SYSTEM SAFETY AND HUMAN FACTORS: HOW TO FORECAST CREW BEHAVIOUR COPE WITH A SYSTEM FAILURE.

SURETE DES SYSTEMES ET FACTEURS HUMAINS : COMMENT PREVOIR LE COMPORTEMENT DE L'EQUIPAGE FACE A LA PANNE D'UN SYSTEME.

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Résumé

Le métier de pilote a évolué avec l'automatisation des cockpits et la robustesse croissante des systèmes techniques. L'ajout et/ou l'amélioration de fonctions auparavant inexistantes, facultatives ou peu robustes amènent des modifications profondes dans les compétences nécessaires à ce métier. Ces modifications doivent être anticipées sur un temps assez long. En effet, les hypothèses de conception réfléchies aujourd'hui, pour des programmes qui ne verront le jour que dans une dizaine d'années, devront se baser sur une estimation des compétences qu'auront les pilotes dans les années 2050 ! Cette évolution des compétences peut avoir un impact sur la performance de l'équipage lorsque, pour surmonter la panne d'un système par exemple, les concepteurs vont faire appel à une compétence antérieure du pilote, qui a pu être érodée faute d'une moindre sollicitation. Ce constat amène le problème suivant : Comment reconnaitre une hypothèse de comportement pilote qui pourrait, demain, être amenée à évoluer ? Afin d'esquisser une réponse à cette problématique, après avoir défini le cadre théorique, nous verrons comment, à partir de scenarios de pannes fonctionnelles prévues nous pouvons trouver des informations concernant les hypothèses de comportement équipage prises durant la phase de conception qui pourraient être amenées à changer sur les futurs programmes.

Summary

With the automation of cockpits and the increasing robustness of technical systems, the pilot profession has evolved. The adding and/or the improvement of functions that did not exist before, optional or not robust, brings deep changes in required skills for pilot profession. The evolution of these skills must be anticipated over quite a long time. Indeed, today projections of design are created for programmes which will only be born in about ten years. The design must be based on the estimation of crew skills in 2050! This skill's evolution could have an impact on crew performance, when, to overcome a system failure for example, aircraft designers will use a crew competence which has been modified because of a slight solicitation. This statement of fact brings the following problem: How to recognize a crew behaviour expected by aircraft designers which could evolve on future programs? In order to draw a solution to these problems, after having defined the theoretical framework, we will see how, during the aircraft design, thanks to scenarios of functional failures, we can find information regarding the expected crew behaviour.

Introduction

This study aims to better identify and anticipate the expected crew behaviour during the design phase and consequently to find the better design that will contribute to increase flight transportation safety. As human error is considered a contributing factor in 70% to 80% of all aviation accidents (Amalberti (1994) or Sarter & Alexander (2000)), a further reduction of the already low accident rate will require investments to better support error management.

Of course, flight crews have a high contribution to air transportation safety because of their ability to continuously assess changing conditions and situations, analyse potential actions and make reasoned decisions. However, even well trained, qualified, healthy, flight crew can commit errors. Some of them may be influenced by the design of system logics and associated flight interfaces even if systems and interfaces are carefully designed. Human behaviour is also impacted by operational contexts and the better the identification of the shaping factors e.g. external conditions as weather, crew internal conditions; the more the aircraft design will have a positive contribution to reducing human error occurrence or their consequences.

Furthermore, with the cockpit automation over the last twenty years and the increase of technical system reliability, required competences of pilot profession have certainly been modified. This competence evolution could be at worst a precursor of "crew errors" or "unexpected behaviour". As a matter of fact, in some cases, to overcome a system failure, designers are waiting for a specific crew competence that has been modified due to a slight use of this competence. Thus, some design hypotheses of crew behaviour (after system failure for example) such as detection or diagnostic which are true today, could be challenged for future aircraft program.

All these facts lead to the following question: How could we define crew behaviour hypothesis that could be modified in future programs?

