A SYSTEMS ENGINEERING METHOD AND SIMULATION OF STANDARD OPERATING PROCEDURES

Abstract

Standard Operating Procedures (SOPs) define flightdeck operations by prescribing the sequence of actions for flight crew to complete each segment of the mission. Well-designed procedures allow the flight crew to perform the required sequence of actions in a feasible progression within the operationally allowable time window. Current practices for developing procedures rely on judgments of domain experts and are tested by experts in simulators. This approach is expensive, time consuming, and dependent on subjective assessments. This paper describes the application of a formal model that complements the work of domain experts by assessing the cueing and timing of SOPs' interactions using a combination of sequence diagram and Monte Carlo simulations to support time-to-complete analysis. The method is demonstrated by a case-study comparing two alternative procedures for a four-engine turbofan aircraft.

Keywords
Human-Machine Interactions; Standard Operating Procedures; Flightdeck Operations; Formal Methods.

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A Systems Engineering Method for Analysis and Simulation of Standard Operating Procedures

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ABSTRACT
Standard Operating Procedures (SOPs) define flightdeck operations by prescribing the sequence of actions for flight crew to complete each segment of the mission. Well-designed procedures allow the flight crew to perform the required sequence of actions in a feasible progression within the operationally allowable time window. Current practices for developing procedures rely on judgments of domain experts and are tested by experts in simulators. This approach is expensive, time consuming, and dependent on subjective assessments. This paper describes the application of a formal model that complements the work of domain experts by assessing the cueing and timing of SOPs' interactions using a combination of sequence diagram and Monte Carlo simulations to support time-to-complete analysis. The method is demonstrated by a case-study comparing two alternative procedures for a four-engine turbofan aircraft.

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INTRODUCTION

During the engineering and deployment of a system, the greatest demand in time and cost is imposed by the specification, design, analysis, and testing of the system and its interaction with the operational environment. These activities include the design of: (1) the physical interface (i.e. the sensors), (2) the actuators and their control surfaces, (3) the effect of the external environment - to name a few: temperature, vibration, and radiation etc., as well as (4) the user-interface.

Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [1]. Along with Computer Aided Design (CAD), MBSE has greatly improved the system design process allowing the virtual analysis of the system throughout its design and implementation phases well before real life operation.

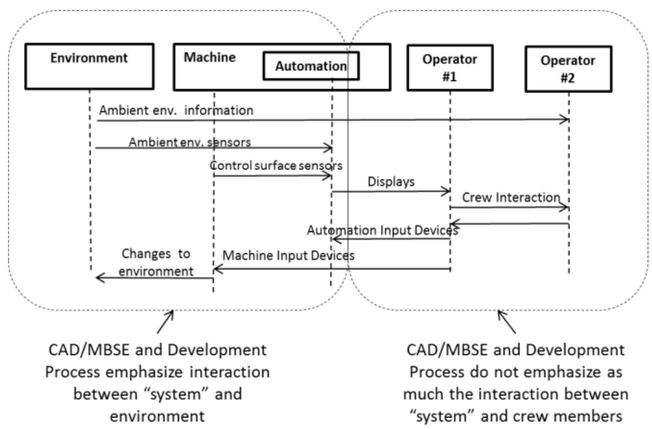


Figure 1 CAD/MBSE rigor does not exists for the specification, design and analysis of the interaction between the operator and the machine

Human-Machine Interaction (HMI) is the interaction between the operator and the machine (including the automation). There are three main components in the Human-Machine Interaction: (1) the human operator, (2) the machine (that includes the automation), and (3) the environment in which the machine and/or operator operate. The interactions between the machine and the environment have benefited from technological improvements including the use of CAD/MBSE, but despite the emphasis on human factors and the design of human-centric user-interfaces, the same level of CAD/MBSE rigor does not exist for the specification, design and analysis of the interaction between the operator and the machine (Fig. 1).

The root of the problem is that the human-machine interaction is not explicitly specified in the system requirements, and that development of procedures and training material, and human factors task analyses are conducted after the design process is completed. Existing task analyses and cognitive engineering methods [9] may also not be compatible with the hardware/software engineering process [3], do not account for the operational factors such as the operational time window to complete a task, stochastic machine performance, multiple operators, operational disruptions or a range of user performance (e.g. fatigue, experience).

