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TASK ANALYSIS FOR HMI DESIGN LEVEL OF AUTOMATION STUDY OF AIRCRAFT NAVIGATION FUNCTIONS

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ACRONYMS AND ABBREVIATIONS

ACTA	Applied Cognitive Task Analysis
ADC	Air Data Computer
ADF	Automatic Direction Finder
AL	Autonomy Level
ALFUS	Autonomy Levels for Unmanned Systems
ANP	Actual Navigation Performance
ATC	Air Traffic Control
ATS	Air Traffic Service
CAC	Contextual Autonomous Capability
CAS	Calibrated Air Speed
CDM	Critical Decision Making
CIT	Critical Incident Technique
CPA	Critical Path Analysis
CPDLC	Controller-Pilot Data Link Communications
CTA	Cognitive Task Analysis
DARPA	Defense Advanced Research Projects Agency
DME	Distance Measuring Equipment
DoD	Department of Defense
DVI	Direct Voice Input
EC	Environmental Complexity
EFIS	Electronic Flight Instrument System
EFOB	Estimated Fuel on Board
FCU	Flight Control Unit
FL	Flight Level
FMS	Flight Management System
FOB	Fuel on Board
GNSS	Global Navigation Satellite System
GOMS	Goals, Operators, Methods and Selection Rules
GPS	Global Positioning System
GS	Ground Speed
HCI	Human-Computer Interaction
HEI	Human Error Identification

HF	Human Factors
HI	Human Independence
HMI	Human-Machine Interface
HRI	Human-Robot Interaction
HTA	Hierarchical Task Analysis
IAS	Indicated Air Speed
ILS	Instrument Landing System
INS	Inertial Navigation System
IRS	Inertial Reference System
KLM	Keystroke-Level Model
LNAV	Lateral Navigation
LOA	Level of Automation
MC	Mission Complexity
MCDU	Multifunction and Control Display Unit
MoD	Ministry of Defense
ND	Navigation Display
NDB	Non-Directional Beacons
OODA	Observation, Orientation, Decision, Action
OR	Operational Relationships
PA	Pilot's Associate
PACT	Pilot Authorization and Control of Tasks
PBN	Performance-Based Navigation
RAC	Root Autonomous Capabilities
RNAV	Area Navigation
RNP	Required Navigation Performance
SA	Situation Awareness
SID	Standard Instrument Departure
SME	Subject Matter Expert
STAR	Standard Terminal Arrival Route
TA	Task Analysis
TACAN	Tactical Air Navigation
TOD	Top of Descent
TTA	Tabular Task Analysis
UAV	Unmanned Arial Vehicle
UGS	Unattended Ground Sensors
UGV	Unmanned Ground Vehicle

UM	Unmanned Munitions
UMS	Unmanned System
US&R	Urban Search & Rescue
USAF	United States Air Force
UUV	Unmanned Underwater Vehicle
VHF	Very High Frequency
VNAV	Vertical Navigation
VOR	VHF Omnidirectional Range
VPA	Verbal Protocol Analysis

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1 INTRODUCTION

Advancements in technology have enabled increasingly sophisticated automation to be introduced into the flight decks of modern aircraft. Generally, this automation was added to accomplish worthy objectives such as reducing flight crew workload, adding additional capability, or increasing fuel economy. Automation is necessary due to the fact that not all of the functions required for mission accomplishment in today's complex aircraft are within the capabilities of the unaided human operator, who lacks the sensory capacity to detect much of the information required for flight. To a large extent, these objectives have been achieved. Nevertheless, despite all the benefits from the increasing amounts of highly reliable automation, vulnerabilities do exist in flight crew management of automation and Situation Awareness (SA). Issues associated with flight crew management of automation include:

- Pilot understanding of automation's capabilities, limitations, modes, and operating principles and techniques.
- Differing pilot decisions about the appropriate automation level to use or whether to turn automation *on* or *off* when they get into unusual or emergency situations.
- Human-Machine Interfaces (HMIs) are not always easy to use, and this aspect could be problematic when pilots experience high workload situations.
- Complex automation interfaces, large differences in automation philosophy and implementation among different aircraft types, and inadequate training also contribute to deficiencies in flight crew understanding of automation.

1.1 OBJECTIVE

Among the different systems installed in today's aircraft, the Flight Management System (FMS) could be considered a key element. The FMS receives inputs from the various systems that are installed on board to perform the necessary navigation calculations and provide information to the flight crew via a range of display units. The key interface with the flight crew is via the following displays:

- Captain's and first officer's Navigation Displays (NDs) that provide the pilots with phase of flight-dependent navigation and steering information necessary to fly the intended route.
- Multifunction Control and Display Units (MCDUs) that display information and act as means for the flight crew to manually enter data.

Starting from the definition of two operational scenarios, the aim of this work is to study the interaction between pilots and the FMS for what concerns entry and modification of route data, in order to present options on how to improve the latter. First, the interaction is described in detail with the aid of Task Analysis (TA) methodologies. Then, a Level of Automation (LOA) is allocated to each operation by employing an appropriate scale. Successively, possible improvement hypotheses are presented and analyzed in terms of interaction sequences and LOA. Finally, a comparison between the MCDU-based FMS and the proposed hypotheses is performed using specific metrics.

1.2 STRUCTURE OF THE THESIS

This document is structured in such a way as to first provide the reader with the theoretical notions that are needed to understand the topics of subsequent chapters, and then present the results of the analysis in the final part.

Chapter 1 gives an introduction and explains how the document will develop in order to guide the reader through the different steps of the analysis.

Chapter 2 introduces TA methodologies and describes the different techniques that could be used to analyze tasks, hence allowing to select the most suitable one for the aim of this work.

Chapter 3 introduces the concept of automation, illustrates how it is applied in the aviation domain and outlines some of the scales that are available to assess the LOA of a given system, therefore allowing to select the most appropriate one.

Chapter 4 first summarizes aircraft navigation techniques and gives a brief description of the FMS. Then, a detailed description of the operational scenarios is provided. Finally, the main results of the TA are presented.

Chapter 5 analyzes the LOA of MCDU-based FMS and attempts to present possible improvement hypotheses. In the final paragraph of the chapter, a comparison between MCDU-based FMS and the proposed improvement hypotheses is presented.

Finally, the conclusive chapter summarizes the results of the analysis and suggests possible future developments related to the topics of this work.

2 TASK ANALYSIS METHODS

2.1 INTRODUCTION

Task Analysis (TA) techniques are used to understand and represent human and system performance in a particular scenario under analysis, and Human Factors (HF) practitioners often rely on this approach. According to Diaper & Stanton (2003), there have been over 100 task analysis techniques described in the literature. Task analysis consists in (Stanton, 2003):

a. Identify the different tasks that are involved.
b. Collect task data.
c. Analyze the data in order to understand the tasks.
d. Produce a documented representation of the analyzed tasks.

Typical task analysis techniques break down scenarios into the required individual task steps in terms of the required interactions, which can be either human-machine or human-human. According to Kirwan & Ainsworth (1992), task analysis can be defined as the study of what an operator is required to do, in terms of actions and/or cognitive processes, in order to achieve system goals. As of today, different variations of task analysis techniques exist.

Task analysis techniques are applied in a wide range of domains, including military operations, aviation, air traffic control, product design and nuclear power plants. According to Diaper (2003), task analysis is potentially the most powerful technique available to Human-Computer Interaction (HCI) practitioners and it can be applied at each stage in system design and development. Stanton (2003) also suggests that task analysis is the central method for the design and analysis of system performance, involved in everything from concept design to system development and operation. Almost all of the techniques that are available provide a description of the observable aspects of operator behavior at various levels of detail, together with some indications about the structure of the task.