In order to give a first answer to this question, this work will give (I) a quick theoretical framework, (II) the method used, then (III) a results presentation and finally (IV) we will give a conclusion to the study.

Problem study and theoretical framework

Defining an "expected crew behaviour" or a "crew behaviour hypothesis" is strongly linked with the notion of "basic airmanship". This is why, we will give elements to understand (1) the definition, (2) the utilisation, (3) the evaluation of "basic airmanship" in order to understand the (4) study framework and build an appropriate method.

1 "Airmanship" and "basic airmanship":

As the name indicates, **"airmanship"** corresponds to skill and knowledge applied to aviation transport. Airmanship covers a range of desirable behaviours and abilities in aviation. But it is not simply a measure of skill or technique, but also a measure of a pilot's awareness of the aircraft, the environment in which it operates, and of pilot capabilities (Jouhanneaux, M. (1999)).
It is important to understand that there is no shared definition of "airmanship" but several key components could be found in many definitions (Kern, A. (1997)). For our study, we will use the definition given by DeMaria, C. (2006). DeMaria's definition gives the following axis: (i) Situational Awareness, (ii) Personal Minimums, (iii) Assessing and Managing Risks, (iv) Common Sense, (v) Discipline. We have added to these previous points the (vi) "team spirit". In order to keep in mind needed notions we will give here a quick overview.

1.1 Situation awareness

Situational Awareness refers to the degree of accuracy by which one's perception of one's current environment mirrors reality. Key components of situation awareness are the ability to compare the expected with the actual (subjective perception vs. objective reality), understanding the changing environment (structuring the new knowledge) and using the resulting knowledge to manage the dynamics of your changing environment (imaging how things may change) (adapted from Endsley, M. (2004)).

1.2 Personal minimum

Personal minimum refers to the specific state of pilots such as illness, medication, stress, alcohol, drugs, fatigue, hunger; but also could include pilot training, experience and external pressures.

1.3 Assessing and managing risk

In order to assess and manage the flight risk the pilot has to analyse his mission (Amalberti, R. (1996)). Mission analysis can refer to the ability to develop short term, long-term or contingency plans, as well as to coordinate, allocate and monitor crew and aircraft resources. Phases of mission analysis include pre-flight (flight planning, briefing), in-flight (short-term planning, monitoring flight progress, identifying and reporting challenges) and post-flight (timely and interactive flight review).
Analysis necessarily leads to judgment and to the "decision making process" (Reason, J. (1990).; Jambon. F. (1998)), that is to say: detection step, diagnostic step, action plan step and action step, which will be described later in figure 2.

1.4 Common sense

Common sense consists in several components. This is not exhaustive, but it gives several key steps of common sense in aviation acquired by training and experience: adopt consistent, practical and repeatable procedures, know the rules, be assertive and advocate your position from a place of safety and efficiency, be prepared for the flight.

1.5 Discipline

Discipline refers to respecting rules and generalising good practice.

1.6 "Team spirit"

Teams spirit refers to crew cooperation. It's necessary during all mission's phases to allow a good flight realisation.

"Basic airmanship" corresponds to elementary behaviours that designers could reasonably expect from a flight crew according to the definition of airmanship. A precise description of "basic airmanship", does not exist in concrete terms, but this notion exists within each aircraft designers, pilots, safety specialists, Human Factors specialists... And it is used in a discrete and indirect manner to build aircrafts today. Indeed, the knowledge sharing created thanks to the integrated process between these several disciplines, allows the integration of "basic airmanship" notion within aircraft design.

