A MODEL-BASED APPROACH FOR THE QUALIFICATION OF STANDARD OPERATING PROCEDURES

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Abstract

Standard Operating Procedures (SOPs) define the sequential actions performed by operators to complete a mission. The SOPS are designed to ensure safety and operational efficiency and are especially important for complex, non-normal, and emergency operations. In the aviation industry, airlines derive their SOPs from manufacturer's SOPs to match their company policies and operational constraints. SOPs are designed and revised by Subject Matter Experts (SMEs) and depending on available resources may be tested with a small sample of pilots. Due to the small sample size of subjects and the complexity of the environment and operations, the modified SOPs cannot be exhaustively tested. This is especially true for procedures that must be completed within an Allowable Operational Time Window (AOTW) that varies based on vehicle performance and environmental conditions. In these cases, the Time on Procedure (ToP), also variable due to variance in human performance, must be completed within the AOTW. Verifying the SOP for all the possible combinations of AOTW and ToP is critical to safe operations.

This paper describes a formal method to quantify the performance of SOPs while taking into account variability in AOTW and ToP. The SOPs can be modeled and simulated in a Model-based System Engineering (MBSE) tool using standard modeling languages such as SysML and LML. A case study of the method is presented, and the results and limitations are discussed.

Introduction

Standard Operating Procedures (SOPs) define the sequential actions performed by crew members to interact with the aircraft. These steps, when performed correctly, aid in the safe operations of the aircraft [1][2].

In the aviation industry, airlines derive their SOPs from the manufacturer's SOPs. The SOPs are modified to match their company policies and operational constraints. SOPs are designed and revised by Subject Matter Experts (SMEs) and depending on available resources may be tested with a small sample of pilots. Due to the small sample size of subjects and the complexity of the environment and operations, the modified SOPs cannot be exhaustively tested. This is especially true for procedures that must be completed within an Allowable Operational Time Window (AOTW) that varies based on vehicle performance and environmental conditions. In these cases, the Time on Procedure (ToP), also variable due to variance in human performance, must be completed within the AOTW. Verifying the SOP for all the possible combinations of AOTW and ToP is critical to safe operations. Qualifying the procedures early in the development life-cycle as part of the standard engineering development process has significant quality, time, and cost benefits.

Kourdali and Sherry [3] defined a procedure for SOP evaluation using LML/SYSML Sequence Diagrams and SOP Performance metrics: Allowable Operational Time Window (AOTW), Time-on-Procedure (ToP), and Procedure Buffer Time (PBT). An SOP must be performed within the AOTW. Both the AOTW and ToP, being distributions and not a fixed number, exhibit variance. To evaluate an SOP, the designer must evaluate the Procedure Buffer Time (PBT), which is defined as the difference between the AOTW and the PBT [3]

To assess the AOTW, ToP, and PBT metrics associated with SOPs, the designer must first model the SOP, then run the model using Monte Carlo techniques.

This paper presents a method to model SOPs using LML/SysML Action Diagrams (Figure 1). The resulting SOP Action Diagram is then

simulated to obtain the aforementioned metrics. An overview of SOP modeling is discussed in the next section. The following section discusses a method to create an SOP Action Diagram from a text SOP. The results and implications are furthermore examined.
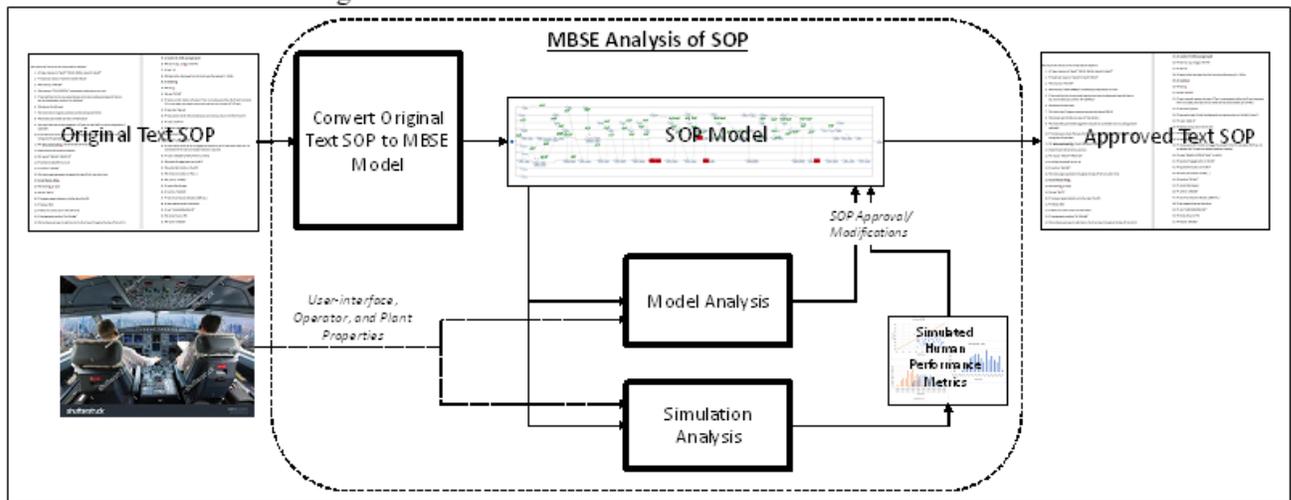

