Chapter 16

Trapping Paper Checklists into Screens: how to free the resilience capability of digital checklists for emergency and abnormal situations

Guido Carim Jr.1, Geraldine Torrisi-Steele2 and Éder Henriqson3

1 Safety Science Innovation Laboratory, Griffith University, Brisbane, QLD 4111, Australia
2 School of ICT, Griffith University, Brisbane, QLD 4111, Australia
3 School of Business, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, RS, Brazil
g.carimjunior@griffith.edu.au

Abstract. Aviation digital non-normal checklists neither solve the problematic nature of procedures as organisational control mechanisms, nor capitalise on the benefits of the technology. To create resilient operational systems, it is necessary to shift towards seeing abnormal and emergency checklists as resources for the activity: a piece of information that helps pilots assess the severity of the problem, diagnose the cause and plan, and implement a proper response, when needed, if needed. Fragmented checklists, integrating different resources in just one place, and Decision Support System technology are mechanisms to enhance the potential of the digital quick reference handbook.

Keywords: Resilience engineering, digital checklist, QRH, Safety rule, Emergency.

16.1 Introduction

Checklists and procedures, in different forms, are common in industries where safety is of concern: from medicine, chemical process and manufacturing to aviation and nuclear; from standard operating procedures, surgical checklists, to minimum equipment list (MEL) and golden rules. In emergencies and system failures, the situation is not different: the operator should action the abnormal and emergency checklist, carefully crafted by those who designed or maintain the operations, technology, and process.

A design assumption of checklists and procedures is that the work context and the fault will unfold as predicted, thus, strictly following a checklist will inevitably lead to the desired, anticipated outcome. Procedures are necessary because, after all, humans are vulnerable to choosing erroneous actions and making bad decisions. And what better way is there to reduce human error other than rigidly reduce variability by
constraining the action and requiring compliance with procedures [1]? At least this is the usual mindset from which procedures and checklists eventuate.

With the advent of the paperless cockpit philosophy and affordable technologies in aviation, Electronic Flight Bags (EFBs), electronic checklists and digital Quick Reference Handbooks (QRHs) are now part of every commercial aircraft cockpit. In the case of a system failure, the aircraft warning system draws the pilot’s attention to a critical or urgent problem [2, 3]. The fault message presented on the display prompts pilots to retrieve and action a digital non-normal checklist. The drill contains actions, decision points and notes [4], mostly organised in a sequence aimed at containing the failure, restoring the system, or maintaining the continuity of the flight despite the faulty system or component [5]. Hundreds of digital checklists are organised in a QRH according to announced and non-announced problems, aircraft systems or the fault severity.

Despite best efforts to digitalise and continuously improve the QRH, pilots still experience novel or ill-structured problems for which a procedure either does not yet exist or is not entirely captured by checklist [6]. From the procedure as organisational control mechanism perspective [7], the efforts lie on closing this gap, to make the checklist as closely representative of the activity as possible [8]. However, this effort often results in additional, longer, and more prescriptive checklists. Similarly, digital checklists, except for some rudimentary functionalities, become just a translation of the paper-based checklists that perpetuates the design assumptions underlying traditional paper checklists.

In an era when organisations are constantly challenged, it is paramount to create resilient operational systems able to cope with both well- and ill-structured, expected and unexpected abnormal and emergency situations. From the resilience engineering perspective, operational resilience is the capacity to anticipate, adapt, absorb and bounce back from variations, changes, disturbances, disruptions and surprises that fall outside the system designed boundaries [9]. Rather than waiting for situations that match their capacity, these systems self-organise their components to cope with whatever situation that pushes their boundaries [10].

To increase cockpit resilience, there is a need to shift away from non-normal checklists as prescriptions for the activity, to understanding them as tools that support operators to cope with the residual uncertainty that is ever-present in operational contexts [11-12]. Checklists should be seen as resources for activity: information structures that support activity when needed, if needed [13-14].