While its use is widespread and ongoing, the concept of task analysis has evolved with the introduction of new methods which take into account the cognitive aspects of work and analyze what happens when work is distributed across teams and systems. These techniques focus on the mental processes which underlie observable behavior, e.g. decision making and problem solving. This new category is called Cognitive Task Analysis (CTA) and will also be described in more detail in the following paragraphs.

The usefulness of task analysis techniques is highlighted by the fact that many HF methods require some sort of task analysis as their input. It is important to understand that TA is a fundamental methodology to assess human error. Thus, TA methods can be used to identify and possibly eliminate the preconditions that give rise to errors before they occur.

2.2 TASK ANALYSIS METHODS

In this paragraph, the following TA methods will be described:

- Hierarchical Task Analysis (HTA)
- Critical Path Analysis (CPA)
- Goals, Operators, Methods and Selection rules (GOMS)
- Verbal Protocol Analysis (VPA)
- Tabular Task Analysis (TTA)

2.2.1 HIERARCHICAL TASK ANALYSIS (HTA)

HTA was developed in response to the need to analyze complex tasks, such as those found in the chemical processing and power generation industries (Annett, Duncan, Stammers & Gray, 1971). Nevertheless, its domain of application is generic.

HTA is a systematic method used to describe how an activity is organized in order to meet the overall objective. It involves identifying in a top down fashion the overall goal of the task, the various sub-tasks and the conditions under which they should be carried out in order to achieve that goal. By doing so, it is possible to represent complex tasks as a hierarchy of goals, operations and plans:

- *Goals*: the unobservable task goals associated with the task in question;
- *Operations*: the observable behaviors or activities that the operator has to perform in order to accomplish the goal of the task in question;

- *Plans*: the unobservable decisions and planning made on behalf of the operator.

In order to perform an HTA, it is advisable to follow these steps:

- Step 1: determine the overall goal of the task under analysis and place it at the top of the hierarchy. An example of a goal can be "Land Boeing 737 at New Orleans airport using the autopilot".
- Step 2: determine task sub-goals, i.e. break the overall goal into four or five meaningful sub-goals.
- Step 3: sub-goal decomposition. The sub-goals identified in the previous step should be broken down into further sub-goals and operations, according to the task. It is important to understand that the bottom level of any branch in an HTA will always be an operation; whilst everything above the latter specifies goals, operations actually say what needs to be done. Thus, operations represent the actions that need to be done by the operator in order to achieve the sub-goals.
- Step 4: plans analysis. Once all of the sub-goals have been fully described, plans need to be added since they dictate how goals are achieved. Plans do not have to be linear and can come in any form. Once goals, sub-goals, operations and plans are exhausted, a complete diagram made up of all these parts makes up an HTA.

Advantages:

- HTA is a technique that is both easy to learn and implement.
- HTA is often the starting point of numerous HF techniques such as Human Error Identification (HEI) and mental workload assessment.
- HTA is a comprehensive method that covers all sub-tasks of the task in question.
- HTA has been used extensively in a wide range of contexts.
- Tasks can be analyzed to any level of detail, depending on the purpose.
- When used as an input to design, HTA allows functional objectives to be specified at the higher levels of the analysis prior to final decisions being made about the hardware. This is important when allocating functions between personnel and automatic systems.

- HTA is an excellent starting point when further analysis is required; when performed correctly, HTA depicts everything that needs to be done in order to complete the task in question.
- HTA can be carried out using only pencil and paper.

Disadvantages:

- HTA mainly provides descriptive information rather than analytical information.
- HTA alone cannot provide design solutions.
- HTA does not take into account cognitive components of a task.
- For complex and large tasks can be time consuming.
- HTA requires a good basic knowledge in relevant HF principles.

Figures 2.1 and 2.2 represent an example of an HTA; in this particular case, plans are written in a flowchart-style notation on a separate page.