Figure 1. MBSE Analysis of Standard Operating Procedures

An Overview of Modelling the SOP

This section provides an overview of (i) the metrics used to evaluate an SOP and (ii) Action Diagrams in the context of SOP modeling.

SOP Evaluation Metrics

The performance of the SOP is measured by the Time on Procedure (ToP). The ToP differs each time the SOP is completed due to the varying level of expertise of the operators performing the SOP, attention, fatigue, and other human factors. The Allowable Operation Time Window (AOTW) is defined by the time in which the procedure must be completed [4]. The AOTW can also differ due to variability in aircraft performance and the operational environment, which explains why it is given as a distribution and not a fixed number. When the ToP exceeds the AOTW it indicates that the SOP failed to meet its goal. From the ToP and AOTW, the Procedure Buffer Time (PBT) can be derived by the following relation: PBT is the difference in AOTW and ToP for each time the SOP is performed. Because AOTW and ToP are governed by distributions, PBT is represented as a distribution, where the left tail below zero (i.e. ToP> AOTW) is defined as the Probability of Failure to Complete (PFtC). The longer the left tail is, the more unreliable the SOP is.

LML/SYSML Action Diagrams

An SOP Action Diagram consists of (i) actions, (ii) branches, and (iii) inputs/outputs (I/Os). Actions, depicted by squares, are performed by actors. Actors are depicted by the branches, and each actor performs the actions on its branch. An action can be triggered by a preceding action done by the same actor, or it may be triggered by an action from another actor, using I/Os to depict the information flow between the two actions. I/Os are depicted as parallelograms. An example Action Diagram for Engine-out Procedure is shown in Figure 2.
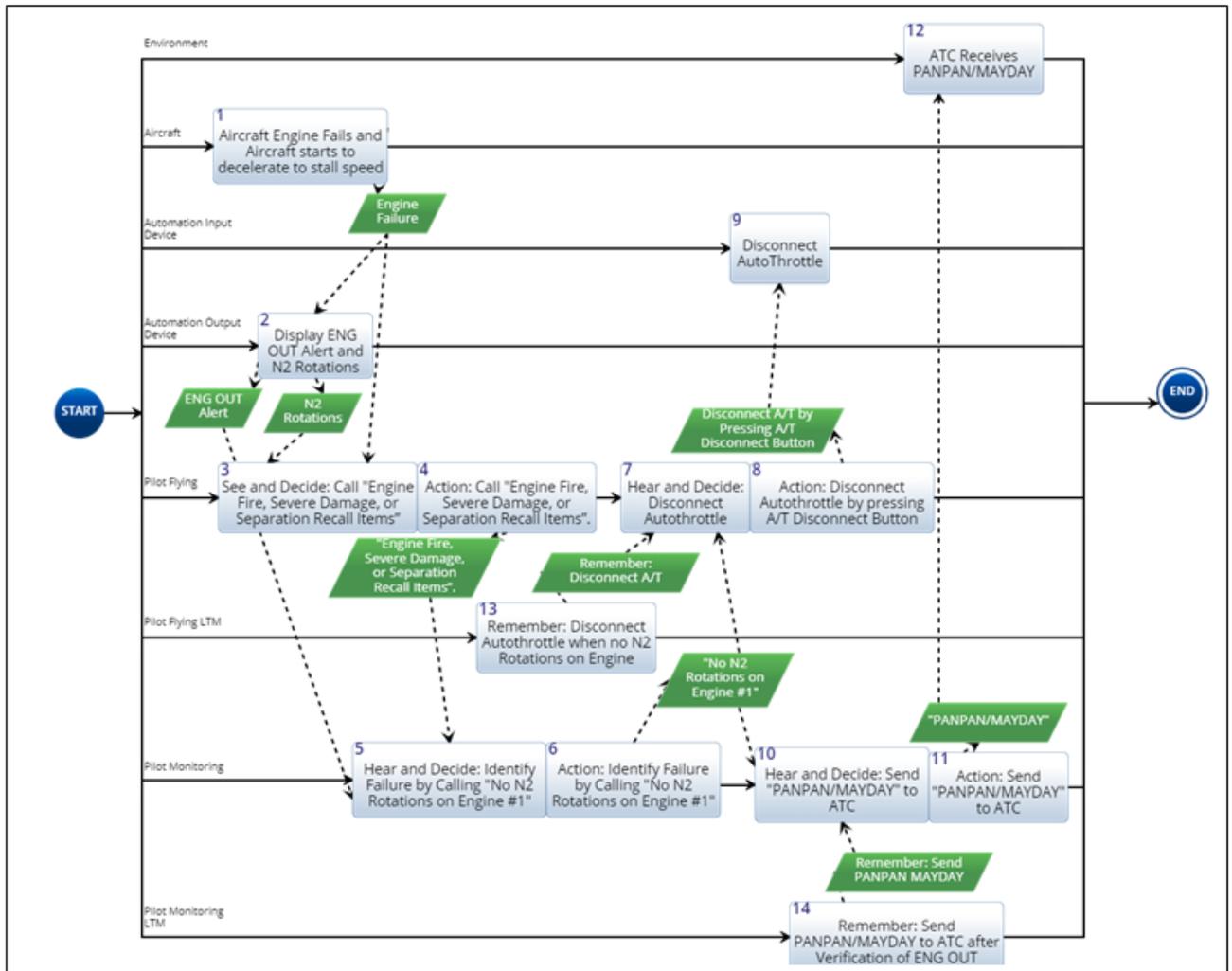
Figure 2. Example Action Diagram, with Actors, Branches, and I/Os, for an Engine-out Procedure

Method for Modelling SOPs using Action Diagrams