In this chapter, we propose a progressive approach to checklists, which imbues resilience to the cockpit systems by helping pilots assess the severity of the problem, diagnose the cause, and plan and implement a proper response when needed, if needed. After the introduction, section two describes the current state of the digital QRH, and non-normal checklist used in the cockpit of commercial aircraft. Then, section three highlights the challenges and limitations present with the increasing digitalisation of procedures are section. Lastly, section four explores different pathways to redesign digital checklists.
16.2 Digital Checklists and Manuals in the Cockpit

Since the emergence of the paperless cockpit philosophy in the 90s, and tablets and EFB’s in the 2000s, aircraft manufacturers, airlines and technology companies have been developing dedicated applications for everything; from digital maps, manuals, regulations, airport, weather information through to maintenance report, aircraft status and digital checklists.

Boeing [15] was the first manufacturer to release a digital version of the QRH in 2013 (see Fig. 16.1). The tablet based QRH enabled functionalities and interactivity not possible in paper formats including [16]:

- Tracking the actions performed.
- Easy to retrieve index list, allowing quick retrieval of any checklist by title.
- Dynamic forms that direct the next steps according to the previous actions and answers. This replaces flowcharts used to guide pilots through the lines of the checklist.
- Calculators for the aircraft performance, either embedded in the drill or available in dedicated applications. They replace the performance charts and tables in the paper based QRH, removing the need for pilots having to flick between the pages to complete the checklist and analyse the landing performance.
- Flexible interface, in which the background colour or the font size can be adjusted.
- Hot buttons that reduce the time required to retrieve and action the most critical checklists.

Fig. 16.1: Screens of the Boeing Interactive e-QRH. Source: [17]

With many independent applications, the EFB’s desktop quickly became cluttered, compromising pilots’ ability to easily retrieve information and navigate among the many windows and documents. The industry soon realised that most of the applications relate to each other: the input or output of one application could become the input for another. Subsequently, the focus shift to making information retrieval easier by
integrating different applications and sources of information in one place, commonly referred to as Integrated Onboard information System (IOIS) [18].

The FlySmart of Airbus is an IOIS which enables crew to compute the aircraft performance for all the flight phases, generate documentation such as the load sheet, manage the flight progress through the flight plan, consult navigation charts, and access all the operational manuals such as the Flight Crew Operating Manual, Flight Crew Training Manual, Minimum Equipment List, and so on [19].

Despite advancements, the e-QRH for Airbus models is not yet completely integrated into FlySmart. The digital QRH layout resembles the layout of the warning system, the search function only displays checklists containing searched terms in their title, and hyperlinks have been added to direct pilots to other checklists if needed. Unlike Boeing’s e-QRH, the performance calculations are directed to the FlySmart [19].

16.3 Constraining capability: The limits and challenges of procedures and checklists

In high-risk industries, procedures and checklists are one of the most problematic area of human work [12]. The limitations of procedures and checklists arise from conceptualisation of procedures as control mechanisms [7]: they limit the operator’s degree of freedom [1]; are repositories of organisational knowledge; and reduce the probability of error and counterbalance human fallibility [20-21].

Abnormal and emergency checklists are a special category for four reasons. Firstly, it is not possible to capture beforehand all possible unfolding pathways and contextual elements of a problem [12]. Secondly, it is not possible to include in just one place all of the knowledge required to deal with a fault. Thirdly, while it is widely accepted that the gap between procedures and actual work always exists [22], efforts are made to bridge the gap, usually with better content, better interface, more accuracy and more smart features [23]. Lastly, the focus on translating the paper-checklist to digital medium leads the e-QRHs to mimic the paper-based procedures and avoids further exploring the benefits of the technology during the management of non-normal situations.

