A Comparison of Two Takeoff Flap Retraction Standard Operating Procedures

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Abstract— Takeoff Flap Retraction is a procedure that is conducted following takeoff to retract the flaps and slats from a takeoff configuration to a clean-up-and-away configuration. During this period the aircraft accelerates from the takeoff V2 speed to 250 knots and generally includes a maximum thrust reduction from the takeoff thrust setting to the climb thrust setting. Timing of the flap retraction is critical to avoid over speed or under speed. Also, due to the vicinity of terrain and traffic, the vehicle performance and airspace must be carefully monitored all the while staying responsive to Air Traffic Control voice communication. As a result the design and certification of these procedures must resolve multiple conflicting objectives.

This paper describes a formal analysis of alternate takeoff flap retraction procedures for the BAE 146 (Avro) aircraft. One procedure requires the “call out” by the Pilot Flying (PF) for each flap retraction. The other procedure delegates flap retraction to the Pilot Monitoring (PM). A formal analysis of the procedures using the HMI-Sequence Diagram method yielded equal utility. Overall, the Callout procedure is more robust to interruption and provides a better shared mental model between the crew members. However, the Delegate procedure can be completed on average 4.5 seconds faster providing more time for monitoring and dealing with interruptions. The implications and limitations of the formal analysis of procedures is discussed.

Keywords—Human-Machine Interface; Standard Operating Procedures; flight deck operations; formal methods

I. INTRODUCTION (HEADING I)

The airline cockpit is a heavily proceduralized environment in which all operations are governed by standardized procedures performed the same way in each operational circumstance by the flight crews. This ensures that any flight crew can be paired with any other flight crew and perform seamlessly. It also ensures that flight crews adhere to the airline prescribed procedures to guarantee safe and efficient operations.

Each procedure defines unambiguously: (1) the objectives, (2) the conditions when the task is conducted (time and sequence), (3) which crew member, (4) the sequence of events and actions, (5), and the type of feedback is provided (callout, indicator) [1] [2]. Well-designed procedures can be performed in the allowable operational time window (AOTW) in a logical sequence that minimizes interruptions or waiting for information, and is robust to variations in aircraft performance or airspace constraints.

The design and qualification of procedures for specific aircraft is a critical activity performed by the airline and the certification regulatory authority. The traditional approach to the design and inspection of the procedures is an adhoc process that is reliant on subject matter experts (SMEs). Due to the complexity of the procedures and the need to tradeoff multiple conflicting performance objectives, comparing alternate procedures and establishing strengths/weaknesses can be a challenge without a formal method for specifying the procedure and measuring the characteristics of the procedure.

This paper demonstrates a formal process for comparison of two procedures using HMI-Sequence Diagrams and Multi-Attribute Utility Theory [3].

Takeoff Flap Retraction is a procedure that is conducted following takeoff to retract the flaps and slats from a takeoff configuration to a clean-up-and-away configuration (i.e. 24° to 18° to 0° flaps). During this period the aircraft accelerates from the takeoff V2 speed to 250 knots and generally includes a maximum thrust reduction from the takeoff thrust setting to the climb thrust setting (Figure 1). Timing of the flap retraction is critical to avoid over-speed or under-speed. Also, due to the vicinity of terrain and traffic, the vehicle performance and airspace must be carefully monitored all the while staying responsive to Air Traffic Control (ATC) voice communication.

FIGURE 1: Flap Retraction procedure
Two procedures for flaps retraction during takeoff for the Avro-146 aircraft were analyzed. Both Procedure 1 and Procedure 2 are performed via the coordination between the Pilot Flying (PF) and the Pilot Monitoring (PM). Procedure 1 is performed with the PF calling out for a specific stage of flap retraction at the appropriate speed (and after reaching safe altitude) triggering the actions of the PM who then executes the order after double-checking safe conditions exist. When the stage of flap reaches the called for stage, the PM communicates it to the PF, and so on until the flaps are set to $0\degree$. Procedure 2 is performed by delegating the procedure to the PM at a specific safe altitude. At the end of Procedure 2, the PM report the clean configuration of the aircraft (i.e. flaps set to $0\degree$) to the PF.