2 Conception and "basic airmanship":

In the framework of a user-centred design, there is a real need of "basic airmanship". User-centred design can be characterized as a multi-stage problem solving process. It requires not only designers to analyze and foresee how users could use an interface, but also to test the validity of their assumptions. These tests are done by analysing the user behaviour in real world tests with actual users. Such testing is necessary as it is often very difficult for the designers of an interface to understand intuitively what a first-time user of their design will experience, and what each user's learning curve may look like (adapted from: ISO 13407; ISO/TR 16982 & (Boy, G. (2003) chap. 8: Robert, J. M.)). In an ideal world, all designers want to imagine product utilisation and would like all real utilisation situations to be tested during the design phase. Nevertheless, the design of complex systems such as commercial aviation, can test only a little number of scenarios. Even if they are well thought, debated, traced during all the design processes, the reality will explore a huge amount of new situations: a simple and exhaustive aircraft utilisation forecasting is not possible.
Nevertheless, we had to build methods and tools in order to forecast real aircraft utilisation and bring back, as much as possible, potential divergent states of man/machine system into a stable one, which will guarantee system safety.
Airbus has acquired a large expertise for taking into account Human Factors during cockpit design and certification (Reuzeau, F. (2010)). All Human Factors studies undertaken on aircraft cockpits are organized as a logical sequence of scientific experimentations: with the realisation of hypothesis tests, experimental protocols, data collection and analysis that have allowed the integration of Human Factors during the design cycle for about fifteen years. Safety notion is a key part during aircraft design particularly the crew's error management: how to forecast human errors, how may their consequences be controlled, do some recovery mechanisms exist...
Now, basic airmanship notion comes in stage. To answer these questions, in a common process several actors will get involved (Pilots: test, training, companies; Human Factors specialists; safety specialists; system architecture designers;...) in order to integrate, in the product, elementary features of aircraft users: that is to say "basic airmanship". This knowledge is hard to measure, to quantify, to extract in a simple manner. It is partly described and scattered in various documents (operational procedures, training program, safety analyses...). Generally the easiest way to recycle it, is to use part of previous design for a new product.
In order to ease innovation and maintain the high level of aviation safety it is necessary to have, during the earliest phases of design, a precise, justifiable, traceable hypothesis on crew behaviour: what can we reasonably expect from the crew?
In the next part we will see that these hypotheses cannot be static and that it is very hard, maybe impossible, to create a consensus of opinions on these hypotheses but there are other ways to reach our objectives.

3 Systems and environment constrain "basic airmanship":

Now that we have defined what "airmanship" and "basic airman ship" are and how they are used during design, let's see how they can be modified. We have gathered these modifying factors: automation and man-machine task sharing principles, system complexity, system reliability, airline policy, workload modification. This list is not exhaustive.

3.1 Automation and system complexity:

The automation of cockpits over the last twenty years and the increase of technical system complexity, have modified competences for the pilot profession and the crew's role has evolved from a flying one to a management one. Several studies in the aviation domain (in particular Starter & Woods ones) shows that cockpits automation is a significant variable in aircraft crew activities. Indeed, the crew can delegate some tasks to automatisms so, the aircraft/flight management is easier. But the increase of system complexity could potentially complicate the crew's understanding of system functioning. Thus, there is an interaction between these two effects: help and complexity. Faced with a system failure, pilots will search to understand the failure without losing the help of the instrument. Then, Boy, G. (2003) chap. 3: Amalberti, R. & chap 5: HOC, J. M., underlines that the choice between automatic and manual control depends on what the crew could reasonably imagine of the system behaviour. Finally, Rasmussen & Golstein (1985) explain that there will be a loss of competence in all domains that are usually took in charge by the automatism. All these facts will shape "basic airmanship".

3.2 Increase of reliability:

The increase of automatisms reliability leads to a very slight rate of face to face between pilot and system failures. In case of a problem, the pilot will have a tendency to challenge his activity instead of the automatism. Otherwise, for a novice or an expert, the lack of being confronted with system failures (training cannot cover the large diversity of real situations) means pilots could potentially tend to lose confidence in their ability to manage the failure.

3.3 Airline policies:

All aircrafts in a family are globally the same whatever the airline (country, pilot training, cost policy,...). Airline internal constraints, linked to their development policies, will have an impact on the airmanship.