16.3.1 Increasing number of ill-structured problems

The design assumption of the e-QRH is the same as for a paper-based QRH: the fault evolves as expected and the outcome is always the same if the guidelines are strictly followed [5]. Presumably, all the other systems were working perfectly before the fault occurred, only a single, or a group of interrelated faults occur at the time, and the warning system always directs pilots’ attention to the real problem [8].

The assumptions underlying QRH design do not always hold true though. As aircraft become more robots than machines [24], the possibility of complex anomalous behaviour increases exponentially [2], leaving pilots to cope with an increasing number of ill-structured technical faults. These are defined as problems that go beyond the QRH and warning system scope.
Carim Junior et al. [6] found that pilots often must deal with false alarms, unclear faults that go off and then disappear without any apparent reason, faults related to deferred maintenance items, known as ‘Minimal Equipment List (MEL) items’, and multiple concurrent non-related faults, also known as ‘Christmas tree’ [25]. As yet, neither digital nor paper checklists encompass these challenging situations.

16.3.2 Checklist can never cover the knowledge required to deal with non-normal situations

Non-normal checklists are insensitive to the context [26] and are always based on the worst-case scenario [24]. Therefore, the knowledge required for the activity is much broader than what is encapsulated in a checklist. Still, checklist designers try to cover as much contextual variation, and as many action pathways, as possible through decision-trees and conditional flows, usually presented in programming syntaxes such as ‘IF’, ‘WHEN’, ‘THEN’, ‘AND’ and ‘OR’ [27].

If the conditions intrinsically built into the checklist do not happen or the situation evolves unexpectedly, then the prescribed actions become irrelevant, leaving to pilots the decision of ‘what to do next’ based on a wide range of resources [6]. For example, Carim Jr. et al. [6] revealed that the Embraer 190/95 pilots that participated in the study always verify if the fault is genuine. They do so because of the high incidence of false alarms in the fleet and because in some checklists ‘resetting’ the system or the component is a common initial set of actions [24]. In instances where resetting does not work, pilots may opt for not completing the available checklist because the drill could have worsened the situation [28].

It is also assumed that checklist designers and pilots will frame the situation in the exactly the same way. Non-normal checklists are directly linked to the warning system, as though it could precisely indicate the root cause for the problem. Thus, pilots only need to find the checklist whose title corresponds exactly to the fault message. However, as reported by Burian [8], is not uncommon for pilots to accomplish a wrong checklist because the warning system may point to a disturbance rather than to the main problem [29]. This is even more problematic when pilots have to use checklists for problems not covered by the warning system [30].

16.3.3 Continuous improvement through better design and better content alone

Studies proposing guidelines or improvements to the design and use of the non-normal checklists adopt the human fallibility perspective. After analysing a number of safety reports and aircraft accident reports, Burian and Barshi [23] found nine conditions related to pilot errors when using the checklist. For each condition, the authors provide design guidelines as a way to make the checklist error-proof. Therefore, the ultimate goal of the checklist is to compensate for some design flaws, overcome human limitation, reduce the possibility for error and increase compliance [20-21, 31-33]. As put by De Brito [32, p. 92], non-normal checklists should “reduce the number of deviations leading to serious consequences”. The assumption is less errors and more compliance lead to safer operations.
Improving non-normal checklists requires the analysis of checklists as a stand-alone emergency tool, taken out of the context [16]. The emphasis is on the “process of following (or not) written procedures” [32, p. 93, 33] rather than on the management of abnormal and emergency situations [6]. Therefore, most of the concerns are around the checklist itself: Is the situation framed in a checklist as a pilot would do? Is the checklist content easy to retrieve and follow? Is the checklist aligned with the SOP and other manuals, both provided by the operator and manufacturer? Is the checklist length adequate to the time available? Have human limitations and fallibility under time pressure and stress been taken into consideration when designing the checklist content and layout? [21, 34-35]. Therefore, most of the best practices to design paper and digital checklists gravitate around physical characteristics of the display, the layout and format, and the instructions sequence correctness, completeness and coherence [4, 5, 20-21, 35-36].