This paper describes a method for capturing the HMI using a modification of a traditional system engineering sequence diagram. A sequence diagram (SD) is a two dimensional diagram where the horizontal axis represents the components of the system studied (including the computer part of the machine and the multiple crew), and the vertical axis represents time. This diagram is found in most MBSE CASE tools and is compatible with systems engineering process.

This HMI-SD can be used to identify the weaknesses in the procedure using measurable metrics that include performance measures such as time-on-task and probability of failure to complete the task in the operational time window. The HMI-SD can also be executed in a Monte-Carlo Simulation to analyze the performance of the procedure across a population of operators, across range of operational circumstances, and in the presence of disruptions.

This paper is organized as follows. The next section provides an overview of operational procedures and the HMI process. The following sections describe the HMI-SD, analysis of the HMI-SD and a case study. The paper concludes with a discussion of the implications of this method, limitations and future work.

STANDARD OPERATING PROCEDURES (SOPs) AND HUMAN-MACHINE INTERACTION (HMI)

A good definition for the word "procedure" given by Degani and Wiener is that in general, procedures exist in order to specify, unambiguously, six things [2]. Those things are (1) What the task is, (2) when the task is conducted (time and sequence), (3) by whom it is conducted, (4) how the task is done, (5) what the sequence of actions consists of, and (6) what type of feedback is provided (callout, indicator) [2]. Flight management that takes place in the flightdeck, the command and control center of the aircraft, is an example of dynamic environment management [8]. It is an environment with a very fast tempo, a high level of "proceduralization" where information is gathered through systems, and commands are executed either directly (manual control) or indirectly through automates [8]. To ensure safe and predictable operations, support to the pilot often comes in the form of SOPs. These provide the crew with step-by-step guidance for carrying out their operations [2]. They indicate to the pilots the manner in which operational management intends to have various tasks performed [2]. They are specific and elaborate, and operations, training, and standardization depend on them [2].

SOPs are designed for complex human-machine systems, and are mandated by the operational management of the organization [2]. Well-designed procedures ensure that all the information is available to complete the procedure and that the procedures can be completed in a logical sequence to avoid overlaps and disruptions. SOPs are categorized depending on the type of operations. They can be for normal operations (routine), abnormal operations (less frequent), or emergency operations (rare and hazardous).

Because of their complexity and the associated safety consequences linked to their application, SOPs are subject to approval by the operator. This approval is currently performed on an ad-hoc basis based on subject matter experts (SME)/senior level pilots' recommendations. Generally, the SMEs perform the evaluation of the procedure in an aircraft simulator and provide their recommendations. In aviation, the regulator defines the likelihood of occurrence of a safety hazard per operational hour to be as small as 10^{-5} (Probable) to less than 10^{-9} (Extremely Improbable) [4] making it almost impossible to cover all the safety risks due to the potential time and cost constraints.

Further, procedures in a flight deck are dynamic meaning that to safely complete their mission, it is important for the crew to perform their duties in a timely manner. This paper describes the concepts of Time-on-Procedure (ToP) and the Allowable Time Window (AOTW). Both of these measures are variable because they depend on context and/or human performance variability. They are therefore expressed in a time distribution as opposed to discrete values (fig 2). When they overlap, the procedure was not completed in time and the overlap can be translated into a Probability of Failure to Complete the Procedure (PFtoC). This result is a key metric that is proposed for use by regulators and designers to assess the performance of the procedure in a way that acknowledges the stochastic nature of the process.

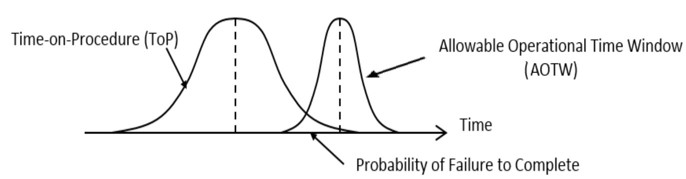


Figure. 2. Time-on-Procedure (ToP) relative to the Allowable Operational Time Window (AOTW). When the ToP is longer than the AOTW (i.e. overlapping region), the procedure cannot be completed in the required time frame and the procedure is considered to be incomplete. The probability of occurrence is key performance metric

Human-Machine Interaction

In executing a procedure pilots perform a series of "OODA loops". An OODA loop is a loop of Observe, Orient, Decide, and Act in commanding and controlling a force [7].