The procedures were documented in HMI Sequence Diagrams. Characteristics for the two procedures were read from the HMI-Sequence Diagrams and from the Monte Carlo simulation of the procedures. Attributes were scored and utility for the procedures was calculated:

- Callout procedure has 18 HMI loops, the Delegate procedure 15 HMI loops
- Callout procedure has a buffer time of 3.6 seconds, while the Delegate procedure has a buffer time of 7.9 seconds
- Both procedures can be completed more than 95% of the time in the operational allowable time window
- Callout procedure has a better Shared Mental Model between the flight crew than the Delegate Procedure
- Both procedures are missing one communication item
- Callout Procedure has an overall utility of 0.775 and the Delegate Procedure 0.770, based on weights assigned to attributes by SMEs.

Overall, the Callout procedure is more robust to interruption and provides a better shared mental model between the crew members. However, the Delegate procedure can be completed on average 4.5 seconds faster providing more time for monitoring and dealing with interruptions.

This paper is organized as follows: the next section describes the flap retraction phase of flight and the required procedure along with the hazards associated to incorrect flap retraction. The Methods section describes the HMI Sequence Diagram method for specification and evaluation of the procedures as well as the Value Hierarchy and multi-attribute analysis. The results section 4 describes the formal comparison of the procedures. The limitations and implications of the analysis are discussed in the Conclusions section.

II. THE TAKEOFF FLAP RETRACT PROCEDURE

Flaps retraction is part of the takeoff procedure. Flaps are extended on the ground before takeoff to increase the lift at low speeds. Once the aircraft has achieved a stabilized climb and a safe airspeed, the flaps are retracted to achieve the optimum lift and drag configuration.

<table>
<thead>
<tr>
<th>Flap Setting (degrees)</th>
<th>Maximum Airspeed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 takeoff and approach</td>
<td>220</td>
</tr>
<tr>
<td>18 low speed hold</td>
<td>175</td>
</tr>
<tr>
<td>24</td>
<td>180</td>
</tr>
<tr>
<td>30</td>
<td>170</td>
</tr>
<tr>
<td>33</td>
<td>155</td>
</tr>
</tbody>
</table>

Flap retraction remains a manual task performed by the flight crew due to the hazards and complexity associated with the maneuver. Since flaps are relatively small movable surfaces hinging to the aircraft wings, their robustness to aerodynamic forces is less than that of the remaining control surfaces. Operation of flaps under high speed conditions causes structural damage. As a result, flaps retraction and extension are limited by maximum permissible speeds (Table 1).

An example for flaps maximum speed limitations is shown in Table 1. Note that the higher the angle of flaps the lower the maximum permissible speed, pilots must closely monitor speed during the takeoff procedure to make sure the retraction occurs before the aircraft reaches the maximum allowable speed for that configuration.

Another hazard linked to flaps retraction during takeoff relates to the stall speed ($V_s$). This speed is the slowest airspeed at which the aircraft can sustain a sufficient lifting force. One of the benefits of the flaps is that they lower the stall speed. Extended flaps provide a comfortable margin above $V_s$, but retracting flaps will bring this critical value back to a higher number. As a result, when retracting flaps, pilots make sure their speed is at a safe margin above the stalling speed for the next stage of flap.

Lastly, it is critical to retract the stages of flaps in sequence to avoid abrupt loss of lift amid dangerous proximity to the ground. This is the reason why flaps are retracted at a company appointed safe altitude above ground level.

A typical aircraft can take-off with different flaps settings. The company calculates a margin below the maximum allowable speeds for flaps operation and provides its pilots data on safe flaps retraction speeds as shown on Table 2. This compiled table is called the “flap retraction schedule” for an Avro-146 taking off with a mass of 38,000 kg. To explain, in a scenario where pilots flying an Avro-146 with flaps set to $24\degree$, this table informs the pilots that at this take-off mass, the speed at which flaps are to be retracted from $24\degree$ to $18\degree$ is 135kts. That speed is referred to as $V_{F18}$.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>FLAP RETRACTION SCHEDULE FOR AVRO-146</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/O FLAP</td>
<td>18\degree</td>
</tr>
<tr>
<td>$V_R$</td>
<td>126</td>
</tr>
<tr>
<td>$V_2$</td>
<td>135</td>
</tr>
<tr>
<td>$V_{F24}$</td>
<td>N/A</td>
</tr>
<tr>
<td>$V_{F18}$</td>
<td>N/A</td>
</tr>
<tr>
<td>$V_{F0}$</td>
<td></td>
</tr>
</tbody>
</table>
Also, due to the vicinity of terrain and traffic, the vehicle performance and airspace must be carefully monitored all the while staying responsive to ATC voice communication.