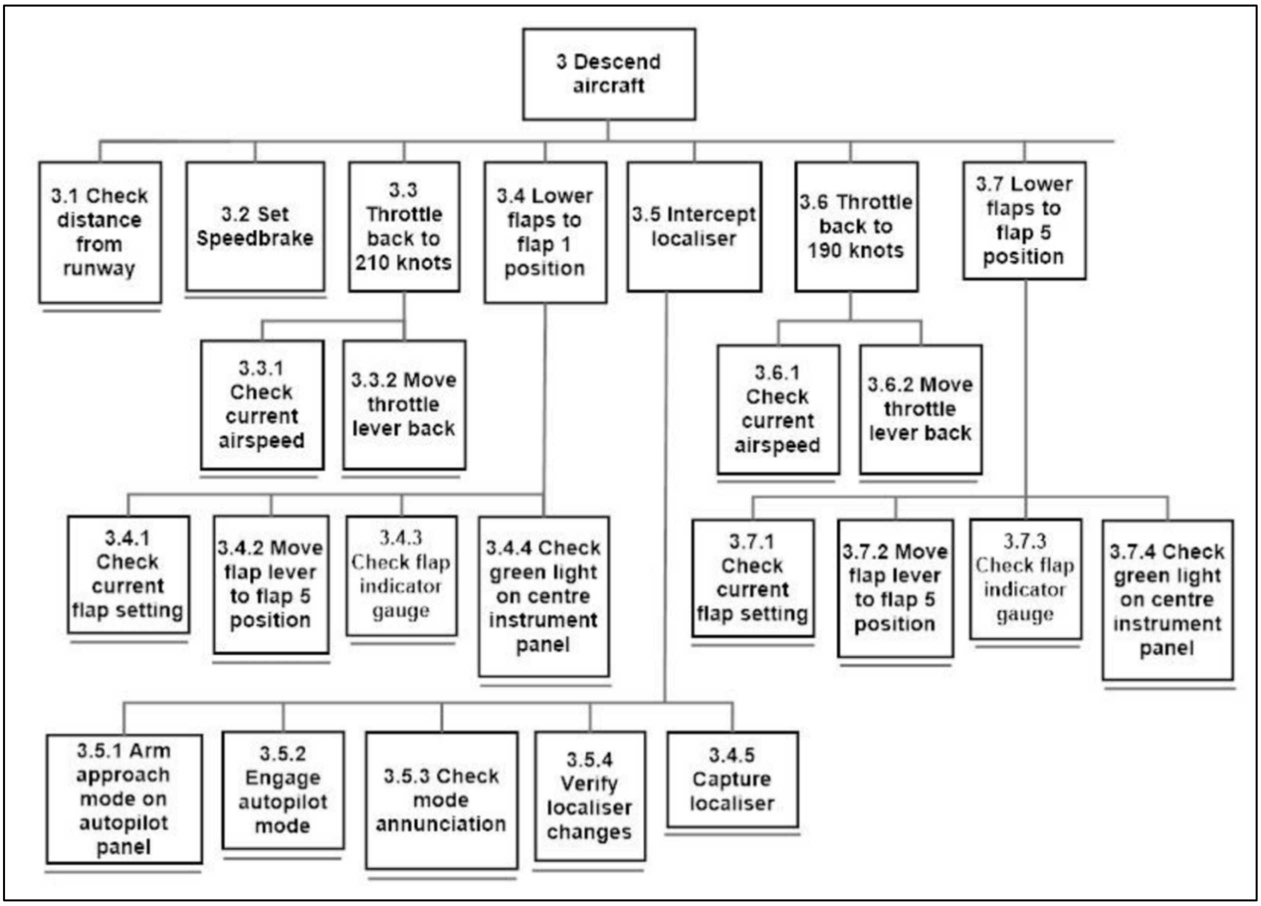


Figure 2.1: HTA example, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

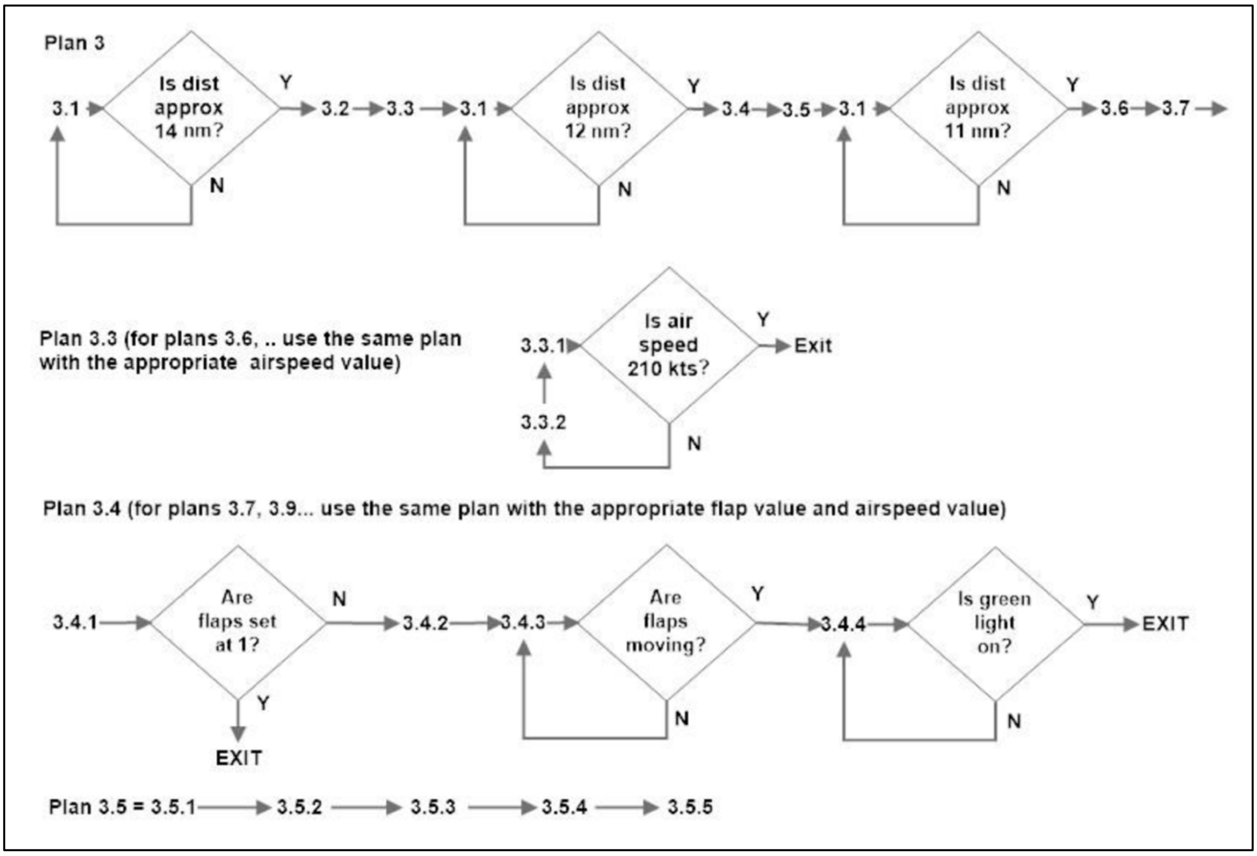


Figure 2.2: Plan example, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

2.2.2 CRITICAL PATH ANALYSIS (CPA)

CPA is a project management tool that is used to determine the combination of tasks that will most affect the time needed to complete a job (Harrison, 1997). Any change in the tasks on the "critical path" will change the overall job completion time. Hence, any change in tasks off the critical path can be accommodated for, with certain limitations.
In order to perform a CPA, it is advisable to follow these steps:

- Step 1: define tasks. This could take the form of a TA or could be a simple decomposition of the activity into constituent tasks. Therefore, if we consider as an example the activity of retrieving money from an ATM, we could write the following task steps: 1. Retrieve card from wallet, 2. Insert card into ATM, 3. Recall PIN, 4. Wait for screen to change, 5. Read prompt, 6. Type in digit of PIN, 7. Listen for confirmatory beep, 8. Repeat steps 6 and 7 for all the digits of the PIN, 9. Wait for screen to change.

- Step 2: define the tasks in terms of input and output sensory modalities (manual, visual, auditory, cognitive, speech); depending on the activity, also system responses might need to be considered. By doing so, Table 1 can be constructed. It is noted that effective CPA application might require a degree of judgement from the analyst because some task steps might require more than one modality or might not easily fit into this scheme.

Table 1: Modality table, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

Task step	Manual-L	Manual-R	Speech	Auditory	Visual	Cognitive	System
Retrieve card	X	X					
Insert card		X					
Recall PIN						X	
Screen change							X
Read prompt					X		
Type digit		X					
Listen for beep				X			
Screen change							X

- Step 3: construct a chart (Figure 2.3) that shows the task sequence and the dependencies between tasks. The following figure shows a chart for the example that is being considered. For space reasons, the chart is stopped after entering the first digit. Each node is linked by an action which takes a definable amount of time.

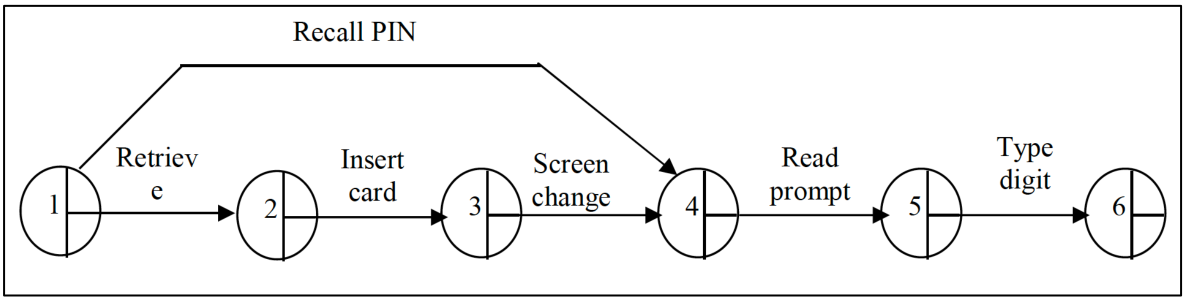


Figure 2.3: CPA chart, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

- Step 4: assign completion time to the different tasks.
- Step 5: calculate the “forward pass”. Begin from the first node of the chart and assign an Earliest Start Time (EST) of 0. The earliest finish time for the task from this node will be equal to 0 plus the duration of the task step; for instance, if the task “retrieve card” lasts 500 ms, the earliest finish time will be equal to 500 ms. The next phase of this step is to move to the following node, remembering that the earliest finish time of one task becomes the earliest start

time of the subsequent one. When more than one task ends up into a node, the highest time is taken. This process is applied till the last node is reached. By doing so, Table 2 can be constructed.

