# A Socio-technical Holistic ABM Simulation Framework to Assess Pilots Performance Variability

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**Abstract.** One major limitation of developing cognitive computing cockpit supporting tools to maintain the pilots' workload between acceptable lower and upper thresholds is the time variability of humans to perform a well-trained action in a dynamic environment. There are several human factors related issues such as fatigue, stress and workload among others that are reported as the major contributor to human performance variability. Without a deep understanding of the mechanisms that affect pilot performance during the different phases of flight, any support such as a recommended action to improve aircraft stability can affect as an interruption to current cockpit task that increments the workload, forcing pilots to comprehend the consequences of the proposed actions and take a decision about accepting or rejecting the recommendation. This paper presents a socio-technical approach to understand the causes of a degraded mode pilot performance while providing a simulation framework to predict the time windows at which supporting tools could be fired to lessen the pilot workload.

## Introduction

The aviation industry has experienced a huge technological evolution from early Clipper Model 314 with five crew positions (navigator, radio operators, flight engineer and two pilots), with each position having specific operating responsibilities (aviate, navigate, communicate and manage system) to today's fly-by-wire and computer systems with two flight crew members in the flight deck.

The introduction of new technologies in the flight deck has allowed important advances in flight control, communication, navigation, and engine management technologies.

This has resulted in a simplified and consolidated control mechanism that reduces flight crew workload for a variety of skill-based and rule-based tasks lessening the amount of manual or repetitive tasks that flight crew have to carry out.

Successful multicrew cockpit achievements through flight deck automatisms have fostered the need for further automatisms to move towards the Single Pilot Operations (SPO) challenge which can provide important cost savings while improving safety [1]. A review of the different conceptual approaches to only one pilot in the flight deck could be found in [6], where the authors recommended an architecture which combines human and automation agents both in air and ground.

However, despite the shift of skill-based and rule-based human operator tasks towards more knowledge-based tasks has been successful in different application fields such as Industry 4.0 [3], the increased system complexity that comes with the new technologies creates novel issues that could increase flight crew workload above their capabilities.

Some issues arise in the cockpit, because the new supporting tools do not simply replace the human in performing a cognitive task but also transforms the actions and introduces new tasks which cannot be predicted at design stages. Thus, for example, shortages of an adequate feedback and support arise at latest stages during validation experiments. Literature [5] describes several automation-related problems and surprises that usually are detected when the human operator is in-the-loop uncovering feedback problems and cognitive task load increments.

**Figure 1** represents the task load in a multi-crew cockpit at different phases of a flight [8]. As it can be observed, the peak task load at landing phase could overload a pilot in SPO if an extra task appears, such as an interrupting event (i.e. Air Traffic Controller instruction or Electronic Centralized Aircraft Monitor signal), that requires the attention of the Pilot.

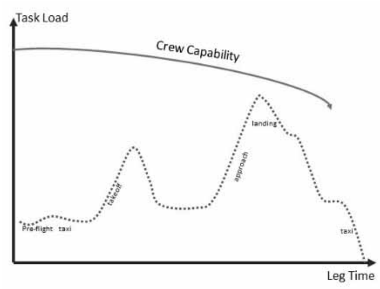


**Figure 1:** Crew Task load in nominal flying scenarios.

Considering the Wickens' multiple resource theory processing channels [9], and the effects of simultaneous demand on a single channel [2], it can be easily noted that an auditive or visual support to pilot during the peak task load could be counterproductive since task demand could exceed pilot cognitive capacity.

This article describes a socio-technical simulation model to better understand particular requirements for a supporting tool to lessen the cognitive task of a pilot. The remaining of this technical note is organized as follows: Section 1 introduces the socio-technical challenges to tackle the role of the pilot. Section 2 discusses the FRAM modeling formalism while Section 3 presents a FRAM model describing a crew task at approach phase. Section 4 illustrates some results validated during a simulation trial.

# 1 Socio-technical Modeling Challenges

Airline pilots are trained with formal written procedures acquiring the skills for setting switches, buttons or introducing data in flight systems at the different phases of flight. **Figure 2** represents the pilot situational awareness cognitive processes attending aviate tasks assuming the human in the loop behaviour.

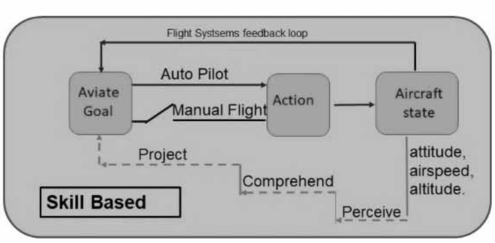


**Figure 2:** Aviate Pilot in the loop.

Assuming a human-in-the-loop pilot behaviour in which the pilot performs a sequence of actions according to linear procedures, a discrete event simulation model could be built in which an ordered sequence of events, each one described by a deterministic or stochastic time, could replicate the pilot task load and generate similar results to monitored times in training exercises.