The Human Machine Interactions loops (HMI-Loops) fall under this same framework.

The first and second step is the pilot Observes and Orients the state of the environment and its uncertainty [6] through sensory cues (i.e. visual, aural, tactile, or smell) or a memory cue (i.e. portion of a procedure trained and stored in Long-Term Memory (LTM)). Cues come from the environment, or from the machine including the automation. In modern “hermetically sealed” command and control centers, the cues are displays on the automation derived from environmental or machine sensors.

The third step is the Decide step. The pilot makes the selection of the appropriate action(s). It is possible that the action is performed as an automatism without a conscious thought or intention. This type of decision making is referred to as automaticity. The decisions are part of well defined, detailed procedures, and are fast and reliable.

The other type of decision is the rule based. This type of decision making uses IF-THEN rules to decide the input to the computer/machine that matches a target output. A feedback loop checks the correct output is reached via a hit or miss probing and backtracking for a new trial in case of a miss. These decisions are slower than automaticity and exhibit lower reliability.

In the absence of rules, the pilots rely on their knowledge to take decisions. They rely on heuristics, common-sense, and mental model building using trial-and-error to logically create the rules for the decision. These decisions are very slow and exhibit the lowest reliability.

Decisions can also be affected by information provided by the triggering event of the HMI-loop. This information is stored in Short-Term Memory (e.g. instruction for crew member) and subject to natural decay over a period of time and limits in capacity (i.e. 4+/-3).

The fourth step is the Act step of the OODA loop. It is the execution of the decision in a form of an input to the automation/machine or a communication item.

Generally procedures include between 7 and 100 HMI-Loops that must be completed in a specific sequence (e.g. a display page must be accessed before an entry can be made). When the completion of an HMI-Loop is delayed, subsequent HMI-Loops in the procedure are also delayed resulting in longer times to complete the procedure i.e. longer time-on-procedure (ToP).

Time Distributions in the HMI-loop

The cumulative HMI-Loops timings make up the ToP mentioned above. Any delays in the HMI-Loop can be traced back to the characteristics of the OODA loop steps.

The time distributions for receiving and responding to visual cues triggering the HMI-loops are in Table 1. When there are no visual cues, triggering the HMI-loop relies on long term memory (LTM). The presence of visual cues does not guarantee accurate perception of their meaning. A study of the cueing resulted in the following cases:

1. Visual cue absent and decision relies on long-term memory
2. Visual cue present but not in field of view (FOV)
3. Visual cue present and in FOV, but in the presence of competing cues (i.e. lost in the clutter)
4. Visual cue present, in field of view, no competing cues, but label has erroneous semantic match with the procedure
5. Visual cue present, in field of view, no competing cues, and label does match the semantics of the procedure

Table 1. Categories for Visual Cues and their Associated Time Distributions

Visual Cue	***Time Distribution N(μ, σ) [sec]***
Not present, rely on LTM	TBD[1]
Visual cue present, but not in FOV	Multimodal mixture of two normal distributions: N~(6.46, 5.92), and N~(50.95,0.23)
Visual cue present, in FOV, but competing cues	Multimodal mixture of three normal distributions: N~(3.40,1.37), N~(13.51,3.87), and N~(44.28,5.64)
Visual cue present, in FOV, no competing cues, but erroneous semantic match with task	Multimodal mixture of three normal distributions: N~(6.04,3.84), N~(35.18, 10.10), and N~(121.98, 41.04)
Visual cue present, in FOV, no competing cues, and proper semantic match with task	N~(5.49, 4.72)

A similar model exists for aural and tactile cues.

Time distributions for decision-making depend on two parameters: (1) type of decision, and (2) use of working-memory (WM). Decisions made by habit are known as Automaticity. The decisions are part of well defined, detailed procedures, and are fast and reliable. The time distribution for these decisions has one mode.