3.4 Crew workload: Basic airmanship local variation:

Because of flight activity variation, it is impossible to think about a "basic airmanship" which will stay the same during the whole flight. Indeed, the crew decision making process will evolve according to external constraints such as system failure, meteorological conditions, flight phase... This is why, the "basic airmanship" capability is linked to crew workload.
Crew workload can be linked to aircraft systems and the external context of their use. As a matter of fact, these systems are built to help the realisation of crew tasks. In this context, "help" corresponds to crew workload reduction. Globally, aircraft automation has reduced crew workload according to some tasks, but in a paradoxical manner. As matter of fact, "automation irony", as Bainbridge calls it (Boy, G. chap. 3: Amalberti, R. (2003)), is that automatic systems have encouraged the emergence of new tasks (as manipulation, management or monitoring tasks). These news tasks could be potential sources of errors and could be time-consuming. Nevertheless, we would emphasize that safety state increases with automation level. Furthermore, crew workload is badly shared out. For example, there are some hypo vigilance problems during cruise phase and at the opposite during approach the workload is increased. As a matter of fact, the problem could be formalized as follows: automatic systems tend to globally reduce crew workload but this could locally create some points of low workload with a lack of crew concentration and a decrease of crew efficiency in case of critical situations and some high point workload with an increase of resource consumption (Boy, G. chap 5: HOC, J. M. (2003)) .
The effect of external situations, such as traffic or weather, could be a source of crew workload. The design of systems must take these facts into account.

To conclude this part, we would like to emphasize that all these constraints do not help the realisation of a consensus on "basic airmanship". The complexity of "basic airmanship" is a brain teaser for all aircraft designers and a source of long negotiations between all of them.

4 Study framework and realisation axis:

This study is done in an industrial framework, so in order to help the design process in a efficient manner we do not try to gather all the crew behaviour hypotheses that form basic airmanship.
We prefer to have a none exhaustive list of relevant and challenging design hypotheses of crew behaviour that will allow to constrain the earliest phases of design, instead of a long list of design hypotheses which will take a lot a time to gather. The method described here after take into account this point of view.

Method

1 Study object:

The starting point of this study is a document that contains a group, as exhaustive as possible, of scenarios that describes systems functional failures' repercussions on existing aircrafts: **functional failure scenarios**. We focus on key systems that involve different kind of human-machine interactions: **control and displays, energy management and autopilot management**. The total number of scenarios is $\mathcal{N}$ = 2173. The number of scenarios for each analysis is respectively $\mathcal{N}$ = 697 for control and display systems, $\mathcal{N}$ = 969 for flight management (autopilot) and, $\mathcal{N}$ = 507 for the energy management. Chosen systems do not show any distinctive defects during the aircraft's life. This supplementary analysis is only undertaken to complete safety experts' judgment and all simulations already done on the aircraft program during the development phase and thus, to improve, if possible, our design and validation processes and develop optimized means of mitigation. Furthermore, analysis choice must help to build an applicable method whatever the aircraft.

A functional failure scenario contains three distinct parts. (1) The first one deals with the failure description, that is to say the different functional levels impacted by the failure, the type of failure and gives some context description (meteorological elements, flight phase...). (2) The second one describes the failure, that is to say the effects on aircraft and on its occupants (this part contains the expected crew behaviour). (3) To finish, the third part classifies failure repercussions according to the consequences on flight safety. The classification categories are the following:

- Category 1: failures with a slight increase of crew workload.
- Category 2: failures with a significant increase of crew workload.
- Category 3: failures with an excessive crew workload and with serious injuries of aircraft occupants.
- Category 4: failures with fatalities and aircraft structural damages.

These categories are linked to design requirements in order to make extremely improbable failure with serious consequences. The figure 1 below shows failure categories proportion according to system type.