III. METHOD OF ANALYSIS: HMI-SEQUENCE DIAGRAMS AND MULTI-ATTRIBUTE UTILITY ANALYSIS

A. Procedures and Human-Machine Interaction (HMI)

A procedure is performed by a sequence of operator actions: (1) Observe and Orient, (2) Decide, and (3) Act [4], [5], [6]. Each execution of these three actions is known as an HMI-loop. The initiation of each HMI-loop is triggered by a sensory cue (i.e. visual, aural, tactile, or smell) or a memory cue (i.e. portion of a procedure trained and stored in Long-Term Memory).

The Observe and Orient cues may come from the environment, from the machine or from the automation. In modern “hermetically sealed” flight decks, the cues are largely derived from displays on the automation that are sourced from environmental or machine sensors.

The Decide step determines the selection of the appropriate action(s). When the action is prompted directly by a cue (e.g. a label indicating the next action), or the decision is based on habit, the decision-making is trivial and reliable. When decisions are made without visual cues for an infrequent circumstance they may require the application of memorized procedural rules or reflection and reasoning. These decisions are less reliable.

The Act step involves manipulating the input devices on the automation or machine.

A typical procedure may involve between 20 and 200 HMI-loops. In general, the HMI-loops must be completed in the prescribed sequence (e.g. a display page must be accessed before an entry can be made). In this way delays in completing an HMI-loop ripple forward through the procedure and result in delays in completing the procedure in the allowable operating time window (AOTW).

The AOTW is calculated using the operational environment constraints such as the time to accelerate to a required airspeed, the time to descend to an altitude, or the time before the next ATC instruction.

B. HMI Sequence Diagrams

HMI-Sequence Diagrams (HMI-SD) can be used to document and simulate Procedures [3]. The HMI-SD diagram has two dimensions: the vertical axis that represents time and the horizontal axis that represents the agents (Figure 2).

C. Time-to-Complete Procedure

The observe & orient, decide and act actions all have associated time distributions (e.g. N(μ, σ). When the appropriate distribution is assigned to the actions, the HMI-SD model can be run in a Monte Carlo simulation to establish the overall time to complete the procedure.

D. Allowable Operational Time Window

Each procedure has, by definition, an Allowable Operational Time Window (OATW) that represents the distribution of time in which the procedure must be completed (see Figure 3). In the HMI-SD in Figure 4, this time is shown by the double headed arrow Between HI1 and HI7. The flight crew are expected to have completed a specific number of HMI loops (here 3) by the end of that time window.

The HMI Sequence Model is run in a Monte Carlo simulation to generate information about the time it takes a sample of pilots to perform a procedure (or some part of it). This information is given in the form of a statistical distribution as shown in Figure 3. The difference between the 95%-tile of the right tail of the time to complete the distribution and the 5%-tile of the OATW distribution, represent the Buffer Time. This is the excess time in which the procedure can absorb delays in any of the HMI-Loops.
E. Shared Mental Model

In addition to the sequence and timing of HMI-loops in a procedure, the procedure must also ensure a shared mental model between human operators. Each operator must share the same understanding of the state of the flight, the future plans, and any actions taken to configure the machine or automation. For example, critical procedures (e.g. takeoff) are briefed prior to execution and “call-outs” are made by one operator to let the other verify the setting or to let the other know an action has been taken. These interactions are shown in the HMI-SD by interactions 4 and 6. Together the HMI-Loop 2 and HMI-Loop 3 constitute a Shared Mental Model (SMM-1) in Figure 3.

