

Finally, CRM training methods are inadequate. Because the early training initiatives were characterised as being designed to provide familiarity with the domain,

---

[6] Speculation in hindsight is rarely wise in these cases but, given the haphazard nature of the conduct of refuelling throughout the day, such an outcome was no less likely than the actual final result.

they are typically rooted in classroom study of abstract concepts illustrate through the use of case studies. However, if failure is rooted in individual performance, future CRM training will need to address the metacognitive aspects of skilled behaviour. The goal of training must be to allow individuals to better integrate information into models of task execution that deliver robust workplace performance.

Conclusion

This paper examines activity at multiple hierarchical levels converging on a single episode. Both pilots were engaged in private activity, in that they each engaged in sense-making to resolve the problem of aircraft imbalance followed by apparent engine failure. The pilots worked as a team to manage the events and to agree courses of action. Thus, the pilots had to bring to bear their personal understandings of processes and aircraft systems to create a public, shared response. The Captain drew upon a knowledge base that extended beyond the information provided in company manuals. The manner in which pilots acquire knowledge about the way the aircraft functions is significant in that it shapes the performance of the crew in workplace. Crew training tends to work with a prescribed set of routines and manoeuvres. However, training conforms to Frosch's concept of Self Organized Criticality in that it delivers training to a minimum standard in the shortest possible time. The crew of the ATR applied trained responses to a situation in which aberrant cues could be rationalised or ignored. Most company training courses lack the resources to tackle training to cope with situations such as this, relying instead on generic CRM inputs to bridge the gap. Topics such as 'Human Information Processing', 'Situational Awareness', 'Decision-making' and 'SOPs' would cover material relevant to this incident. However, such classroom training is often abstract and removed from the problems crews confront on a daily basis. Hierarchical systems models allow us to better identify sources of poor performance and safety drift and to configure training in such a way as to deliver more robust working practices better able to cope with the uncertainty of normal operations.

References:

AAIB (2005) Formal Report No 2005-014
CAA (2006) CAP 770: No-frills Carriers: Revolution or Evolution? A Study by the Civil Aviation Authority
Dekker. S. W. A. (2005) 'Why we need new accident models' Technical Report 2005-02. Lund University School of Aviation
Dekker, S. W. A. (2006). Resilience engineering: Chronicling the emergence of confused consensus. In E. Hollnagel, D. D. Woods & N. Leveson (Eds.), Resilience Engineering: Concepts and precepts, 77-92. Aldershot, UK: Ashgate Publishing Co.
Frosch. R.A (2006) Notes Towards a Theory of the Management of Vulnerability in Seeds of Disaster. Rots of Response Ed Auerswald. PE Branscomb LM La Porte T & Michel-Kerjan EO Cambridge

Gherardi. S, & Nicolini. D. (2000) The Organizational Learning of Safety in Communities of Practice. Journal of Management Inquiry 9,1 7-18
Helmreich, R.L., Merritt, A.C., & Wilhelm, J.A. (1999). The evolution of Crew Resource Management training in commercial aviation. International Journal of Aviation Psychology, 9(1), 19-32
JAR-OPS 1
Lauber. J. K. (1984) Resource management in the cockpit. *Airline Pilot 53* 20-23
Leveson, N., Daouk, M., Dulac, N. & Marais, K. (2003) A Systems Theoretic Approach to Safety Engineering
MacLeod, N. (2001) Training Design in Aviation, Ashgate
Rasmussen, J & Svedung, I. (2000) Proactive Risk Management in a Dynamic Society. Swedish Rescue Services Agency, Karlstad, Sweden.
Reason. J. (1990) Human Error, Cambridge
Wright, P., Pocock, S. and Fields, R.E. (1998). The Prescription and Practice of Work on the Flight Deck