Rule-based decisions require the operator to use memorized IF-THEN rules to fill-in the gaps in the procedure. In many cases, the operator will make the decision by trial-and-error (i.e. make a selection, realize it is the wrong selection and have to back-track. The time distribution for these decisions is bi-modal. One portion of the population will make the decision rapidly as in the automaticity. The other portion will have a longer distribution.

Reasoning decisions are performed in the absence of instructions in the procedure. They rely on using first-

[1] Experiments in progress

principles, common-sense, and mental model building using trial-and-error to logically create the rules for the decision. The time distribution for reasoning has three modes.

Decisions are also subject to a time penalty when they require use of working memory (WM). When the HMI-loop is triggered by information that has to be stored in WM for longer than 7 seconds, it is subject to a memory decay penalty of 3 seconds. Further, if more than 3 items are required to be held in WM, the time distribution is subject to a 3 second penalty.

Actions make a small contribution to the time distributions in the HMI-loop [5] and are summarized in Table 2. Small additional time penalties are incurred when the device is not in range for a normal reach, the operation of the input device is confusing (e.g. unlabeled pull or push of knob), the input device is moded (i.e. works differently in different situations), and/or the input device does not acknowledge an input.

Table 2. Categories and Time distributions for Actions

Act	***Time Distribution N(μ, σ)[sec]***
Basic	N(0.3, 0.01)
+ Not normal reach	N(0.5, 0.01)
+ Input device manipulation confusing (e.g. pull of push knob)	N(0.75, 0.01)
+ Input device is moded (i.e. works differently in different situations)	N(1, 0.01)

The time distribution for an HMI-loop is the sum of the steps defined as follows:

$$\mu_{HMI-Loop} = \sum \mu_i \tag{1}$$

$$\sigma_{HMI-Loop} = \sqrt{\sum \sigma_i^2} \tag{2}$$

For the bi-modal distribution, the mean μ is weighted by *p*, and *p-1*, the density of the two modes. For the tri-modal distribution, the mean μ is weighted by *p1*, *p2*, and *p1+p2-1*, the density of the three modes.

The time distribution for the procedure is the sum of the steps defined as follows:

$$\mu_{Procedure} = \sum \mu_i \tag{3}$$

$$\sigma_{Procedure} = \sqrt{\sum \sigma_i^2} \tag{4}$$

As above, multi-model distributions are weighted by the density of the modes.

The probability of ToP exceeding the AOTW is calculated as the P{ToP > AOTW} which is equivalent to P{ToP – AOTW}. For arbitrary distributions, this would be calculated as a convolution integral. For the special case that ToP and AOTW are normally distributed and independent, then ToP – AOTW is a normal distribution with $\mu = (\mu_{ToP} - \mu_{MAOTW})$, $\sigma^2 = (\sigma_{ToP}^2 - \sigma_{MAOTW}^2)$. This reduces to find the probability that such a normal distribution > 0.

HUMAN-MACHINE INTERACTIONS SEQUENCE DIAGRAM (HMI-SD)