This section provides step-by-step instructions to create an SOP Action Diagram and how to analyze the design of the SOP.

Step-by-Step Method to Create an SOP Action Diagram from a Text SOP

Step 1: Identify and create branches for the Action Diagram (AD).

7 actors perform actions in an SOP Action Diagram (see Figure 2). The actors are:

- Environment
- Plant
- Automation Input Device
- Automation Output Display
- Operator(s)
- Operator(s) Long Term Memory (LTM)
- Operator(s) Working Memory (WM)

After identifying the actors, they are added to the diagram as branches.

There must be a branch for each actor and following the order above is preferred to minimize clutter in the action diagram produced.

Step 2: For each operator, insert operator actions.

Operator actions are next identified directly from the SOP. The actions are added to the diagram by adding a square on the appropriate branch. Each action in the action diagram should be preceded by the word "Action:", followed by the action from the SOP.

Step 3: For each operator action, add a "See and Decide" or "Hear and Decide" or "Remember and Decide" action to the action diagram.

Each action must be preceded by a "See and Decide", "Hear and Decide", or "Remember and Decide" action to act as the decision-making action. Decision-making actions are actions where the actor must act after observing a trigger to the action. These decision-making actions are added to aid in the process of assessing action performance discussed in step 15.

Step 4: Add the initiation action and cue of the SOP.

Each SOP is initiated by an I/O that triggers the first See/Hear/Remember and Decide action on the operator's branch. The trigger, also known as a cue, may come from (i) the Automation Output Display, (ii) the Environment, (iii) the operator's LTM, or (iv) the operator's WM. The initiating cue can be either visual, aural, or from memory.

Step 5: Insert Automation Output Display and Automation Input Device actions.

This step is initiated by extracting all non-operator actions and sorting them to Automation Output Device and Automation Input Display actions.