F. Scoring Procedures from the HMI-SD

The following properties of a procedure can be measured directly from the HMI-SD:

- Number of Interaction
- Number of HMI-loops
- Number of HMI-Loops not supported by salient/unambiguous visual cues
- Allowable Operational Time Window (AOTW)
- Sub-procedure Time on task (from Monte Carlo simulation)
- Procedure Time-to-complete- (from Monte Carlo simulation)
- Cumulative buffer time (from Monte Carlo simulation)
- Probability of Failure to Complete (PFtC)
- Shared Mental Models Loops
- Communication Ratio
- Missing Communication Items

G. Multi-Attribute Utility Analysis of Procedures

Discussions with SMEs designing and certifying standard operating procedures have identified the following attributes for assessing the performance of a procedure:

1. Ease-of-Performance
   a. Number of Interactions
   b. Number of HMI-loops
   c. Number of HMI-loops not supported by salient/visual cues (i.e. not rely on Long-Term Memory or Working Memory)

2. Hazard Mitigation
   a. Probability of Failure-to-Complete Procedure within the Allowable Operating Time Window (AOTW)
   b. Number of Sub-procedures failing to complete within the OATW

3. Robustness to Disruptions
   a. Shared Mental Model
   b. Missing Communication Items
   c. Buffer Time

The measures used to assess the attributes are listed above. Ease-of-Performance is based on the complexity of the interactions required to complete the procedure. The lower the number of interactions and HMI-loops the easier to train, learn and perform the procedure. A key component is the degree to which the procedure relies on salient cues to observe/orient, decide and act.

Hazard mitigation is probability of completing the procedure within the AOTW and the number of Sub-procedure buffer times less than zero (i.e. sub-procedure was not completed within the AOTW for the sub-procedure).

Robustness to disruptions has three components. First the degree to which the procedure ensures a shared mental model. That is crew members share the same operational picture and do not perform interactions that are not confirmed or hidden form each other. Second, the number of missing communication items. Third, the degree to which the procedure allows excess time to complete in order to absorb disruptions and interruptions (e.g. ATC communications).

The overall utility can be expressed as follows:

$$U = \text{Weight of Attribute} \times \text{Value for Attribute}$$

Weights are derived from SMEs using a pair-wise comparison method.

IV. COMPARISON OF TWO ALTERNATE TAKEOFF FLAP RETRACTION PROCEDURES

A. Procedures

Two flap retraction procedures have been proposed (See Fig 4 & 5). Both procedures are initiated when the aircraft achieves 80 knots. Both procedure are the same through the decision speed ($V_D$), the rotation speed ($V_R$), Gear-up and confirmation of (autopilot) navigation modes.
The next step is the flap retraction. For the Callout procedure, the PF issues requests to the PM to retract flaps from 24 degrees to 18 degrees, then to 0 degrees (i.e. clean configuration). During this procedure, both pilots are monitoring the airspeed for the appropriate conditions. For example, for the retraction from 24° to 18°, the appropriate speed is $V_{F18} = 135$ kts. The PM moves the flap lever and confirms when the flap setting has been achieved (“FLAP at 18°”). Note that the convention on callouts is that they are differentiated from the rest of the procedure interactions by the capitalized words between quotes.

For the Delegate procedure, the PF requests “CLIMB SEQUENCE” and the PM unilaterally sets the flap setting at the appropriate conditions. When the sequence is complete, the PM alerts the PF with a “FLAP AT ZERO” callout.

Both procedures end with the after takeoff checklist.

### Table III. Properties of Procedures From HMI-SD’s and Relating Attributes Values

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Callout Procedure</th>
<th>Normalized</th>
<th>Delegate Procedure</th>
<th>Normalized</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Interactions</td>
<td>44</td>
<td>-</td>
<td>38</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$v_{j1}$</td>
<td>Number of HMI-Loops</td>
<td>18</td>
<td>0.75</td>
<td>15</td>
<td>0.80</td>
</tr>
<tr>
<td>$v_{j2}$</td>
<td>Number of HMI-Loops not supported by salient/unambiguous visual cues</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**B. Assumptions**

For this case study, the AOTW was assumed to be the time to reach the Maximum Allowable speed for flaps 18, That is 220 kts. Buffer Time was calculated using the difference between the Monte Carlo distribution Mode+3σ and the time for the flap retraction speeds from the schedule.

**C. HMI-Sequence Diagrams**

The HMI-SD for the procedures are shown in the Appendix. The properties of the procedures are summarized in Table 3.
The analysis documented both procedures can be completed within the AOTW. Also, the long-term memory items for checking the speeds was not included in the HMI.