Unfortunately, aviate tasks also co-exist with communicate and navigate tasks each one with different priorities that can interrupt the current task, forcing the pilot to attend the interruption, determine the priority with respect to the current task and decide which tasks should be postponed. Thus, pilot behaviour in the flight deck cannot be assumed as a human-in-the-loop attending a sequence of well-trained tasks, rather pilot must constantly attend different sources of aviate, communicate and navigate interruptions such as:

- Air Traffic Controllers (ATCo) can issue an auditive (radio communication) or a visual (data link) instruction at any time, which can cause an interruption to current aviate task.
- Aircraft: Flight deck aircraft are equipped with a warning system to inform crew about abnormal aircraft problems. Thus Boeing implements the Engine Indication and Crew Alerting System (EICAS) while Airbus implements the Electronic Centralized Aircraft Monitor (ECAM) to inform pilot about an aircraft component failure.
- Crew: Pilots can be interrupted at any time by crew through the Service Interphone chime. When it sounds, pilot must react and listen to the Flight Attendant.

In a realistic scenario pilots are frequently interrupted while performing a procedure. Regardless of the particularities of the interruption, pilots must carefully screen the information attached to the interruption and fire a cognitive task that consists of a set of mental actions to predict the future aircraft state if the ongoing task is prioritized to a convenient stopping point before responding to the interruption, or the state that would be reached if pilot attends the interruption and returns to the interrupted task later. Regardless of the pilot choice, there is an increment of pilot mental workload since he must constantly remember to return to the deferred task later.

Furthermore, a pilot can perform maximal two concurrent actions, if they do not require the same cognitive channel (i.e. he can monitor a display at the same time he is performing a psychomotor action on a flap), but a third concurrent action usually forces to postpone the lowest priority action and generates a pending memory item that affects the performance, forcing the pilot a "remember to remember" action.

The design of cognitive computing flight deck supporting tools to assist pilots preventing peak workload requires a socio-technical model description of pilot behaviour to understand how and when the assistance should be provided to improve pilot performance [7] and avoiding a degraded mode due to pending memory items.

## 2 Functional Resonance Analysis Method (FRAM) Formalism

Lack of a modelling guideline to formalize the interaction between cockpit supporting tools and pilot behaviour is an important source of model maintenance problems when new changes must be introduced in the model to predict the impact on new cockpit functionalities.

Furthermore, a scarce understanding about the hidden dynamics on how the context affects interdependencies between human operator and automatisms affects not only the maintenance of the model but also the acceptability and transparency of the results. To overcome present modelling shortages, the FRAM approach (Functional Resonance Analysis Method; [4]) has been used, which provides an excellent functional structure to represent socio-technical systems supporting different abstraction levels in each FRAM component when implemented in an Agent Based Modelling framework. FRAM formalism enhance modellers with a socio-technical approach to formalize Procedures, Actor behaviour, Component Behaviour and the Interdependencies.

In the present implementation, the human cognitive tasks have been described by means of non-linear relationships which consider static attributes and operational context to change the dynamic attributes. Behavioural rules are used also to describe the decision making process considering the dynamic attributes which guides a trade-off between performance and workload. A functional entity is described in FRAM by the six following relations and represented graphically in **Figure 3**.

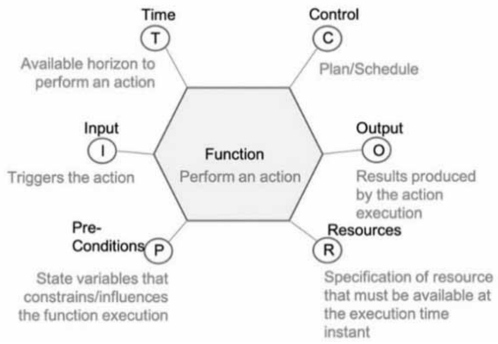


**Figure 3:** FRAM component.

The interface of FRAM components consists of:

- Input: Triggers an action to be implemented by a computer service, a machine or by a human.
- Time: Available time horizon to perform an action. It can be immediate or with a latency in the case of computer service, or can be a stochastic time parametrized by values of influence variables in case of a human action.
- Resources: Provides an estimation of resource availability at a particular time instant, required to perform the action.
- Control: An action usually requires the adjustment of a function that can be a plan, a procedure or a human task.
- Output: The results produced by an action.
- Preconditions: State variables that must be fulfilled to proceed with the action.