Table 2: Forward pass, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

Task step	Duration	Earliest start	Latest start	Earliest finish	Latest finish	Float
Retrieve card	500ms	0		500		
Insert card	350ms	500		850		
Recall PIN	780ms	0		780		
Screen change	250ms	850		1100		
Read prompt	350ms	1100		1450		
Type digit	180ms	1450		1630		
Wait for beep	100ms	1630		1730		

- Step 6: calculate the “backward pass”. Begin from the last node and assign a latest finish time (which in this case will be equal to the earliest finish time). To come up with the latest start time, subtract the task duration from the Latest Finish Time (LFT). The number that is obtained will become the LFT of the previous node. When more than one task ends up into a node, the lowest time is taken. This process is applied till the first node is reached. By doing so, Table 3 can be constructed.

Table 3: CP calculation table, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

Task step	Duration	Earliest start	Latest start	Earliest finish	Latest finish	Float
Retrieve card	500ms	0	0	500	500	0
Insert card	350ms	500	500	850	850	0
Recall PIN	780ms	0	320	780	1100	320
Screen change	250ms	850	850	1100	1100	0
Read prompt	350ms	1100	1100	1450	1450	0
Type digit	180ms	1450	1450	1630	1630	0
Wait for beep	100ms	1630	1630	1730	1730	0

- Step 7: Determine the Critical Path (CP). Defining the difference between EST and LFT as float, the critical path consists in all the nodes that have zero float. In this example, the task step “recall PIN” has a non-zero float and this means that it can be started up to 320 ms into the other tasks without having an impact on the total task performance.

Advantages:

- Splitting the tasks into the activities that need to be carried out, allows the analyst to gain a better understanding of the task.
- CPA predicts task times for both the full task and each individual task step.
- CPA provides a logical, temporal description of the task that is being analyzed.
- CPA is a structured and comprehensive procedure.
- CPA does not require excessive training.

Disadvantages:

- CPA can be tedious and time consuming for complex tasks.
- CPA only models error-free performances and cannot deal with unpredictable events.
- CPA cannot be used with tasks that are mainly cognitive in nature.

2.2.3 GOALS, OPERATORS, METHODS AND SELECTION RULES (GOMS)

The GOMS method is used to provide a description of human performance in terms of the user’s goals, operators, methods and selection rules. GOMS first defines the user’s goals, then decomposes them into sub-goals and finally demonstrates how these goals are achieved through user interaction.

GOMS can be used to provide a description of how a user performs a task, to predict performance times and to predict human learning.

Even though GOMS techniques are most commonly used for the evaluation of existing designs or systems, they could be used to determine the impact of a design on the user.

GOMS techniques are based upon the assumption that the user’s interaction with a computer is similar to solving problems. Problems are broken down into sub-problems, and these are broken down even further.

The four basic components that make up this technique are:

- Goals: is what the user wishes to achieve through the interaction. Goals are decomposed until an appropriate stopping point is achieved.

- Operators: they are the actions, either cognitive or motor, that the user performs during the interaction. Goals are achieved through performing the operators.
- Methods: they describe the user’s procedures that are needed to accomplish the goals; it is very likely that there exist more than one set of methods available to the user.
- Selection rules: they highlight which of the available methods should be used to accomplish the goals.

When using this technique, it is advisable to follow these steps:

- Step 1: define the top-level goals and make sure that they are described at a very high level in order to ensure that no possible method is left out of the analysis.
- Step 2: goal decomposition. Once the top-level goals have been specified, the following step is to determine a set of sub-goals. According to Kieras (2003) the analyst should always assume that each top-level goal is achieved by performing a series of smaller steps.
- Step 3: describe the operators. Each goal/sub-goal should be considered, and high-level operators described.
- Step 4: describe the methods. Methods describe the set of procedures used to achieve the goal (Kirwan & Ainsworth, 1992). In this stage of the GOMS analysis, the analyst should describe each set of methods that the user could employ to achieve the task.
- Step 5: describe selection rules. If there is more than one method of achieving a goal, the analyst should determine selection rules that predict which of the available methods will be used by the user to achieve the goal.

Advantages:

- GOMS technique allows the analyst to describe a number of different potential task routes.
- Since performance and learning times can be specified, GOMS analysis can aid designers in choosing between systems or design solutions.

Disadvantages:

- GOMS is a difficult method to apply and far simpler TA techniques are available.
- GOMS is time consuming.
- GOMS domain of application appears to be restricted to HCI.
- GOMS does not take into account error occurrence.
- A high level of training and practice is required.

2.2.4 VERBAL PROTOCOL ANALYSIS (VPA)

VPA is used to derive the processes, both cognitive and physical, that a person uses to perform a task. VPA involves creating a written transcript of the behavior of an operator as he/she performs the task under analysis. The transcript that is produced is based upon the operator “thinking aloud”. VPA has been used extensively within HF as a means of gaining an insight into the cognitive aspects of complex behaviors.
Even though there are no mandatory rules to conduct a VPA, it is advisable to follow this procedure:

- Step 1: define the scenario under analysis. An HTA is often used at this stage, in order to specify which tasks are to be analyzed.
- Step 2: instruct the participants. Once the scenario is set, the participants should be briefed regarding what is required of them during the analysis. Walker (2004) suggests that participants should be told that they should continue to talk even when what they are saying does not seem to make much sense. A practice run may also be undertaken.
- Step 3: begin scenario and record data. The participant should begin to perform the scenario under analysis and the whole performance should be both audio and video recorded.
- Step 4: verbalization of the transcript. Once collected, data should be transcribed into a written form.
- Step 5: encode verbalizations. The written form that has been produced in the previous step should be coded; depending upon the requirements of the analysis, data is coded into one of the following five categories: words, word

senses, phrases, sentences and themes. This step can be summarized by a table.

- Step 6: devise other data columns. Once the encoding is complete, the analyst should devise any “other” data columns. This allows the analyst to note any mitigating circumstances that may have affected the verbal transcript.
- Step 7: establish reliability. In VPA, reliability is established through reproducibility, i.e. independent raters need to encode previous analyses.
- Step 8: perform pilot study. The protocol analysis procedure should now be tested within the context of a small pilot study. This will demonstrate whether the collected verbal data is useful, whether the encoding system works etc. Any issues that come out in this phase should be dealt with before conducting the VPA for real.
- Step 9: analyze the results from the VPA. During any VPA, the responses given in each encoding category require summing, and this is simply achieved by adding up the frequency of occurrence noted in each category.

Advantages:

- VPA provides a rich data source.
- VPA is particularly effective when used to analyze sequences of activities.
- Verbalizations can provide a genuine insight into cognitive processes.
- VPA has been used extensively in a wide variety of domains.
- VPA is simple to conduct if the right equipment is available.
- The reliability of the technique is reassuringly good.

Disadvantages:

- Data analysis can become extremely laborious and time consuming.
- It is difficult to verbalize cognitive behavior.
- Strict procedure is often not fully adhered to.
- VPA is prone to bias on the participant’s behalf.

2.2.5 TABULAR TASK ANALYSIS (TTA) OR TASK DECOMPOSITION

According to Kirwan & Ainsworth (1992), TTA is a methodology that can be used to produce a detailed task description. Task decomposition begins with a task description, such as an HTA, to describe how each step of the task under analysis is performed. The analyst then gathers further information about specific aspects of each task step (such as time taken, controls used, etc.). The information for each of the task steps can then be presented using a set of sub-headings. This allows relevant information for each task step to be decomposed into a series of statements regarding the task (Kirwan & Ainsworth, 1992). The categories used to decompose the task steps should be chosen by the analyst based on the requirements of the analysis. The task decomposition technique can be used at any stage in the design process and its domain of application is generic.