Automation input and output device actions could be extracted by analyzing operator actions. For example, if an operator's action was to raise the landing gear lever, then the modeler may expect to see an Automation Input Device action to do so. The same operator action can be used to find the Automation Output Display action, as an action to display landing gear raised confirmation is expected.

The identified actions are then added to the diagram.

Step 6: Identify the cues of the SOP, and identify the type of each cue; visual, aural, memory.

First, identify the cues present in the SOP. Cues may be easily extracted from the SOP, or they may be implied by looking at operator actions. For example, if an operator's action was to call out V-One speed, then there should be an aural cue as a result.

After identifying as many cues as possible, the next step is sorting each cue according to the type, either visual, aural, or memory.

Visual cues are cues that can be seen, typically through the Automation Output Display or the Environment. Aural cues are those that can be heard, and they are typically produced through the operator or the Automation Output Display. Memory cues are those generated by the Operator's long-term memory or working memory.

Step 7: Identify the source action/actor of each cue identified in step 6.

For each cue identified in step 6, identify the source action that generates the cue. The originating actor is also identified in this step. The Environment and the Automation Output Display typically generate visual and aural cues. The WM or LTM generates memory cues.

Step 8: For each "See/Hear and Decide" or "Remember and Decide" action, add an appropriate cue as an input to the "See/Hear and Decide" action from the list identified in step 6.

Using the cues identified in step 6, add the cues to the diagram, connecting them to appropriate See/Hear/Remember and Decide actions. During the first iteration, not all cues may be connected to Operator actions, however, eventually, all See/Hear/Remember and Decide actions will be triggered by a cue.

Step 9: For the list of actions identified in step 7, add the actions to the diagram, connecting the actions to appropriate cues as identified in step 6.

Add each action identified in step 7 to the diagram, making sure to connect each action to the appropriate cue.

Step 10: Re-write the cues to follow the "Cue Wording Rules".

For all I/Os that are connected to an input and output, rewrite the I/Os based on what actor originated them and what actor they are going to.

- Outputs from the Plant to the Automation Output Display: nouns, e.g. climb rate, lights. Sound.

- Outputs from the Automation Output Display to the Operator(s): nouns, e.g. altitude, speed.

- Outputs from the Automation Input Device to the Plant: verb-noun, e.g. extend flaps, raise landing gear

- Outputs from the Operator(s) to the Automation Input Display: verb-noun, e.g. move flap handle, raise landing gear lever

- Outputs from an Operator to another Operator: A word or phrase coming from an operator. E.g. "V-One"

- Outputs from the LTM – WM to an Operator: Verb sentence E.g. Recall check for V-One speed.

Step 11: For each operator action, add an Automation Input Device action and I/O as appropriate.

Connect any Operator physical actions to the actions on the Automation Input Device branch on the diagram, making sure to add I/Os between connecting actions following the rules in step 10.

Step 12: For each Automation Input Device action, add an output to a Machine Action and add I/Os as appropriate.

For each Automation Input Device action, add a Plant action as a result, making sure to add I/Os following the rules in step 10.

Step 13: For each Machine Action, add an output to an Automation Output Display Action and I/O as appropriate.

Connect Plant actions to Automation Output Displays as appropriate, again making sure to add I/Os that follow the wording rules specified in step 10.

Step 14: Compare SOP to action diagram, go back to step 5 as appropriate.

This concludes the first iteration of creating an SOP Action Diagram. Look through the SOP and compare it to the generated Action Diagram. Go back and redo the steps as appropriate.

Step-by-Step Method to Analyze SOP Action Diagram

Once the SOP action diagram is complete, the next steps are to analyze the human performance and simulate the diagram.

Step 15: Assess Operator Actions Performance.

Assess each Operator See/Hear/Remember and Decide action pair by looking at the cues that trigger the See/Hear/Remember and Decide action, as well as the frequency of completing the physical action [3].

Cues are assessed by looking at (i) the presence of the cue, (ii) whether the cue is in the operator's field of view (FoV), (iii) whether the cue is lost in the clutter, and (iv) the ambiguity of the semantics.

When the cue is (i) not present, or (ii) present, but not within the FoV, or (iii) present, in the FoV, but lost in the clutter, or (iv) present, in FoV, not lost in the clutter, but the semantics do not match the semantics of the action, this leads to a longer time to complete the action. A good quality cue is defined as a cue that is present, in the FoV, not lost in the clutter, and the semantics match the semantics of the action.