Note, that the FRAM approach is mainly oriented to resilience engineering, trying to determine how variability may interact within a system in a manner that leads to adverse performance outcomes.

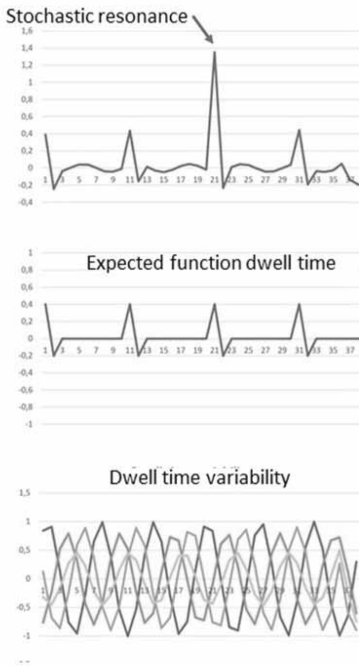


**Figure 4:** Dwell time variability.

Figure **4** represents graphically the effects of performance variability on the execution of tasks. As it can be observed, the coexistence of time variability when performing different concurrent tasks (lower part of the figure) can cause a peak resonance on the overall behaviour (upper part of the figure) which sometimes can be observed as a timeout (i.e. a task not finalized before a deadline).

This approach has been very useful to support a deep understanding of the overall behaviour of an aircraft pilot in the flight deck. Thus, it is possible to investigate the flight deck functional architecture and to provide an answer to relevant questions such as:

- Why can the combination of safety procedures be unsafe? The identification of the contextual conditions that can impact negatively on safety is an excellent information to guide the changes in the pilot-cockpit procedures to guarantee a resilient flow of tasks.
- Why can the combination of well performed tasks lessen the performance of the overall aircraft system? Note that small delays when performing critical-safe tasks in a fast changing environment can block the finalization of a procedure.

# 3 Flight Level Authorization FRAM Model

To illustrate the FRAM formalism, this section describes one of the procedures a flight crew should perform during the approach phase.

Flight level authorization procedures describes the main flow of actions and its alternatives the Pilot Flying (PF) performs when an aircraft is located above 8000 ft. and by 40 Nm to the airport, and is initiated by the ATCo which issues a clearance instruction.

The ATC issues the message through the radio to instruct a new FL (flight level), which should be listened by both pilots. Then Pilot Monitoring (PM) repeats the FL instruction to ATC for acknowledgement which is listened also by the PF (action 2-5.1). At that time PF sets FL in the FCU (action 1-5.1). Finally, when PF sets the new FL, then PM crosschecks in the FCU, that the FL is the same that ATC said and, after that, PM should check in the PFD (Primary Flight Display) that FL is blue – with subsequently, PM call-out to PF “nnn FL blue” (nnn is the FL cleared). Moreover, PF had to check that FL was correct in the FCU and has checked “nnn FL blue” in the PFD (action 1-5.3).

| Action Code | Action Meaning | Time–out | Time |
|---|---|---|---|
| 1-5.1 PF | Interpret ATC message | 15 | 4 |
| 1-5.2 PF | Select the FL | 15 | 11 |
| 1-5.3 PF | Check FL blue | 15 | 4 |
| 2-5.1 PM | Interpret ATC message | 15 | 4 |
| 2-5.2 PM | Acknowledge | 15 | 4 |
| 2-5.3 PM | Check FL in FCU | 15 | 6 |

**Table 1:** Pilot Flying (PF) and PM (Pilot Monitoring) actions.

**Figure 5** and **Figure 6** illustrate the main cockpit instruments to perform the FL Authorization task are the Flight Control Unit (FCU) and the PFD (Primary Flight Display) which are required resources to perform actions 1-5.2 and 1-5.3 respectively. In addition, in action 1-5.2 it is also formalized the resource HM that means a psychomotor action (i.e. Handmade), this mental resource is required because PF set the FL in FCU.

Furthermore, there are some actions such as 1-5.3 and 2-5.3 that are the result of an external process, such as the communication among the ATC and the PF or the communication between the PF and PM. Such external processes can be simple actions without any pre-condition, neither control nor required mental resource, firing the output action as consequence of receiving an input.