When performing a TTA, it is advisable to follow this procedure:

- Step 1: hierarchical task analysis. The first step in a task decomposition analysis consists in an initial description of the task under analysis. For this purpose, it is recommended that HTA is used because the hierarchical structure of the analysis allows the analyst to progressively re-describe the activity in greater degrees of detail.
- Step 2: create task descriptions. Once an initial HTA has been conducted, the analyst should come up with a set of clear task descriptions for each of the different task steps. Task description should give the analyst enough information to determine exactly what has to be done to complete each task element.
- Step 3: choose decomposition categories. Once a sufficient description of each task step is obtained, the analyst should choose the appropriate decomposition categories. Kirwan & Ainsworth (1992) suggest that there are three types of decomposition categories: descriptive, organization-specific and modelling.
- Step 4: information collection. Once the decomposition categories have been determined, the analyst should create an information collection form for each one of them.
- Step 5: construct task decomposition. Finally, the analyst should put the collected data into a task decomposition. The table will be made up of all the decomposition categories chosen for the analysis.

Advantages:

- TTA has the potential to provide a very comprehensive analysis of a particular task and it is a flexible technique.
- The structure of the method ensures that all issues of interest are considered and evaluated for each of the task steps (Kirwan & Ainsworth, 1992).
- TTA provides a much more detailed description of tasks than any other traditional task analysis method.
- Since the analyst has control over the decomposition categories that are used, potentially any aspect of a task can be evaluated.

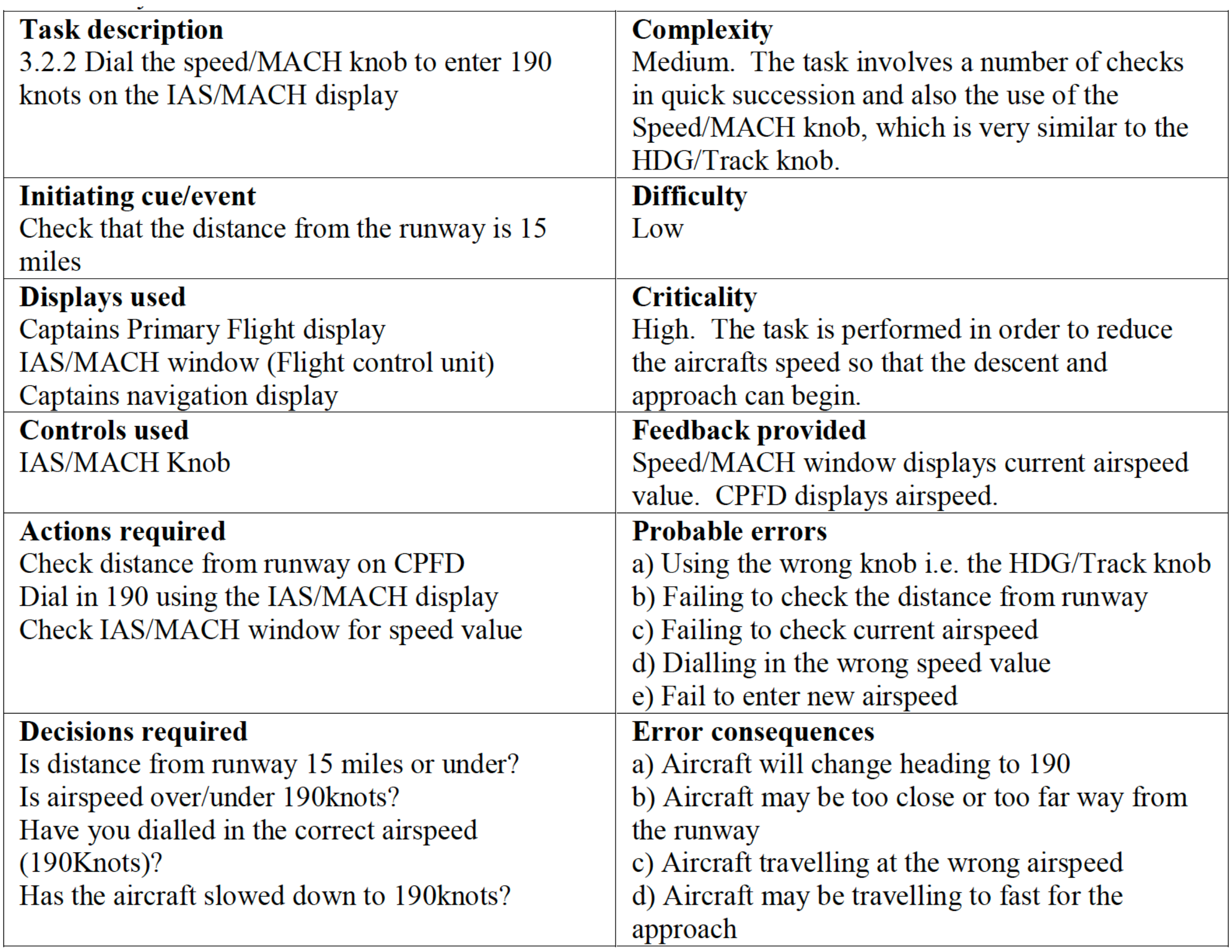
Disadvantages:

- Since TTA is potentially so exhaustive, it is a very time-consuming technique to employ.
- Obtaining information about the tasks (observation, interviews etc.) increases the workload of the analyst.
- Since various techniques are used within a task decomposition analysis, training time associated with the technique is high.

In the following, an example of a TTA application is provided (Table 4). A task decomposition was performed on the task "Land at New Orleans airport using the autopilot". Data collection included the following:

- Walkthrough of the flight task.
- Questionnaire administered to A320 pilots.
- Consultation with training manuals.
- Interview A320 pilot.

Table 4: TTA extract, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)



Task description 3.2.2 Dial the speed/MACH knob to enter 190 knots on the IAS/MACH display	**Complexity** Medium. The task involves a number of checks in quick succession and also the use of the Speed/MACH knob, which is very similar to the HDG/Track knob.
Initiating cue/event Check that the distance from the runway is 15 miles	**Difficulty** Low
Displays used Captains Primary Flight display IAS/MACH window (Flight control unit) Captains navigation display	**Criticality** High. The task is performed in order to reduce the aircrafts speed so that the descent and approach can begin.
Controls used IAS/MACH Knob	**Feedback provided** Speed/MACH window displays current airspeed value. CPFD displays airspeed.
Actions required Check distance from runway on CPFD Dial in 190 using the IAS/MACH display Check IAS/MACH window for speed value	**Probable errors** a) Using the wrong knob i.e. the HDG/Track knob b) Failing to check the distance from runway c) Failing to check current airspeed d) Dialling in the wrong speed value e) Fail to enter new airspeed
Decisions required Is distance from runway 15 miles or under? Is airspeed over/under 190knots? Have you dialled in the correct airspeed (190Knots)? Has the aircraft slowed down to 190knots?	**Error consequences** a) Aircraft will change heading to 190 b) Aircraft may be too close or too far way from the runway c) Aircraft travelling at the wrong airspeed d) Aircraft may be travelling to fast for the approach

2.3 COGNITIVE TASK ANALYSIS METHODS

Operators of complex dynamic systems face an increasing demand upon their cognitive skills and resources. As system complexity increases, operators require training in specific cognitive skills and processes in order to fulfill their duties. Furthermore, designers require an analysis of the cognitive skills and demands associated with the operation of the system under design in order to propose design concepts, allocate tasks, develop training procedures and evaluate the competence of the operator. As a result, a number of techniques have been developed in order to aid HF practitioners in evaluating and describing the cognitive processes involved in systems operation. CTA techniques are used to describe the mental processes used by system operators in completing a task or set of tasks.