The frequency of the action is assessed by assessing the action itself. The action may be frequent, in which the operator has no problem at completing, or it may be infrequent or rare which leads to a longer time to perform that action.

Step 16: Assign Time Distributions to all Actions (from Database) and adjust for performance assessment.

Depending on each cue that triggers a See/Hear/Remember and Decide action pair, the action is assigned a time distribution from the Human Performance Time Distribution (HPTD) Database. For example, the "x" in Figure 3 corresponds to a See and Decide action pair where the cue is not present to the operator, i.e. comes from the Operator's memory, but it is a frequent event. The time distribution associated with that type of cue is TRIANG(0.03, 0.05, 5). The "x" in Figure 4 is also not present to the Operator, however, it is a rare event, which means that the right tail of the distribution is higher, leading to a time distribution of TRIANG(0.03, 51.2, 120).

Distribution Type: Triang	Min	Mode	Max	No Cue (LTM)	Not in FOV	In FOV, Not Salient (i.e. Cluttered /Lost in Noise)	In FOV, Salient, Ambiguous Semantics	In FOV, Salient, Unambiguous Semantics	Frequency (Every Flight, Frequent, Infrequent, Rare)	Data Source	Notes
Triang	0.03	0.05	5	(x)					Every Flight, Freq	CATSR DB	
Triang	0.03	51.2	120	x					Infreq, Rare	CATSR DB	
Triang	0.03	6.4	21		x				Every Flight, Freq	CATSR DB	

Figure 3. Sample of HPTD Database with LTM Cue and Frequent Action

Distribution Type: Triang	Min	Mode	Max	No Cue (LTM)	Not in FOV	In FOV, Not Salient (i.e. Cluttered /Lost in Noise)	In FOV, Salient, Ambiguous Semantics	In FOV, Salient, Unambiguous Semantics	Frequency (Every Flight, Frequent, Infrequent, Rare)	Data Source	Notes
Triang	0.03	0.05	5	x					Every Flight, Freq	CATSR DB	
Triang	0.03	51.2	120	(x)					Infreq, Rare	CATSR DB	
Triang	0.03	6.4	21		x				Every Flight, Freq	CATSR DB	

Figure 4. Sample of HPTD Database with LTM Cue and Infrequent or Rare Action

Step 17: Assign the Probability of Failure to Complete (PFtC) threshold (5th percentile)

Step 18: Run Monte Carlo Simulation to generate distributions for AOTW, ToP, PBT, and to calculate PFtC.

AOTW is calculated by running all plant actions independently from all other actions. the time to complete each run is then fitted to a triangular distribution to get the parameters of the AOTW distribution.

ToP is calculated by running the SOP except for the plant actions. The resulting times are then fitted into another triangular distribution to get the ToP distribution.

PBT is calculated by the difference between the AOTW and PBT, and the result of the relation is fitted into a distribution.

Finally, the PFtC is calculated by the probability of the left tail of the PBT distribution being less than zero.

Step 19: Assess whether PFtC is less than the threshold.

If the PFtC is less than the threshold assigned in step 17, no action is needed.

If the PFtC is greater than the threshold, then the SOP must either be redesigned, or the user interface is redesigned.

Step 20: Redesign the SOP and the user-interface and run again until the SOP satisfies that PFtC criteria.

The method to analyze an SOP Action diagram is concluded by the above step. The next section describes a case study using the method.

Case Study: Engine Out SOP

The method described in the previous section was used to develop an action diagram for a section of an Engine Failure in Cruise SOP shown in Figure 5. The SOP consisted of 4 steps only and produced the complete action diagram in Figure 6.

Figure 5. SOP Followed when an Aircraft Engine Fails during Cruise

Creating the SOP Action Diagram

The steps to create an SOP Action Diagram (see Figure 2) from a text SOP (see Figure 5) were followed.

The actors identified for this SOP were (i) the Environment (ATC), (ii) the Aircraft, (iii) the Automation Input Device, (iv) the Automation Output Display, (v) the Pilot Flying, (vi) the Pilot Flying Long Term Memory, (vii) the Pilot Monitoring, and (viii) the Pilot Monitoring Long Term Memory.