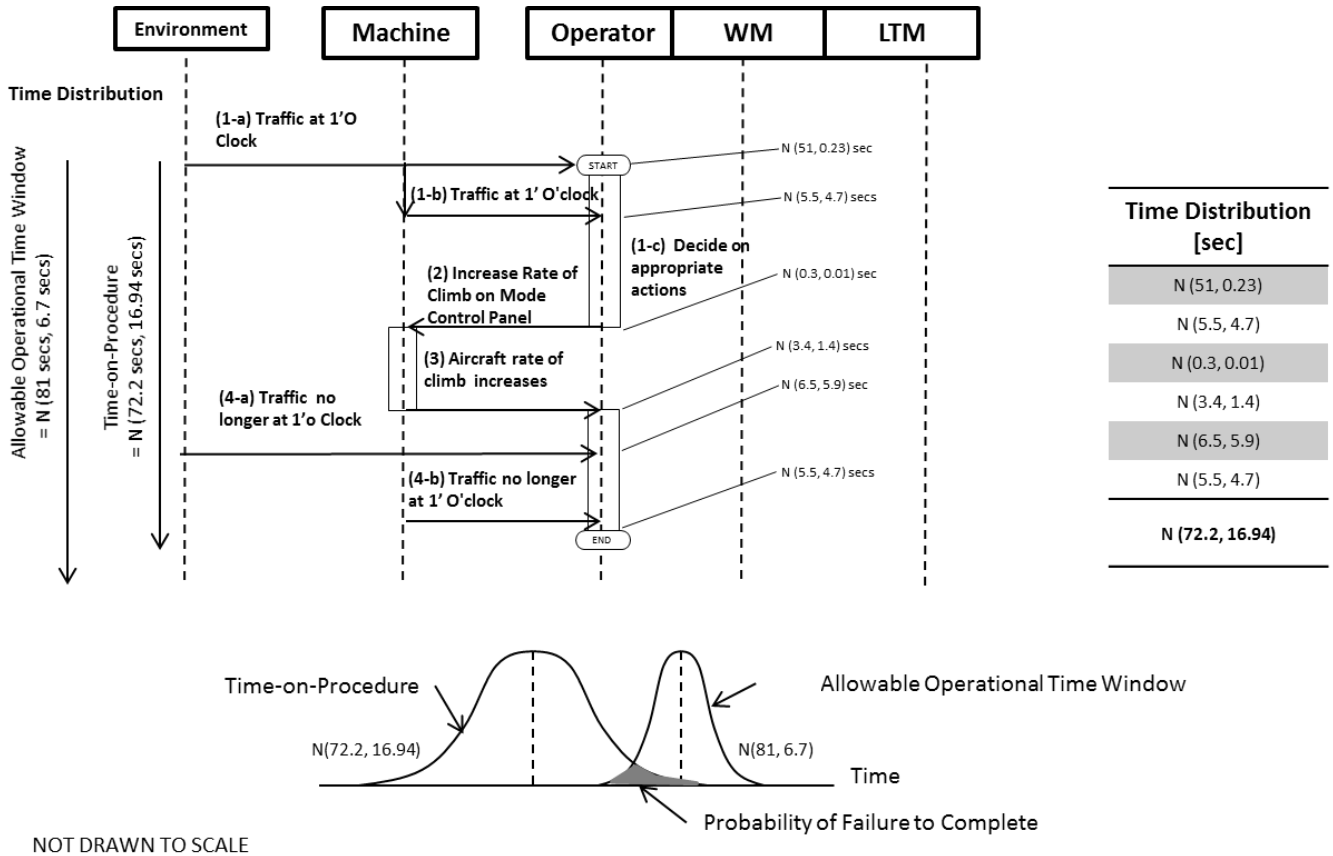
The HMI-SD is a model-based approach to the specification and analysis of the human-machine interaction.

The HMI Sequence Diagram for a single operator is shown in Fig. 3. The agents, shown in boxes across the top, represent the environment, the vehicle/computer, the operator and the operator's working memory (WM) and long-term memory (LTM). Time flows in a top down fashion. Events that occur are shown by labeled horizontal arrows (or messages) flowing between agents.

Fig. 3 shows the HMI-SD for a simple event requiring the intervention of the pilot after seeing traffic at 1 o'clock position. The resulting diagram includes one complete HMI-loop. A single pilot, sees traffic Out-the-Window (OTW). The location of the traffic is confirmed on the automation display. The decision is well rehearsed and made automatically to increase the rate of climb. The command to increase the aircraft rate of climb is made. The aircraft rate of climb increases and subsequently the traffic is no longer a threat.

The Allowable Operational Time Window (AOTW) is defined by the time distribution for the Near Mid-Air Collision (NMAC) with an aircraft at 1 o'clock with the specific relative velocities.

The time distribution for the procedure is shown on the right in the table. These individual distributions are drawn from Table 1 in Section 3 above. The Time-on-Procedure (ToP) is a Normal Distribution with mean of 72.2 secs and standard deviation of 16.94 secs. Due to the tails of the AOTW and ToP distribution overlapping, the probability of failure to complete the task (PFtoC) is calculated from this area. It is shown shaded on the bottom of Fig 3.