Typical CTA techniques use observational, interview and questionnaire techniques in order to gather specific data regarding the mental processes used by system operators. The use of CTA techniques is widespread, and the domain of application is generic. The main problem associated with the use of CTA techniques is the considerable amount of resources required. In this paragraph a detailed description of the following techniques will be given:

- Applied Cognitive Task Analysis (ACTA)
- Critical Decision Making (CDM)
- Cognitive walkthrough
- Critical Incident Technique

2.3.1 APPLIED COGNITIVE TASK ANALYSIS (ACTA)

ACTA is a toolkit of interview techniques that can be used to elicit information regarding cognitive demands associated with the task or scenario under analysis. The output of an ACTA is typically used to aid system designers and no training in cognitive psychology is required (Militello & Hutton, 2000).
ACTA procedure is made of the following components:

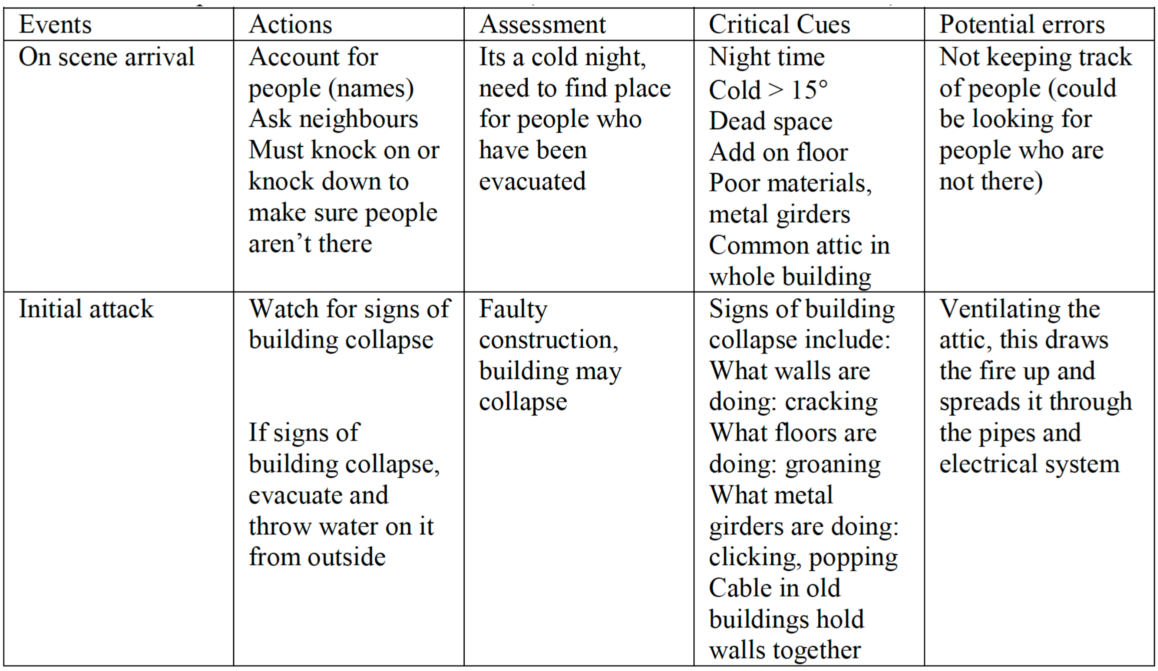
- Task diagram interview: it is used to give the analyst an overview of the task under analysis and allows to identify any cognitive aspect of the task that requires further analysis.
- Knowledge audit: the analyst determines the expertise required for each part of the task. The analyst questions Subject Matter Experts (SMEs) to obtain specific examples.
- Simulation interview: it allows the analyst to probe specific cognitive aspects of the task based upon a specific scenario.
- Cognitive demands table: it is used to group and sort the obtained data.

In order to perform an ACTA, it is advisable to pursue the following steps:

- Step 1: task diagram interview. Firstly, the analyst should conduct the task diagram interview with the relevant SME. This step is used to provide the analyst with a clearer picture of the task under analysis and also to aid the analyst in highlighting the various cognitive elements associated with the task. According to Militello & Hutton (2000) the SME should first be asked to decompose the task into relevant task steps. Once the task is broken down into a number of separate task steps, the SME should then be asked to identify which of the task steps require cognitive skills.

- Step 2: knowledge audit. This interview allows the analyst to identify instances of the task where expertise is used. Once a probe has been administered, the analyst should query the SME for specific examples of critical cues and decision-making strategies. Potential errors should then be discussed.
- Step 3: simulation interview. This step allows the analyst to understand the cognitive processes involved in the task under analysis. The SME is presented with a scenario and the analyst should prompt the SME to recall any major event, including decisions and judgements. Each event or task step in the scenario should be probed for actions, critical cues, potential errors and surrounding events. Any information elicited here should be recorded in a simulation interview table. Table 5 provides an example of its structure.

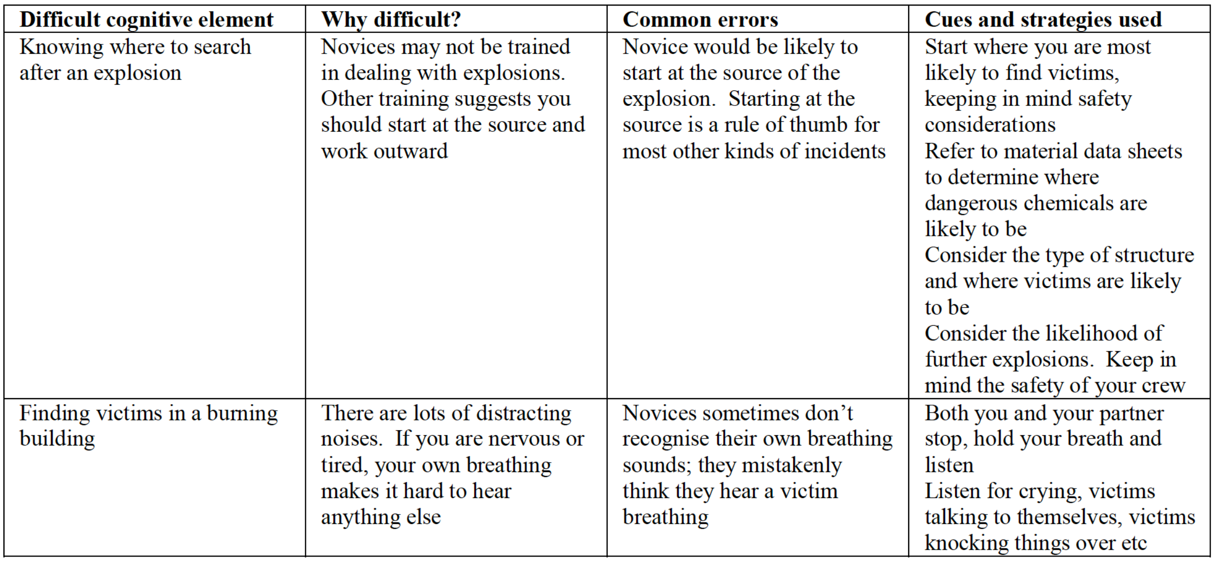
Table 5: Simulation interview table, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)