D. Utility Weights

Weights were elicited from SMEs using a pair-wise comparison method (Table 4).

**Callout procedure: j=1, Delegate Procedure: j=2**

<table>
<thead>
<tr>
<th>AOTW [sec]</th>
<th>Procedure Time-to-Complete</th>
<th>(\mu=)</th>
<th>(\sigma=)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25.87</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.40</td>
<td>0.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(v_j) Probability of Failure to Complete (PFtOC) in Time</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(v_j) Failing Sub-Procedures over Total Number of Sub-Procedures</th>
<th>1/3</th>
<th>0.67</th>
<th>1/3</th>
<th>0.67</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(v_j) Shared Mental Models Loops Ratio</th>
<th>7/8</th>
<th>-</th>
<th>5/6</th>
<th>-</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(v_j) Communication Ratio [# Interactions] SMM M-M-L</th>
<th>44/7</th>
<th>6.3</th>
<th>38/5</th>
<th>7.6</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(v_j) Cumulative Buffer Time (secs)</th>
<th>3.6</th>
<th>0.36</th>
<th>7.9</th>
<th>0.79</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(v_j) Missing Communication Items</th>
<th>1</th>
<th>0.67</th>
<th>1</th>
<th>0.67</th>
</tr>
</thead>
</table>

TABLE IV. PROPERTIES OF PROCEDURES FROM HMI-SD’S

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Symbol</th>
<th>Relative Weights</th>
<th>Overall Weights</th>
<th>Overall Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMI-Loops</td>
<td>(w_1)</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>HMI-Loops not supported by Salient/Unambiguous Cues</td>
<td>(w_2)</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hazard Mitigation</th>
<th>(w_3)</th>
<th>0.5</th>
<th>0.25</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Failing</td>
<td>(w_4)</td>
<td>0.5</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Buffering Disruption</td>
<td>(w_5)</td>
<td>0.4</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>Communication Ratio</td>
<td>(w_6)</td>
<td>0.2</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>

E. Utility Calculation

Utility for the procedures was calculated using the overall weights expressed in the rightmost column of Table 4, and the normalized utility of the attributes are also in the rightmost column of Table 3.

The Callout procedure:

\[
\text{Utility}_\text{Callout Procedure} = \sum_{i=1}^{7} w_i \cdot v_{1i}
\]

\[U = (0.1\cdot0.75)+(0.1\cdot1)+(0.25\cdot0.67)+03.6)+(0.125\cdot0.67)]

\[\text{Utility}_\text{Callout Procedure} = 0.775\]

The Delegate procedure:

\[
\text{Utility}_\text{Delegate Procedure} = \sum_{i=1}^{7} w_i \cdot v_{2i}
\]

\[U = (0.1\cdot0.80)+(0.1\cdot1)+(0.25\cdot0.67)+03.6)+(0.125\cdot0.67)]

\[\text{Utility}_\text{Delegate Procedure} = 0.770\]

V. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

A. Conclusions

Comparison of procedures for the purpose of design and/or regulatory certification evaluation is a challenge due to the complexity of the procedures and the conflicting objectives.

This paper describes an analysis of the procedures for the Takeoff Flap Retraction procedure. The analysis documented the procedure in a formal model (HMI-Sequence Diagrams) and used the properties of the model and the executable model to generate statistics for each procedure.

The utility for the two procedures was equivalent with the defined SME weights. Different weights would yield a different result.

Overall, the Callout procedure is more robust to interruption and provides a better shared mental model between the crew members. However, the Delegate procedure can be completed on average 4.5 seconds faster providing more time for monitoring and dealing with interruptions.

The sub-procedure from 115 knots to 135 knots could not be completed in the AOTW for the sub-procedure. This needs to be evaluated further.

B. Limitations & Future Work

This analysis used discrete values for the AOTW. A more accurate model would use distributions to account for aircraft performance changes and wind. Also, the long-term memory items for checking the speeds was not included in the HMI-SD.

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VI. REFERENCES
VII. APPENDIX

HMI SEQUENCE DIAGRAMS FOR AIRLINE SOPs FOR TAKEOFF FLAP RETRACTION

Callout Procedure
Delegate Procedure