Time Distribution [sec]
N (51, 0.23)
N (5.5, 4.7)
N (0.3, 0.01)
N (3.4, 1.4)
N (6.5, 5.9)
N (5.5, 4.7)
N (72.2, 16.94)

Figure 3 HMI-SD with HMI-loops. Allowable Operational Time Window (AOTW) on left, and time distributions for each event in the sequence diagram on right. The Time-on-Procedure (ToP) is shown in the bottom of the table on the right. The overlap between the AOTW and ToP is shown in the shaded area between the AOTW and the ToP distributions.

Fig. 4 illustrates an HMI-SD that includes crew interaction between the Pilot Flying (PF) and the Pilot Monitoring (PM). The procedure is a portion of the "Initial Climb after Takeoff" procedure for a commercial airliner. An early stage of this procedure is completed to initiate acceleration down the runway. Once the aircraft achieves 80 knots (1) and a thrust setting (N1) greater than a specified threshold (2), the PM calls out "80 KNOTS, THRUST SET" (5) to alert the PF, who has his or her eyes focused out the window (not on the automation) that a key condition for takeoff has been met. The PF glances down at the automation (6, 7) and confirms the conditions from the indicators on that side of the flight deck with a call-out "CHECK". Failure to achieve this condition or a discrepancy between information on the PF and PM instruments would cause to abort the procedure. This pattern, cues and call-outs, is used to double check critical conditions on the flight deck have been met.

The aircraft continues accelerating down the runway. When the aircraft reaches 126 knots (9), the PM makes this observation (10) and alerts the PF with a call-out "V – ONE" (11). The PF confirms this condition (12) and calls out the intention to perform the next critical maneuver with the call-out "ROTATE" (13). The PF pulls back on the yoke (14) initiating a command from the automation to the aircraft (15) which responds by pitching up (16). This condition is reflected on the Horizontal Situation Indicator (HSI) and Vertical Speed Indicator (VSI) on the flightdeck. In this sequence the call-out "ROTATE" does double duty by serving as a confirmation (i.e. "CHECK") and an indication of a next action. The call-out for confirming the pitch-up was deemed unnecessary as both crew members will feel the pitching sensation, see it out the windows and on the automation instruments.

In the next sequence, the PM observes a positive rate of climb (18) and calls out "POSITIVE RATE" (19). This is confirmed by the PF (20), who requests the next action from the PM with a "GEAR UP" command (21). The PM raises the Landing Gear Lever (22) and the distinctive sound of the landing gear being retracted is heard by both crew members (23). Gear sensors indicate that the gear has been fully retracted (24) and the PM and PF observe three green lights above the Landing Gear Lever (25) indicating the completion of that task.

SOP Performance Metrics

A number of attributes can be collected from this diagram:

1. The number of interactions: is a tally of all interactions involved in the procedure

2. The number of HMI-Loops: each MHI-Loop is recorded as defined by the OODA loop. For readability purposes only the first two HMI-Loops were displayed on Fig.4.
3. The number of Shared Mental Model (SMM) Loops: when the pilots communicate to confirm they are seeing the same thing, this communication pattern is delimited by the SMM-Loop. Also for the purpose of clarity, only the first SMM-Loop is marked in Fig. 4. Note that out of this value, the Communication ratio of [(# Interactions)/(S M M-L)] is calculated for a meaningful interpretation of the result.
4. The cumulative Buffer Time: using the time distributions mentioned above to generate random numbers and perform a Monte Carlo Simulation, followed by comparing results against the AOTW gives buffer time that is cumulated within each procedure. The cumulative buffer time is the "idle" time the crew have between finishing off a portion of a procedure and the next one.
5. The ToP and PFtoC: also resulting from the random number generation relating to the time distributions and the Monte Carlo Simulation, the ToP and the PFtoC give a sense of how long and how successful the procedure is given the time constraints.
6. Other: the HMI-SD enables the visualization of certain traits of the procedure to assess its quality (or as a convenient support for communication with decision makers) such as the missing items in the loops. It can also be used to assess the presence of visual/tactile/aural cues used to initiate an HMI-Loop. In particular HMI-