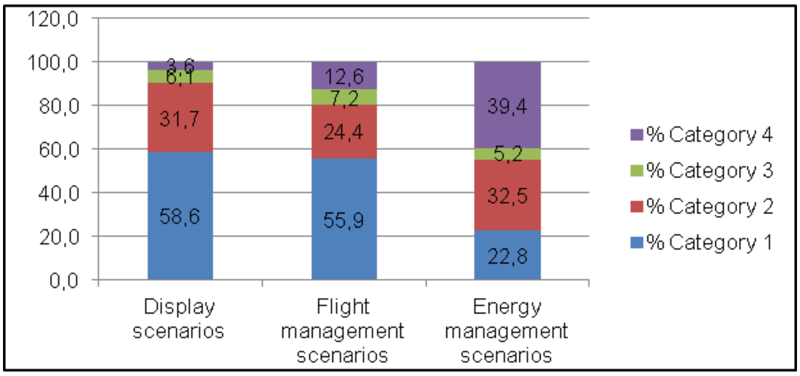

Figure 1: Failures categories proportion according to system type.

2 Scenarios selection:

Scenarios selection presented here, will be done thanks to expert judgment (Anderson, J.R. (1981)). Although the term "expert" seems to have a common meaning, the definition of expertise in empirical studies is not homogenous. Nevertheless, there is a high level consensus: the expert is someone who is recognized by his/her peers as highly competent in his/her expertise domain. This capacity is acquired by extensive practise and repeated training in task domains linked to his/her expertise field (Wolf, M. & Sperandio, J. C. (2004)). Furthermore, expert thought process is mainly based on pattern matching (Aamodt, A. & Plaza, E. (1994)), that will help with scenario selection.
In order to realise this step, two safety specialists and one Human Factors specialist for each system (nine specialists for the study) have studied each failure scenario. Before the beginning of each session of selection, there was a dialogue between analysts and experts in order to define the project objectives, to analyse the problem complexity and to identify key questions for the study. Before the beginning of this step, this protocol was tested on a reduced panel of experts (Lannoy, A; Procaccia, H (2001))
Selected specialists have a great knowledge of the technical system studied. For each scenario, instructions were:

"Please pick up scenarios for which:
- *You think that the real crew behaviour (Detection, diagnostic, action plan, action) can be different of the one expected, please give us your selection rationale.*
- *If the expected crew behaviour is not realised, then the failure consequences will be degraded, please give us your selection rationale."*

In order to find characteristics of wrong crew behaviour hypotheses, the next objective is to study the selected scenarios according to the decision making process (Reason, J. (1990).; Jambon. F. (1998)) (see figure 2).

3 Study of selected scenarios:

To the crew, managing an aircraft system failure can be undertaken in 4 steps (see figure 2). The first step is failure detection. The crew must be aware that a failure has occurred. The second step is failure diagnostic. This step must allow the construction of a current situation representation. The third step the construction of failure specific sequence of corrective actions. To finish, the last step is the implementation of this sequence, also called the action step. These steps can be followed by a verification step which is not represented on the figure. Furthermore, this sequence could be observed from several levels, for example a "low" level action can be a part of a "high" level diagnostic step. These four steps could be gathered into two: the failure understanding one and the failure correction one (Jambon. F. (1998)).
The study according to this process has been done with the help of three Human Factors specialists and with expert explanations collected during scenario selection.

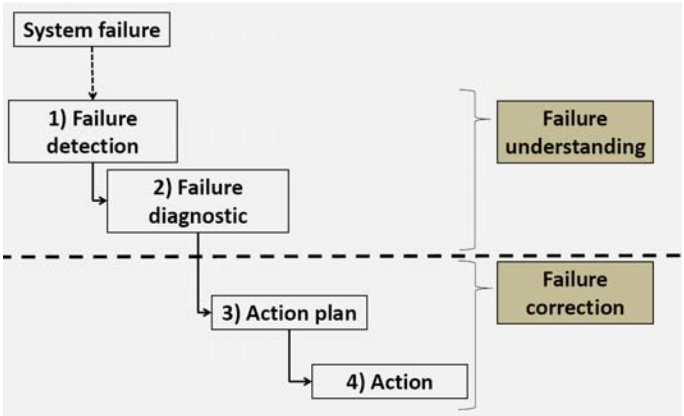

Figure 2: Decision making process, adapted from Reason (1990)

Results

1 Scenarios selection by experts:

Results of scenario selection are summarized on the figure 3. Among 697 scenarios of control and display system, 84 (12,1%) scenarios were selected; amongst 969 scenarios of flight management system, 174 (17,9%) scenarios were selected; amongst 507 scenarios of energy management system, there were no selected scenarios.