Events	Actions	Assessment	Critical Cues	Potential errors
On scene arrival	Account for people (names) Ask neighbours Must knock on or knock down to make sure people aren't there	Its a cold night, need to find place for people who have been evacuated	Night time Cold > 15° Dead space Add on floor Poor materials, metal girders Common attic in whole building	Not keeping track of people (could be looking for people who are not there)
Initial attack	Watch for signs of building collapse If signs of building collapse, evacuate and throw water on it from outside	Faulty construction, building may collapse	Signs of building collapse include: What walls are doing: cracking What floors are doing: groaning What metal girders are doing: clicking, popping Cable in old buildings hold walls together	Ventilating the attic, this draws the fire up and spreads it through the pipes and electrical system

- Step 4: cognitive demands table. Once the knowledge audit and simulation interview are completed, it is recommended (Militello & Hutton, 2000) that a cognitive demands table is used to sort and analyze the collected data. The analyst should prepare the cognitive demands table based upon the goals of the specific project. Table 6 provides an example of its structure.

Table 6: Cognitive demands table, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)



Difficult cognitive element	**Why difficult?**	**Common errors**	**Cues and strategies used**
Knowing where to search after an explosion	Novices may not be trained in dealing with explosions. Other training suggests you should start at the source and work outward	Novice would be likely to start at the source of the explosion. Starting at the source is a rule of thumb for most other kinds of incidents	Start where you are most likely to find victims, keeping in mind safety considerations Refer to material data sheets to determine where dangerous chemicals are likely to be Consider the type of structure and where victims are likely to be Consider the likelihood of further explosions. Keep in mind the safety of your crew
Finding victims in a burning building	There are lots of distracting noises. If you are nervous or tired, your own breathing makes it hard to hear anything else	Novices sometimes don't recognise their own breathing sounds; they mistakenly think they hear a victim breathing	Both you and your partner stop, hold your breath and listen Listen for crying, victims talking to themselves, victims knocking things over etc

Advantages:

- Analysts using this technique do not require training in cognitive psychology.
- ACTA requires fewer resources than traditional cognitive task analysis techniques.
- Probes and questions are provided for the analyst, facilitating the extraction of relevant data.

Disadvantages:

- The technique would appear to be time consuming in its application.
- Training time for ACTA techniques is also quite high.
- As with most cognitive task analysis techniques, ACTA requires further validation.
- The quality of the data obtained depends on both the SME that are interviewed and the analyst applying this methodology. Militello & Hutton (2000) suggest that some people are better interviewers than others and also that some SMEs are more useful than others.

Once the ACTA analysis is complete, the analyst has a set of data that can be either used in system design or to create training procedures.

2.3.2 COGNITIVE WALKTHROUGH

It is a methodology for evaluating the usability of user interfaces. The main driver behind the creation of this technique was the idea to develop and test a theoretically based methodology that could be used in actual design and development situations (Polson et al, 1992). This technique should be used early in the design process of a user interface; nevertheless, it could also be used on existing user interfaces as an evaluation tool. Cognitive walkthrough focuses upon the usability of an interface, in particular on the ease of learning associated with it. Each task and interface under analysis must be evaluated against a set of criteria. Although originally developed to be used in software engineering, this technique could be used to evaluate an interface in any domain.

The cognitive walkthrough process requires that the analyst "walks" through each user/operator action involved in a task step. The analyst then considers each criterion and the effect that the interface has upon the user's goals and actions.

This method is made up of two phases, namely preparation and evaluation; the first phase involves selecting the set of tasks to analyze and determining the sequence of the tasks. The evaluation phase consists in the analysis of the interaction between the user and the interface, based on the criteria mentioned previously. The analyst should follow these steps:

- Step 1: select tasks to be analyzed. To thoroughly examine the interface in question, an exhaustive set of tasks should be used.
- Step 2: create task descriptions. Each task selected by the analyst must be fully described from the point of view of the final user.
- Step 3: determine the correct sequence of actions. For each of the selected tasks, the appropriate sequence of actions required to complete the task must be specified. An HTA of the task would be useful for this part of the cognitive walkthrough analysis.
- Step 4: identify user population. The analyst should determine the potential users of the interface under analysis and a list of user groups should be created.

- Step 5: describe the user’s initial goals. The final part of phase one of a cognitive walkthrough analysis is to determine and record the user’s initial goals. This is based upon the analyst’s subjective judgement.
- Step 6: analyze the interaction between user and interface. During this step, the analyst should “walk” through each task, applying the criteria mentioned previously.

Advantages:

- The cognitive walkthrough technique has a structured approach to highlight the design flaws of an interface.
- Can be used very early in the design cycle of an interface.
- Designed to be used by non-cognitive psychology professionals.

Disadvantages:

- This method requires further validation from professionals.
- Recorded data may require in depth analysis in order for it to be useful and this may be time consuming for complex tasks.
- A large part of the analysis is based upon the skills of the analyst.

2.3.3 CRITICAL DECISION MAKING (CDM)

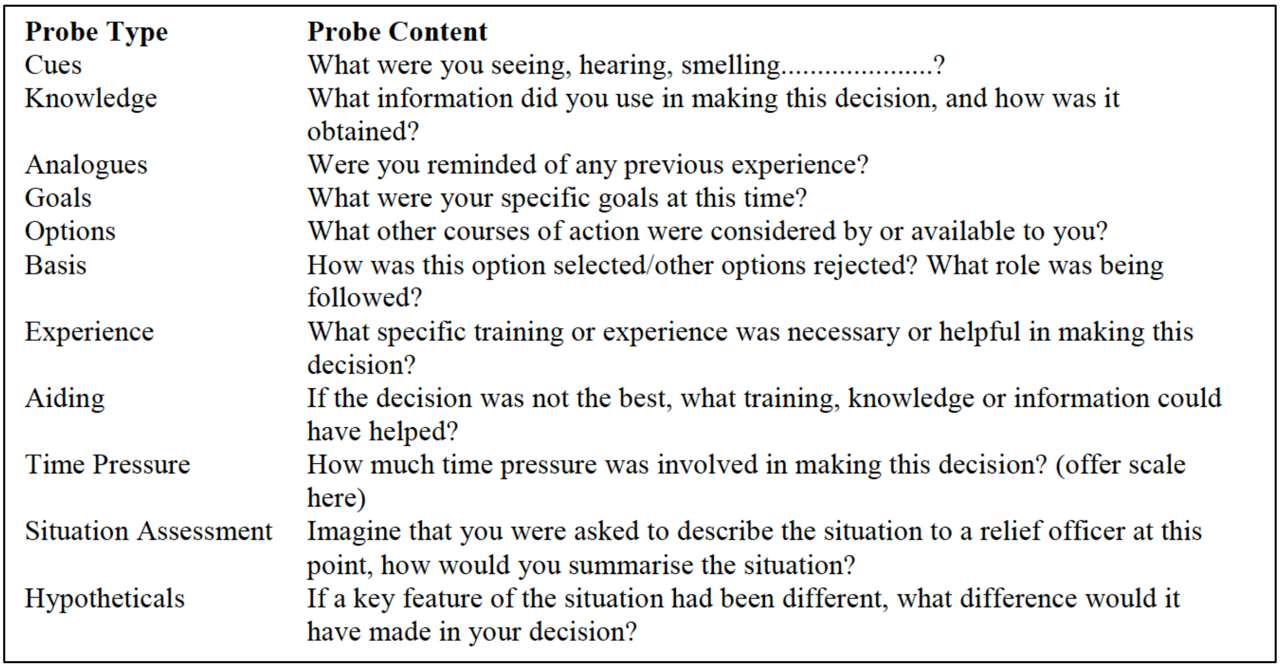
CDM is a semi-structured interview technique that uses a set of cognitive probes in order to elicit information regarding expert decision-making. This technique has been applied to personnel in a number of domains involving complex and dynamic systems, including firefighting, military and paramedics (Klein, Calderwood & MacGregor, 1989).