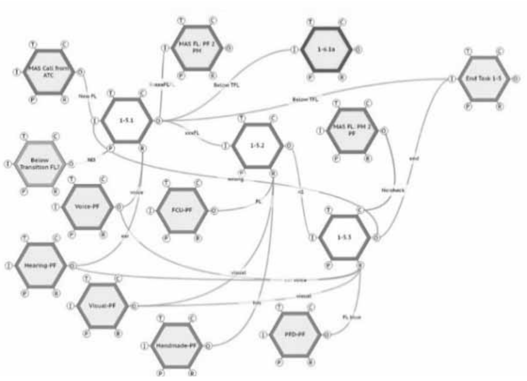

**Figure 5:** FRAM PF FL Authorization Model.

Main functionality of MAS actions is to introduce a delay that could be caused by the communication channel, or a human reaction time. Thus, action “MAS FL: PM 2 PF” is used to describe the PF reaction time to a communication from PM, while action “MAS FL: PF 2 PM” describes the PM reaction time to a communication from PF.

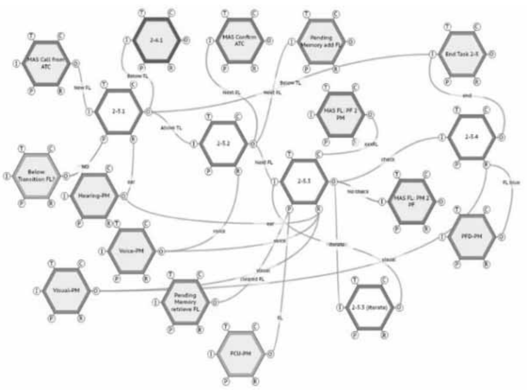

**Figure 6:** FRAM PM FL Authorization Model.

The triggering of the procedures is an external event driven by the ATC represented in purple, while the end of the task is represented in green and the triggering of a new task is represented in red. Grey colour is used to describe the inherent actions of the task already introduced in Table 1. Important to note, that despite the ATC call and the available resources (both cognitive and cockpit instruments), action 1-5.2 will not be fired if the aircraft is below transition FL (P connection to action 1-5.1).

# 4 Simulation Results

To illustrate the benefits of the socio-technical modelling approach, it has been validated three different scenarios.

## 4.1 Nominal FL Authorization Scenario above Transition FL

**Figure 7** represents the different actions performed by the Pilot Flying (PF; top Gantt chart) and the Pilot Monitoring (PM; bottom Gantt chart).

Concurrent tasks are represented as a box in the first two rows, while a postponed task is represented by a black line at the third row, and a Pending Memory Item is represented by a yellow line at the 4th row. In this scenario, the aircraft is above the Transition Flight Level (i.e. from flight level to altitude) when the ATC issues the FL authorization at time 25 s.

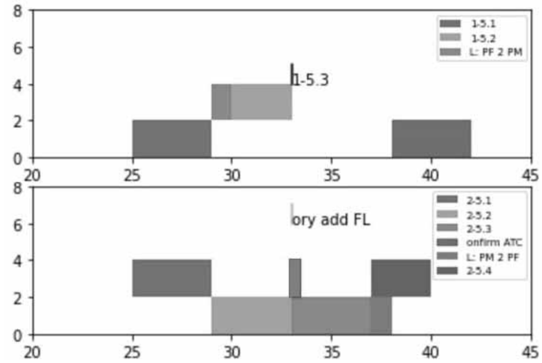


**Figure 7:** Flight Level authorization nominal scenario.

As it can be observed, PF and PM receive the instruction and perform action 1.5.1 and action 2.5.1 resp. A PF callout to PM checks the FL in the FCU, while at the same time PF is selecting the FL in FCU. As a result, PF must wait that PM confirms that the FL in the FCU is the same FL instructed by the ATC which occurs at time 38 s.

Both Gantt charts postpone active actions until all pre-conditions and mental resources are available. Thus PF action 1-5.3 is postponed until PM confirmation, which occurs in parallel to action 2.5.4 (Check FL blue). Worthwhile to note that action “Pending Memory add FL” is a memory action in which PM must remember the FL issued by the ATC and will be retrieved later to validate the FL selected by the PF.

## 4.2 Nominal FL Authorization Scenario below Transition FL

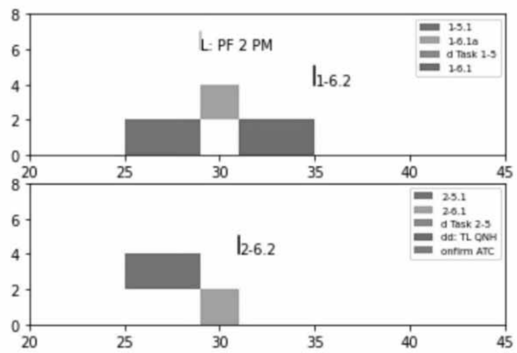


**Figure 8:** Flight Level authorization nominal scenario below transition level.

The FL authorization procedure considers two different aircraft states. The scenario described in section 4.1 represented the aircraft above the transition level, while in this scenario, the ATC issues the same authorization, but the aircraft is below the transition level.