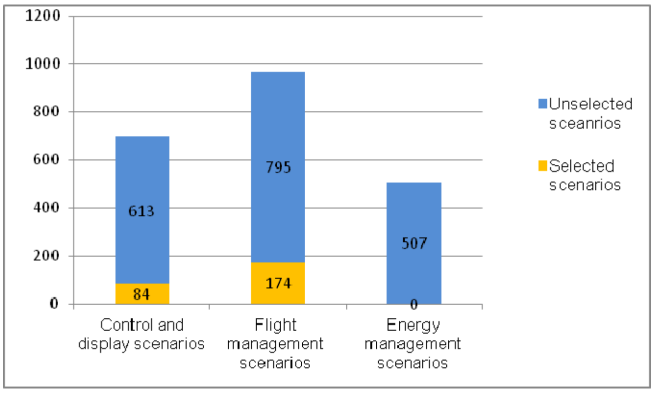

Figure 3: Results of scenarios selection.

There are significant differences (selected scenarios percentage comparison: Khi^2 = 31,39) between control and display and flight management (autopilot) scenario selection results (see figure 3). We do not explain these differences, except by the system nature and the manner in which the analysis redaction was done. An explanation within figure 1 may help to understand why there are no scenarios selected within the set of energy management scenarios. Indeed, the two other systems have significantly more category 4 scenarios than category 1 (Khi^2 = 16,74) and there is no significant difference between category 2 and category 4 (Khi^2 = 2,46). By definition, these categories give a bigger place to a crew corrective action. We could imagine that scenarios of this analysis have been classified without taking into account an active crew corrective action.

For the rest of the study, we will focus on control and display systems and on flight management systems.

2 Study of selected scenarios with the decision making process:

In this part, there could be several steps in the decision making process which could be challenged for one scenario. To calculate the percentage, we have respectively $\mathcal{N}$ = 327 for the flight management systems, and $\mathcal{N}$ = 109 for the control and display systems. For statistical tests, $\mathcal{H}_0$ will be the equal distribution between each steps of the decision making process.

2.1 Study of selected scenarios with high level steps of decision making process: The failure understanding step and the failure correction step:

With an analysis of the two main phases of decision making processes (see figures 4 & 5), there are significant differences for α = 0,01, between the failure understanding phase and the failure correction phase. Khi^2 values are respectively Khi^2 = 31,9 for control and display systems and Khi^2 = 79,2 for flight management systems.

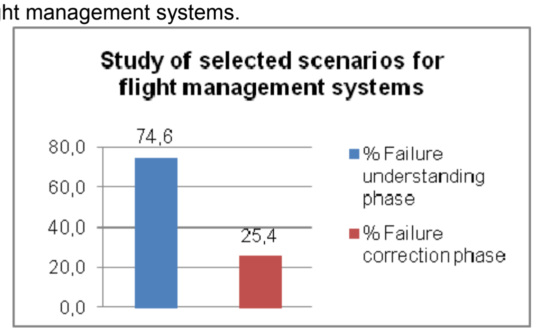

Figure 4: Study of selected scenarios for flight management systems thanks to hight level step in descision making process.

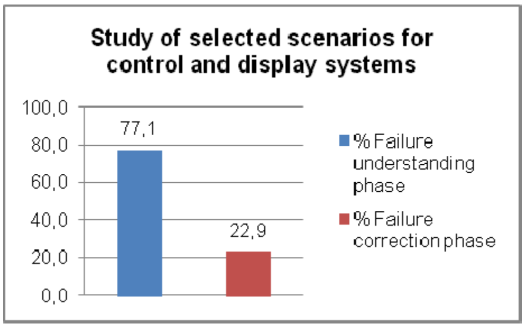

Figure 5: Study of selected scenarios for control and display systems thanks to hight level step in descision making process.