16.3.4 Digital procedures and checklists technology haven’t been exploited; just translated

We acknowledge that recent e-QRHs have embedded essential features that should be kept and even further improved, like tracking actions, dynamic forms, timer, and performance calculators. However, the types of actions, conditional steps, computational syntaxes, and the underlying assumption that all faults will unfold as predicted remain present.

Why do we still have to offer a complete checklist, from beginning to end, if the parts of the checklist are meant to be used only for specific conditions? Why do we still have an ‘enforced’ sequence of actions as if problems always evolve as anticipated? We can understand offering one-problem-one-drill on a paper checklist is the best solution for simple and unique faults, given the space constraints and need to simplify the retrieval of a checklist. However, the capability of digital platforms is immense and can easily overcome most of these problems.

Expressions like Land as soon as possible in the most suitable airport, commonly found at the beginning or the last item on paper checklists, have been transferred to digital QRHs. Pilots question the definitions of as soon as possible (“How much time do I have before the situation becomes worse?”), and suitable (Does suitable mean an airport that has all the resources needed for landing and takeoff again later? Or does it mean any airport that I can land the aircraft safely, regardless of what happens after”?) [24]. As confusing as this one is, some checklists only bring crew awareness after the title. As reported by Carim Jr et al. [6], a pilot who had experienced a problem with a component of the fuel system while taxiing, questioned the expression usefulness. He assumed that the expression required the crew to monitor the problem if it happened while inflight. However, does this apply to the same problem while taxiing? He could not find the answer anywhere.

Although we understand that we cannot integrate geo-location or produce a checklist for the same problem in different phases of flight in a laminated checklist, the same limitation is not found in digital applications. Yet the practices of paper checklists endure in the digital form.
16.4 A way forward

Building a resilient system requires a better description of how pilots actually manage abnormal and emergency situations and how procedures, as well as other resources, are used in practice. Once the activity of managing dynamic faults is understood, we can propose a system that supports pilots with varying experience and knowledge profiles to deal more effectively with inflight faults particularly ill-structured ones. Rather than optimising the current digital checklists to compensate for design flaws, to improve compliance and to reduce human error, the focus should be on supporting the strategies and adaptations required by the operators to successfully complete the activity [37]. We posit that the way forward is forged by challenging existing assumptions implicit in the design and development of checklists, refocusing on the dynamic nature of the management of abnormal and emergency situations, and exploiting technologies to support pilots in their work. Rather than specification of the activity, procedures and checklists need to provide essential information for operators to cope with the residual hazard, variability and constraints, thus guaranteeing a continuing safe and efficient operation.

16.4.1 How pilots actually manage non-normal situations

The revisited anomaly management model proposed by Carim Jr. et al., [6, 28] is a further elaboration of the original proposition by Woods [2] and Woods and Hollnagel [25]. According to the revisited model, a fault, whether well- or ill-structured, is presented in terms of disturbances because of the lack of linear relationship between the fault cause and symptom [29, 38]. Operators manage faults through three iterative and concurrent event-driven cognitive processes: anomaly assessment, diagnosis and response [2]. These three processes operate according to different types of reasoning: often starting with the quickest and less demanding one, such as analogical and heuristics, and progressing to more elaborate states as the problem remains unsolved, such as abductive and analytical [39-41].

Lastly, the cognitive processes operate with the support from not only the QRH and checklist but also a range of documents, manuals, tables, previous experiences, to name a few. Those resources have not been originally designed for this particular purpose and dispersed in and outside the cockpit [28].

16.4.2 Procedures as resource for activity

The alternative approach to procedures as organisational control mechanisms is Resources for Action (RfA), originally suggested by Suchman [13]. RfA contrasts with the prevailing view that maps, plans, scripts, protocols, procedures, checklists and rules direct and control action [42]. Rather, they are one among many different resources that support the operators to conduct a reasonable course of action and to deal with or avoid local constraints [13, 43-45].