The Pilot Flying and Pilot Monitoring's actions were extracted directly from the SOP in Figure 5. The actions were: (i) Call "Engine Fire, Severe Damage, or Separation Recall Items". (ii) Identify by Calling "No N2 Rotations on Engine #1". (iii) Disconnect Auto Throttle. (iv) Send "PANPAN/MAYDAY" message to ATC.

Cues identified from the SOP were (i) "Engine Fire, Severe Damage, or Separation Recall Items", (ii) "No N2 Rotations on Engine #1", (iii) "PANPAN/MAYDAY" and (iv) Disconnect Auto Throttle by Pressing A/T Disconnect Button".

The SOP does not identify when the SOP is initiated, but it was implied. Therefore, the Aircraft action "Aircraft Engine Fails and Aircraft Speed Starts to Decelerate to Stall Speed" and the Automation Output Display action "Display ENG OUT Alert and N2 Rotations" were added, along with cues following the rules mentioned in an earlier section of this paper. The complete SOP Action Diagram is shown in Figure 6.
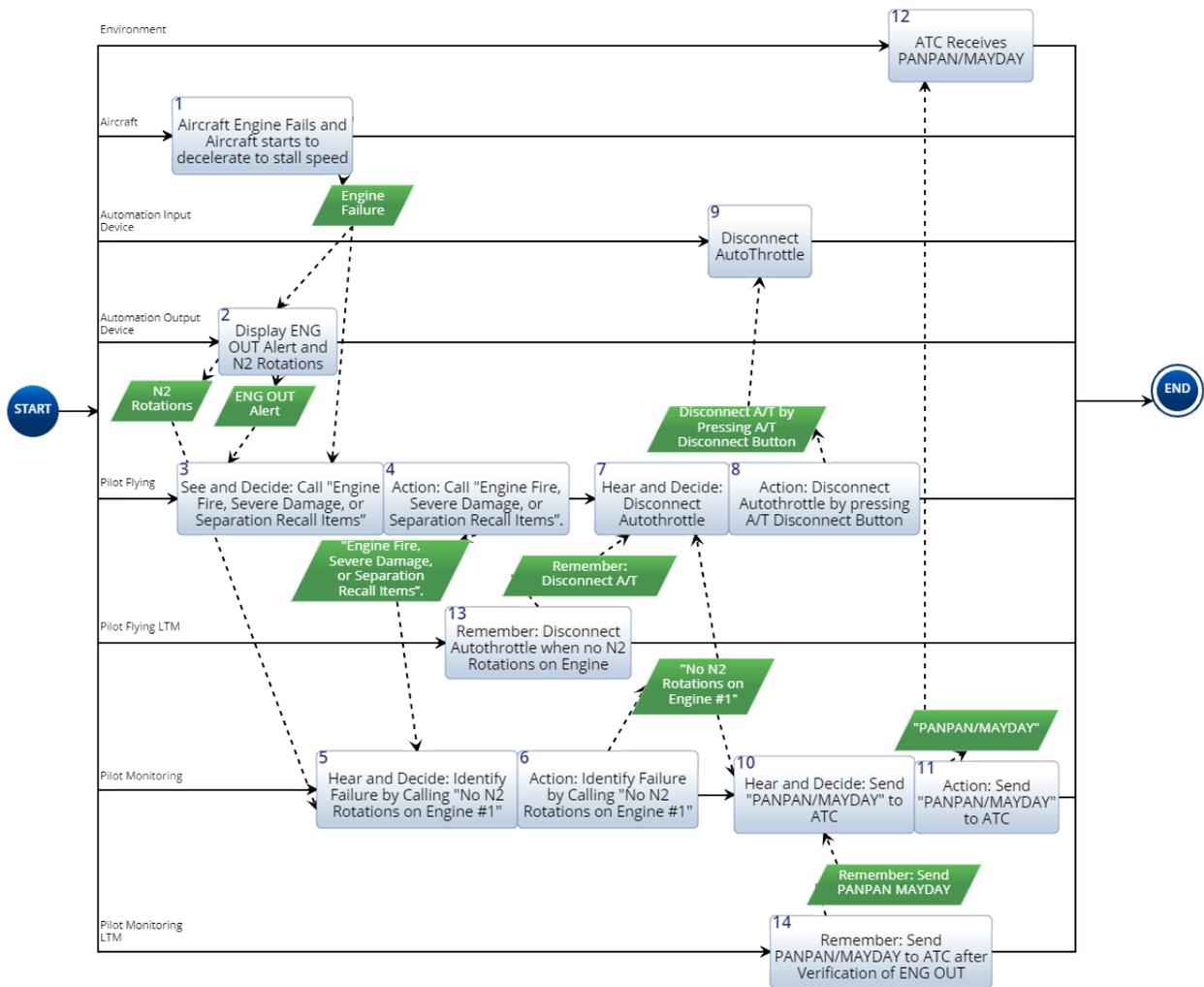