2.2 Study of selected sceanrios with low level steps of decision making process systems:

2.2.1 *Study of selected scenarios of flight management system*

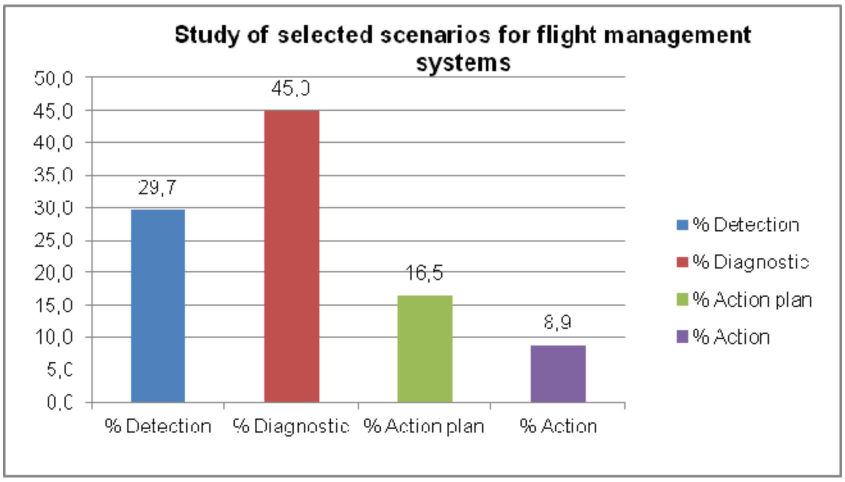

Figure 6: Study of the flight management system scenarios with the decision making process.

The table bellow recapitalates Khi^2 values of cross comparison for figure 6 results. Highligted values are significant values for $\alpha = 0,05$.

Flight management system	Detection	Diagnostic	Action plan	Action
Detection			$\alpha = 0,05$	$\alpha = 0,01$
Diagnostic	10,25		Khi^2 $\alpha = 3,84$	Khi^2 $\alpha = 6,64$
Action plan	12,25	43,03		
Action	36,70	79,11	7,53	

2.2.2 *Study of selected scenarios of control and display system*

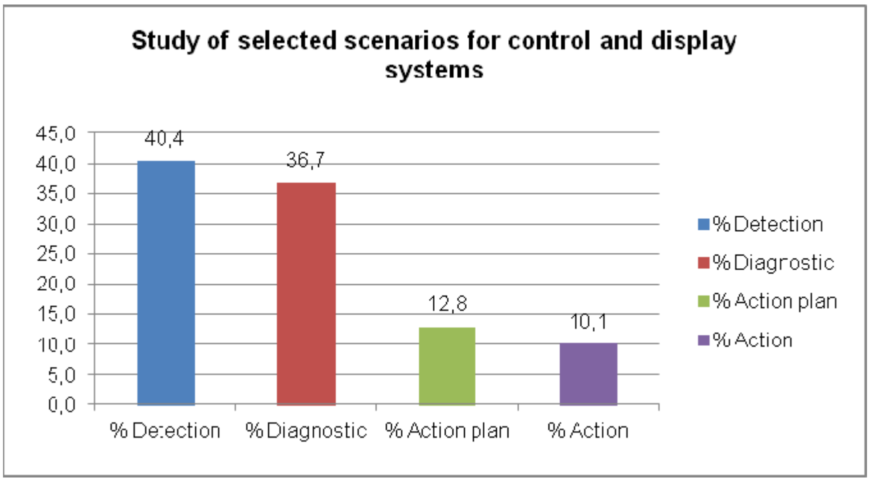

Figure 7: Study of the control and display system scenarios with the decision making process

The table bellow recapitalates Khi^2 values of cross comparison for figure 7 results. Highligted values are significant values for $\alpha = 0,05$.