Wright et al. [14, 42, 46] and Wright and McCarthy [44] further elaborated and applied RfA to information technology. They argued that any piece of information
distributed on an interface, serving the specific purpose to support the operator during the course of action, such as instructions, perceived affordances, interactive features, and previous interaction history, is a RfA. Wright et al. [46] suggest the interface analysis from the RfA perspective should seek to reveal the meaning operators given to the piece of information on the system-interface and its utility in solving a specific circumstance. In using non-normal checklists, Wright et al. [43] point out that pilots intercalate fragments of multiple checklists to manage a certain situation, since the technical problems on board are not always solved in the same sequence as indicated by checklists. For instance, different pieces of different checklists can help pilots achieve specific objectives and solve part of the problem depending on its nature [46].

Validating and expanding the findings from Wright et al. [43, 46] and Wright and McCarthy [44], Carim Jr. [24] and Carim Jr et al. [6, 28] describe four ways in which the QRH are used as RfA during aviation non-normal situations. Firstly, pilots see the checklist as fragments that contain a set of actions, either therapeutic or diagnostic, with a very specific objective in solving part of the problem. For instance, before following blindly the checklists, pilots read and try to infer the fragment objective, contextual assumption and possible consequences before actioning it. Then, they compare their inference with the context faced before deciding whether an intervention is required and, if so, the course of action [33]. Secondly, knowing which fragment of a number of checklists may help to solve a specific feature of the problem increases the pilot’s ability to combine and interleave different checklists to coin unique solutions. Thirdly, pilots not only use fragment of the checklists; they also know that other parts of the QRH, other manuals and previous experiences (both personal and shared by colleagues) carry valuable information as well. Given that pieces from a range of checklists and other resources available in and outside the cockpit help with the whole fault management activity, Carim Jr. et al. [28] propose to use the term Resource for the Activity instead. Fourthly, and most importantly, pilots use RfA when needed, if needed. Some faults are so common and repetitive that pilots already memorised the sequence of actions available in the checklist. In other situations, following the checklist could lead to worse outcomes, therefore prompting the crew to disregard the QRH, return to the departure airport and land as a precaution [6, 24, 28].

Three mechanisms to implement a digital QRH as a RfA emerge from these findings: (a) provide fragmented checklists instead of one-off solution, (b) integrate different RfA in just one place to avoid redundancy and simplify the workflow, and (c) use a decision support system technology to help pilots during ill-structured faults.

**Fragmented Checklists.** The checklist content should be fragmented in interactive blocks or iBlocks [47]. Each block comprises of a set of actions, situation pattern, and post conditions [48] normally dispersed among many different manuals and checklists. As the pilot completes one block, the system verifies the next priority and updates the context. This may lead to the completion of another block which can be part of another non-normal or normal checklist in a paper QRH [49-50].

Although the system may suggest different pathways, pilots are free to decide the best option, bearing in mind that for some aircraft models they also have to complete actions presented by warning system [51]. And each fragment could be improved
dynamically: always feeding back to the system lessons learned on how people coped and how the aircraft system behaved in previous anomalies and emergencies. Helped by a search engine based on an input-process-output format, pilots could access tailored solutions for specific problems under specific conditions rather than following a decision tree with many branches, reducing the need for conditional actions and different pathways.

**Integrating different RfA.** Pilots employ three categories of resources in addition to the QRH [6]: (i) documents physically available in the cockpit, such as Minimal Equipment List and technical logbook, (ii) social resources, such as maintenance professionals and other pilots (when sharing experiences), and (iii) previous individual experience, either personal or third party.

Since the document resources are dispersed in the cockpit, embedding them in a digital QRH and connecting to the checklists is paramount to reduce the time to retrieve information but also avoid task duplication. The input of one resource can be used as input by a checklist and other resources. For example, combing the MEL with the checklist help pilots to assess whether a failure needs to be fixed before the aircraft can take off again and decide which destination airport is better and safely suited. Moreover, some tables and information available in the MEL complement the content of the checklist, thus prompting pilots to consult them eventually while managing a problem.