Figure 6. Complete SOP Action for Engine Failure in Cruise SOP

Analyzing the SOP Action Diagram

There were 4 See/Hear/Remember and Decide Action pairs in the complete SOP Action Diagram.

One See/Hear/Remember and Decide Action pair was cued by a visual cue only, two were cued by an aural and memory cue, and one was cued by an aural and visual cue.

All visual and aural cues were present, in the FoV, not lost in the clutter or noise. However, 2 cues had ambiguous semantics (See notes on Table

1) The frequency of the actions was rare, except for one action (Disconnect Auto Throttle) which was a frequent action.

Based on the previous assessment, the time distributions were added from the HPTD database. The distribution parameters used are given in Table 1. All Distributions are given in seconds. All other actions not listed in Table 1 that were present in Figure 6 had a time distribution of 0 seconds.

Table 1. Distributions Used for Monte Carlo Simulation

Action	Time Distribution Used	Notes
Aircraft Engine Fails and Aircraft starts to decelerate to stall speed	TRIANG(220, 300, 450)	Allowable Operational Time Window
See and Decide: Call "Engine Fire, Severe Damage, or Separation Recall Items"	TRIANG(0.03, 5.2, 24.3)	Generic: In FOV, Salient, Unambiguous Semantics
Action: Call "Engine Fire, Severe Damage, or Separation Recall Items".	TRIANG(0.068,0.07,0.073)	Generic: Typed Entry
Hear and Decide: Identify Failure by Calling "No N2 Rotations on Engine #1"	TRIANG(0.03, 5.2, 24.3)	Generic: In FOV, Salient, Unambiguous Semantics
Action: Identify Failure by Calling "No N2 Rotations on Engine #1"	TRIANG(0.068,0.07,0.073)	Generic: Typed Entry
Hear and Decide: Disconnect Autothrottle	TRIANG(0.06, 121, 250)	Generic: In FoV, Salient, Ambiguous Semantics
Action: Disconnect Autothrottle by pressing A/T Disconnect Button	TRIANG(0.67,0.75, 0.83)	Generic: Input Device Manipulation Required
Hear and Decide: Send "PANPAN/MAYDAY" to ATC	TRIANG(0.06, 121, 250)	Generic: In FoV, Salient, Ambiguous Semantics
Action: Send "PANPAN/MAYDAY" to ATC	TRIANG(0.068,0.07,0.073)	Generic: Typed Entry

The Monte Carlo simulation was executed in Innoslate, a Model-Based Systems Engineering cloud framework, and the results were analyzed in excel to obtain the distributions of the AOTW and the ToP, along with the PFtC.