Control and display system	Detection	Diagnostic	Action plan	Action
Detection			$\alpha = 0,05$	$\alpha = 0,01$
Diagnostic	0,19		Khi^2 $\alpha = 3,84$	Khi^2 $\alpha = 6,64$
Action plan	27,80	12,52		
Action	19,80	22,95	0,36	

2.3 Results interpretation:

The study of selected scenarios according to high level profiles of decision making process shows that there are significantly more selected scenarios with hypotheses of crew failure comprehension than selected scenarios with hypotheses of crew failure correction. There could be two manners to explain this fact. (1) The first one is linked to the difficulty for a designer to forecast crew failure comprehension. Indeed, it is harder to imagine how the crew will interpret failure symptoms than to imagine how the crew will correct the system failure. (2) Furthermore, in case of an undetected failure by the system, it is difficult for experts to precisely anticipate which parameters will be taken into account for failure detection and failure diagnosis. This will depend on the operational context.

Previous facts can also explain differences between the failure detection/diagnostic steps and the action plan/action. Nevertheless, there are, for the flight management system, significant differences between failure detection and failure diagnosis and between action plan and action. These differences can be explained by the needed complexity of the autopilot. Indeed, diagnosis and action plan steps require a good situation awareness. The construction of situation awareness can be difficult in case of a system that is made to cover a large diversity of operational and technical normal and abnormal situations. But a certain level of complexity has to be understood and used by the crew.

Regarding “basic airmanship” notion, this study is in agreement with other studies in the domain on effect of automation and systems reliability (as Boy, G. chap. 3: Amalberti, R. & chap 5: HOC, J. M. (2003)). Furthermore, we have found that some hypotheses of crew detection and crew diagnosis on system failures have to be modified in the future. We are currently working on crossing these first results with the type of system failure (loss of information, erroneous system behaviour, loss of system, failure detected by the system or undetected failure...), flight phases (on ground, take off, climb, cruise, approach, landing, all flight phases), failure rate, external context, in order to understand the evolvement of the expected crew behaviour. We think that these factors will allow us to understand the evolvement of “basic airmanship” and will guide the development of new expected crew behaviours to be in agreement with future required pilot skills.

Conclusion

Given the limitations of scenario databases, findings from this research need to be interpreted carefully. As scenario databases cannot be as exhaustive as reality it will be a nonsense to think that we have studied all hypotheses on crew behaviour during aircraft design. Furthermore, scenario selection was done thanks to expert judgment. We tried to reduce the bias linked to this method (several kind of expertise, verification with test pilots...) but to affirm that the selection is perfect is wrong. Selected scenarios are the result of the best consensus between different experts. Finally, results show tendencies and it does not signify that low percentages are not taken into account.

Still, this research provides initial insights and suggests possible ways to support crew errors forecasting during the early design phase. The coherence of our results with previous studies and with the types of systems guarantees the pertinence of our method. The use of the decision making process model adapted for our study receives was judged relevant by experts. According to them, it allows us to have a good formalism of crew behaviour in order to challenge it. Now, by studying each subset of scenarios according to system functional failure, it could be possible to link some system failures with the crew’s possible difficulties. The aim is to build barriers, protection or means of mitigation for human error during the early design phase.

Furthermore as Airbus tends to do, it is necessary to continuously improve the sharing of knowledge in a collaborative environment, such as aviation. A user centred design in a such complex system cannot be done without good collaboration between different actors of the design. Knowledge construction, mandatory to a mature and safe design, can only be done trough this integrated work. This is the best way to construct an aircraft corresponding to “basic airmanship”.

Finally, we emphasize the importance of collecting more systematic data on expected crew behaviour during design and on human error/difficulties during service in order to better trace the link between these two aspects. Understanding the consequences of a design hypothesis on crew behaviour and human error will be helpful in the design of complex systems.

1 Acknowledgements

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