**Figure 8** represents the different actions performed by the Pilot Flying (PF; top Gantt chart) and the Pilot Monitoring (PM; bottom Gantt chart): the PF does not perform the sequential tasks “Select the FL” (1-5.2) and “Check FL blue” (1-5.3), instead he performs action 1-6.1a, which fires the “Altitude Authorization” procedure.

## 4.3 Interrupted FL Authorization Scenario above Transition FL

There are different sources of interruptions, affecting the actions that pilots are performing, such as an instruction from ATC, an ECAM Warning or a Crew Cabin Call.

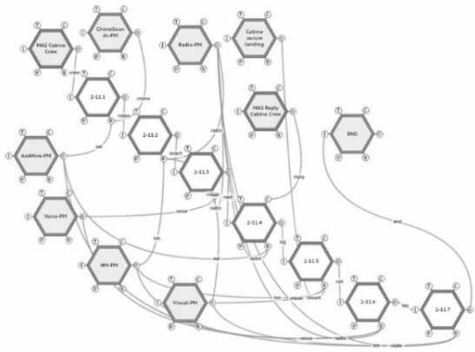

**Figure 9:** Cabin Crew communication.

**Figure 9** represents the sequence of actions Cabin Crew to communicate with PM, while **Table 2** describes the meaning of each action.

| Action Code | Action Meaning | Timeout | Time |
|---|---|---|---|
| **2-11.1** | Listen Call TCP (chime sounds) | 60 | 7 |
| **2-11.2** | Selector changed to CABIN | 15 | 2 |
| **2-11.3** | Reply Cabin Crew | 60 | 2 |
| **2-11.4** | Listen Cabin Secure | 15 | 3 |
| **2-11.5** | Cabin Secure | 15 | 4 |
| **2-11.6** | Reply Cabin Secure | 15 | 2 |
| **2-11.7** | Selector changed to VHF1 | 15 | 1 |

**Table 2:** PM actions attending Cabin Crew.

**Figure 10** represents the different actions performed by the Pilot Flying (PF; top Gantt chart) and the Pilot Monitoring (PM; bottom Gantt chart) when a cabin crew interruption arises five seconds after receiving the ATC authorization. As it can be observed, the amount of PM concurrent actions is increased, and that impacts the performance, since workload is boosted with three pending memory actions that PM should remember to perform once the mental resources are available. The three actions not performed on time are:

- PM Confirms to ATC
- PM Pending Memory add FL
- PM Check FL blue

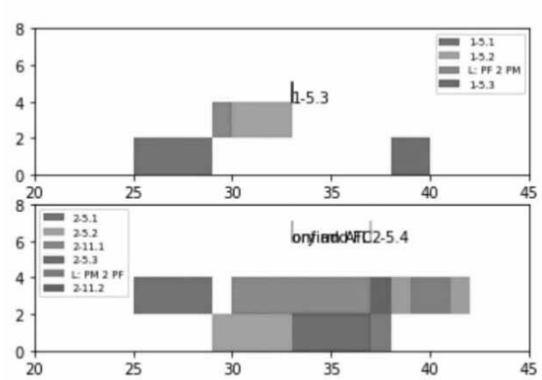


**Figure 10:** FL authorization with Cabin Crew interruptions.

## 5 Conclusions

This paper highlights the main modelling requirements of a socio-technical model to properly represent the human-machine behaviour when interacting in a dynamic context.

Functional Resonance Analysis Method (FRAM) has been used as a modelling formalism since its basic component allows the description of mental resources a human actor requires to implement an action, while at the same time it allows also the specification of technical requirements of the supporting tools to enhance human operator to perform the action. The paper illustrates a particular flight deck procedure, pilots should perform considering different aircraft status and potential interrupting events.

As a result, it has been described by means of a Gantt chart the different actions are executed considering the availability of mental resources and supporting tools, postponing some actions until all requirements are satisfied.

The model described has been developed and validated in the European project E-PILOTS (https://e-pilots.eu/), and provides the baseline to analyze how and when elaborated information should be provided (i.e. visual/auditive) avoiding the postponement of an action because the cognitive channel is busy or the human operator is attending 2 concurrent actions.

### Acknowledgements

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