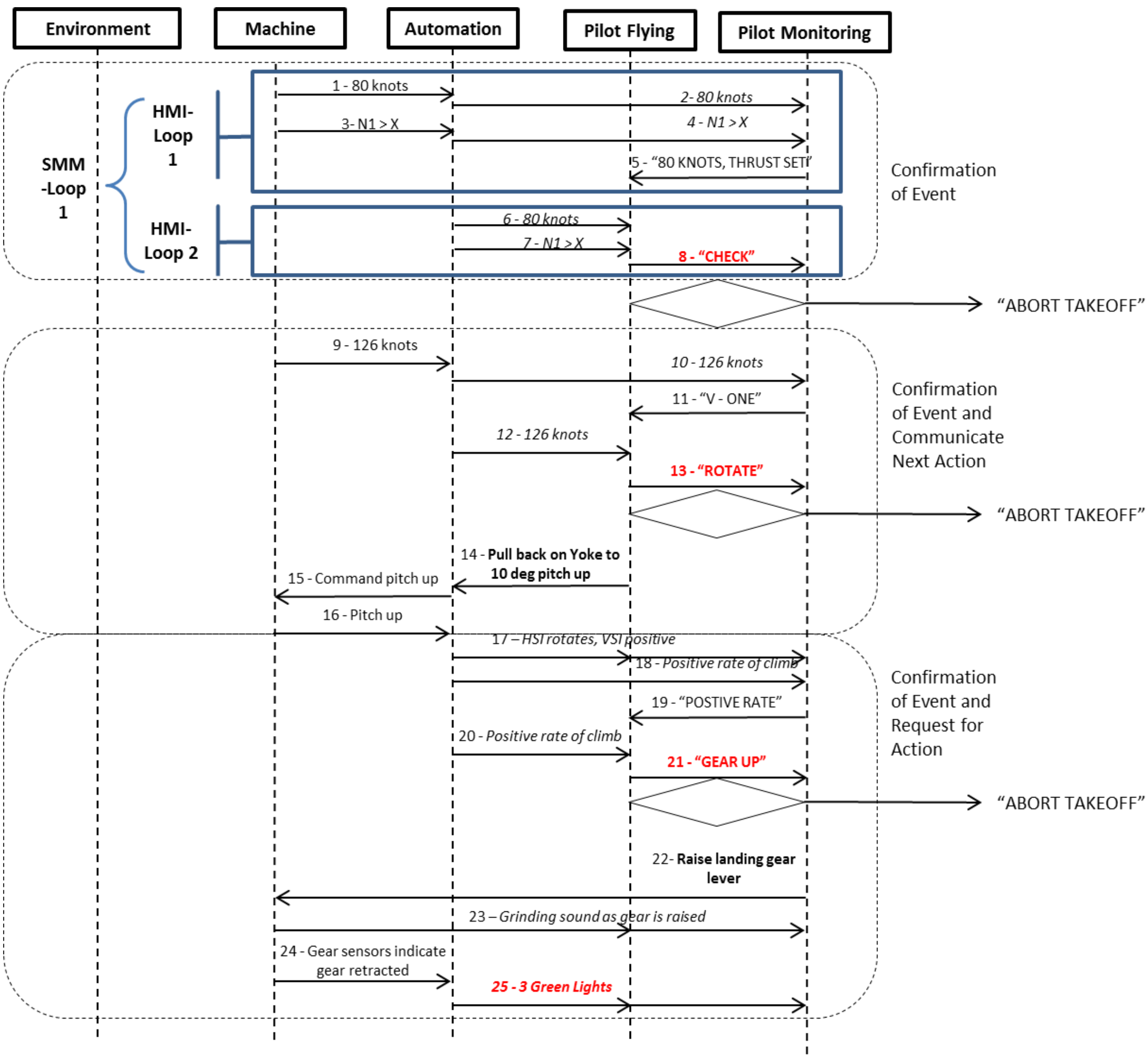


Figure 4 HMI-SD for a portion of the takeoff roll procedure

loops that rely on memorized cues either by recalling procedure steps from long-term memory or from prospective (short-term) memory can be identified. Also HMI-loops in which the stimulus is provided in the presence of competing cues or exhibits a poor semantic match with the decision and action are identified. Procedures that include HMI-Loops with no cues, competing cues, and ambiguous semantics are known to exhibit poor reliability for infrequently performed procedures and are identified by a "grammar checker" associated with the model.