Results

The result of running the Monte Carlo simulation 1000 times is shown in Figure 7. The intersection between the AOTW and ToP Distributions (upper left) is undesired. This overlap results in the distribution of PBT (shown in the upper right) exhibiting a negative left tail below
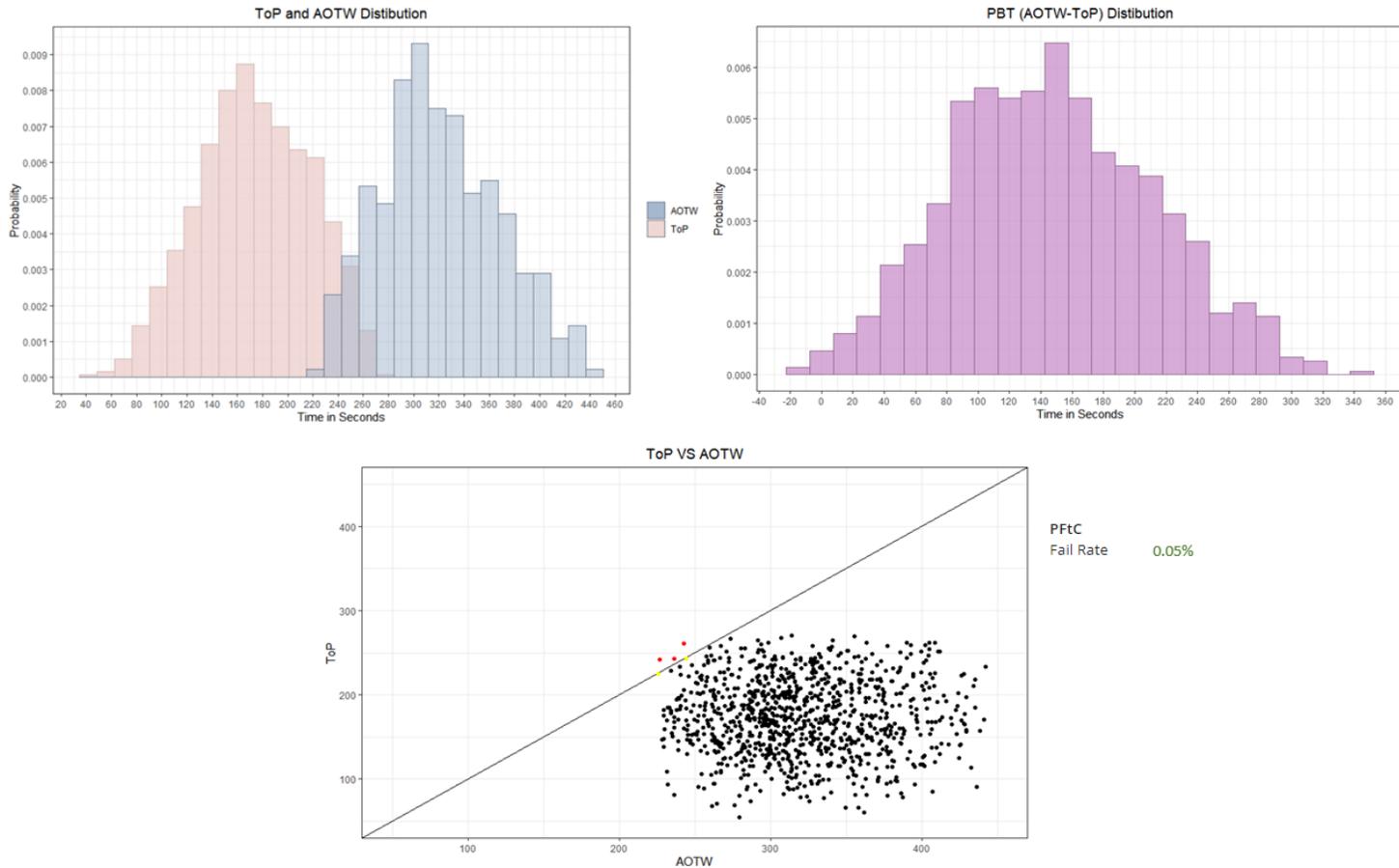
zero. The scatterplot of runs (bottom middle) also confirms that there were runs where ToP exceeded AOTW. The calculated PFtC was 0.05%, which is less than the 5th percentile threshold that was assigned.

Figure 7 Results of Monte Carlo Simulation

Conclusions

When designing SOPs, the designers must keep in mind the varying factors that may affect the completion of the SOP within the AOTW. This can be done quantitatively by modeling SOPs using Action Diagrams and simulating these diagrams in a Model-Based Systems Engineering (MBSE) software (E.g. CORE, Innoslate, Magic Draw/Cameo).

This paper presented a method to develop SOP Action Diagrams and a means for the evaluation of the SOP by calculating the PFtC metric. This enables designers to improve the SOP design early in the development life-cycle which aids in the safe operations of the plant.

A case study was presented where an Engine Failure in Cruise Standard Operating Procedure was created, analyzed, and simulated. The results of the simulation confirmed that the SOP was well designed, and no future redesigning was needed since the probability of failure to complete (PFtC) was less than the specified threshold at 5%.

Future work includes tailoring the Action Diagram to include monitoring tasks, modeling the execution of simultaneous SOPs, as well as modeling the effect of disruptions.

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Acknowledgments

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