Another example is to include the Technical Logbook as part of the digital platform. Rather than presenting as a list containing all past technical problems and maintenance actions and deferred maintenance items, pilots would like to be able to visually, at a glance, assess the aircraft airworthiness status. Pilots would also like to have checklists that take into account the deferred maintenance items, thus not having to remember problems not yet fixed before actioning the checklist [24].

**Decision Support Systems (DSS).** There are three functions that technology should perform to improve pilots’ capability during non-normal situations [24-25, 29]:

- **Representation support** should help distinguish anomalous behaviour from the noisy background and from irrelevant cues. Moreover, the function should represent the multiple factors that influence the disturbances over time (human intervention, automatic system response, false alarm, another fault or faults).
- **Hypothesis generation** should support a better diagnosis by generating as many alternative hypotheses as possible given the set of evidence. It may also highlight the set of evidence covered by each candidate hypothesis.
- **Tailored Actions** should aid pilots with the trade-off between acting under great uncertainty or waiting for more evidence even in the face of undesirable consequences. This function may bring actions aimed to generate more evidence until the system is able to suggest one or more reasonable course of actions.

DSS seem to be the most appropriate technical solution to operationalise these three functions in addition to fragmented checklist and integrated RfA. DSS are defined as interactive, flexible, and adaptable computer-based information systems designed for the specific purpose of improving decision making in non-structured problem domains.
by utilising data from various sources [52-53]. DSS is not an automated problem-solving system, does not generate procedures for which compliance is the goal, nor constrain the decision makers actions. Instead, the user retains their role as autonomous, active decision makers as their insights are crucial to the problem-solving process [54].

A typical DSS includes a knowledge base, inference engine and a user interface (UI). At the core of DSS is the knowledge base (normally developed from strategies employed by experts) which facilitates retrieval, organisation, and manipulation of information through an inference engine. Given inputs, the inference engine manipulates the knowledge and generates the outputs, usually as probabilities. The UI enables manipulation and scaffolding of knowledge elements thus assisting users to more efficiently, effectively, and consistently form an understanding the context, formulate hypotheses for the causes of the problem and delineate courses of action and their potential consequences [55].

Embedded in a digital QRH, the DSS would suggest an action and broaden the possible causes for the technical problem and indicate severity of the situation. Taken together, the three outputs: causes, level of severity and course of action, will expand the pilot’s capability to assess the nature of and diagnose causes of ill-structure problems, and plan and implement a reasonable course of action.

16.5 Conclusion

Paper non-normal checklists are ‘trapped’ into digital QRHs: they perpetuate the checklists as organisation control mechanisms and severely limit the operational resilience in a commercial aircraft. Increasing airlines’ resilience during non-normal situations management requires a paradigm shift from checklists and procedures as activity constraint to resources for the activity.

The chapter operationalised RfA through fragmented checklists and integrating RfA with DSS. Properly designed, the system will increase the resilience capability of the cockpit system during abnormal or emergency situations because the pilot retains control as flexible and active decision maker, and the pilot has the necessary resources to assist in assessing the severity of problems, diagnosing the cause, and planning and implementing a proper response when needed, if needed. This shift promotes operational resilience, enabling system flexibility and adaptive capacity needed to cope with the residual uncertainty of non-normal situations. Even though the discussion has focused on aviation, checklists and procedures are commonplace in many industries. Operational systems are evolving to higher levels of complexity, and conventional checklists fail to impart the resilience to these systems. It is hoped that the discussion within this chapter stimulates reflection and motivates exploration of RfA or other paradigms to exploit the affordances of technology for creating progressive conceptualisation of checklists and their role in dealing with complex operational systems across industry.
References