When performing a comparative analysis, these attributes are further used to calculate for preferred procedure using utility theory.

It is also worth noting that there are at least three different types of communication between the crew. The first one is exemplified by interaction 1 through 8 where the communication is simply intended for confirmation of current aircraft state. The second type adds to the first type the communication of the next item (interactions 9 through 17), and the third one slightly differs in the request for the next action instead of solely communicating it.

CASE STUDY OF ALTERNATE PROCEDURES FOR THE BAE-146 AIRCRAFT

The methodology detailed above was used for the analysis of two procedures with the same objective i.e.: flap retraction during the initial climb out (flaps are high lift devices that are used during take-off but that need to be retracted after a certain altitude is reached) [6].The main difference between the procedures lies in the way tasks are shared among flight crew. The first procedure is proposed to be performed through the close coordination of the flight crew at each step of the flap retraction via callouts while the second alternative is proposed to be accomplished by the delegation of the flap retraction to the pilot monitoring (PM) who then lets the pilot flying (PF) know that the flaps are fully up at the end of the retraction operation. The results are shown on the Table 3 below.

Table 3. Summary of case study results for the comparison of two procedures

Attribute	*Callout Procedure*	*Delegate Procedure*	*Notes*
Number of Interactions	44	38	
Number of HMI-Loops	18	15	
Number of HMI-Loops not supported by salient/ unambiguous visual cues	0	0	
AOTW [sec]	27.95	27.95	
Probability of Failure to Complete (PFtoC) in Time	0	0	Both procedures can be completed within the AOTW
Shared Mental Models Loops	7	5	
Communication Ratio $\left[\frac{\#\ \text{Interactions}}{\text{SMM}-\text{L}}\right]$	6.3	7.6	
Cumulative Buffer Time [secs]	3.6	7.9	
Missing Communication Items	1	1	The callout to confirm landing gear retraction is missing from both procedures

The Callout Procedure exhibited a higher number of Interactions, HMI-Loops and SMM-Loops (44, 18, and 7 respectively as opposed to 38, 15, and 5 for the Delegate procedure). Consequently, the Communication Ratio is higher for the Delegate procedure (7.6) than that for the Callout procedure (6.3). The AOTW is the same for both procedures μ=27.95 as they are operated within the same conditions. The number of missing communication items is also equal for both procedures and that is the purposefully omitted callout for the gear retraction after operation.

Running a utility analysis with weighted attributes trades off the benefits of a faster procedure against a more robust procedure and yields a slight preference for the Callout procedure [6].

CONCLUSIONS

This paper demonstrates a methodology for the analysis of human machine interaction for assessing the performance of airline SOPs using a formal structure provided by the sequence diagram. The model complements the work of domain experts by providing quantitative measures of performance and by providing an executable simulation to experiment with alternative procedure designs.

The model captures the procedure in the formal language of a "sequence diagram" that includes the interactions between agents counting multiple operators, the machine interface, the automation interface, and other external sources of information/changes to the environment.

In addition to "grammar checking" of the HMI-SD, each action of the underlying model can be associated with time distributions (i.e. time to move flap lever, time to recognize a visual cue…) By running the model in a Monte Carlo simulation, a distribution for the time-to-complete the procedure can be generated. This distribution can be compared with the time distribution in which the procedure must be completed (i.e. the Allowable Operational Time Window). Procedures for which a tail of the ToP time distributions exceed the AOTW can be identified.

Future work includes using the simulation to investigate the robustness of the procedure to external interruptions (e.g. air traffic control radio call in the case of aviation, automation alert). These interruptions are modeled by time distributions that extend the time-to-complete the procedure. Procedures for which a tail of the time-to-complete time distributions exceeds the allowable time window can be identified. In addition, Human in the Loop (HitL) experiments could be used to create an accurate database of time distributions for the cueing. Also, machine timings can be inserted, removed, or modified as required.

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