When conducting a CDM analysis, it is recommended that a pair of analysts participate to it. Furthermore, the process should be recorded using either a video or an audio recording device.

In order to perform a CDM analysis, it is advisable to follow these steps:

- Step 1: select the incident to be analyzed. CDM usually focuses on non-routine incidents, such as emergency scenarios or highly challenging situations. The interviewee involved in the CDM analysis should be the primary decision maker in the chosen scenario.
- Step 2: gather and record data about the incident. The interviewee should be asked to provide a description of the incident in question, starting from its beginning (i.e. alarm) to its end (i.e. when the situation was considered to be "under control").
- Step 3: construct incident timeline. An accurate timeline of the incident under analysis needs to be constructed. The aim of this step is to give the analyst a clear picture of the incident and its associated events, including occurrence time and duration. According to Klein, Calderwood & MacGregor (1989), the events included in the timeline should encompass any physical activity (e.g. hearing the sound of an alarm) and cognitive aspects, such as thoughts and perceptions of the interviewee during the incident. This timeline is useful to increase the analyst's knowledge and awareness of the incident. Furthermore, it focuses the interviewee's attention on each event involved in the incident.
- Step 4: identify decision points. While constructing the timeline, the analysts should select specific decisions of interest for further analysis. Klein, Calderwood & MacGregor (1989) suggest that decision points where other courses of action were available to the operator should be probed further.
- Step 5: probe selected decision points. Each decision point selected in the previous step should be analyzed further using a set of specific probes. The probes that are used are dependent upon the aims of the analysis and the domain in which the incident is embedded. Klein, Calderwood & McGregor (1989) summarized the probes that have been used in CDMs in the past. These probes are given in Table 7.

Table 7: CDM probes, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)



Probe Type	**Probe Content**
Cues	What were you seeing, hearing, smelling....................?
Knowledge	What information did you use in making this decision, and how was it obtained?
Analogues	Were you reminded of any previous experience?
Goals	What were your specific goals at this time?
Options	What other courses of action were considered by or available to you?
Basis	How was this option selected/other options rejected? What role was being followed?
Experience	What specific training or experience was necessary or helpful in making this decision?
Aiding	If the decision was not the best, what training, knowledge or information could have helped?
Time Pressure	How much time pressure was involved in making this decision? (offer scale here)
Situation Assessment	Imagine that you were asked to describe the situation to a relief officer at this point, how would you summarise the situation?
Hypotheticals	If a key feature of the situation had been different, what difference would it have made in your decision?

Advantages:

- CDM can be used to elicit specific information regarding decision making in complex systems.
- This technique requires relatively little effort to be applied.
- The incidents on which the technique concentrates have already occurred, removing the need for costly and time-consuming event simulations. This aspect ensures a more comprehensive and realistic analysis.
- CDM has been extensively used in a number of domains and has the potential to be used anywhere.
- The cognitive probes used in CDM have been employed for several years already and are considered to be efficient at capturing the decision-making processes.

Disadvantages:

- CDM requires a team (minimum of two) of interviewers for each interviewee.
- The reliability of this technique is questionable. Methods that analyze retrospective incidents are associated with concerns of data reliability, due to evidence of memory degradation.
- CDM will never be an exact description of an incident.

- CDM cannot be used to produce analyses useful in design processes.

2.3.4 CRITICAL INCIDENT TECHNIQUE (CIT)

CIT (Flanagan, 1954) is an interview technique that is used to collect specific data regarding incidents or events and relate them to operator’s decisions and undertaken actions. This method was first used to analyze aircraft incidents that almost led to accidents and has been used extensively in the aviation domain.

CIT uses interview techniques allowing the operator to recall critical events or incidents, including what actions or decisions have been made and why.

Although the technique is typically used to analyze incidents involving existing systems, CIT can be used to highlight vulnerable system features or poorly designed processes.

In order to perform a CIT analysis, it is advisable to follow these steps:

- Step 1: select the incident to be analyzed. CIT usually focuses on non-routine incidents, such as emergency scenarios or highly challenging situations. The interviewee involved in the CIT analysis should be the primary decision maker in the chosen scenario. CIT can also be conducted on groups of operators.
- Step 2: gather and record data about the incident. The interviewee should be asked to provide a description of the incident in question, starting from its beginning (i.e. alarm) to its end (i.e. when the situation was considered to be “under control”).
- Step 3: construct incident timeline. An accurate timeline of the incident under analysis needs to be constructed. The aim of this step is to give the analyst a clear picture of the incident and its associated events, including occurrence time and duration. Like we have seen previously with CDM, the events included in the timeline should encompass any physical activity (e.g. hearing the sound of an alarm) and cognitive aspects, such as thoughts and perceptions of the interviewee during the incident. This timeline is useful to increase the analyst’s knowledge and awareness of the incident. Furthermore, it focuses the interviewee’s attention on each event involved in the incident.
- Step 4: select required incident aspects. Once the analyst has an accurate description of the incident, the next step is to select specific incident points that are to be analyzed further. The selected points are dependent upon the

nature and aim of the analysis. For example, if the analysis focuses upon team communication, aspects of the incident related to this topic should be selected.

- Step 5: probe selected decision points. Each decision point selected in the previous step should be analyzed further using a set of specific probes. The probes that are used are dependent upon the aims of the analysis and the domain in which the incident is embedded.

Advantages:

- CIT can be used to elicit specific information regarding decision making in complex systems.
- This technique requires relatively little effort to be applied.
- The incidents on which the technique concentrates have already occurred, removing the need for costly and time-consuming event simulations. This aspect ensures a more comprehensive and realistic analysis.

Disadvantages:

- The reliability of this technique is questionable. Methods that analyze retrospective incidents are associated with concerns of data reliability, due to evidence of memory degradation.
- A high level of expertise and training is required.
- CIT cannot be used to produce analyses useful in design processes.
- CIT relies upon the accurate recall of events.
- Operators may not wish to recall events or incidents in which their performance is under scrutiny.
- Analysts may struggle to obtain accurate descriptions of past events.

CIT was the first interview-type technique focusing upon past events or incidents and other methods, such as CDM, have been developed starting from it.
Assuming the analyst is experienced in interview techniques, the training time for CIT is minimal.

2.4 CRITICAL REVIEW

As discussed in the previous paragraphs, there are many techniques that can be applied when performing a task analysis. The question that arises is the following: which method should be chosen and why? The answer is not straightforward and there are many aspects that need to be evaluated before making a final decision.

Before selecting a method, it is very important that the analyst has in mind the final goal of the analysis. Once the goal is known, the number of applicable techniques reduces since some of them are very specific and can be applied in the analysis of well-defined scenarios.

Another important aspect that has to be considered is the fact that some methodologies can be applied in any domain whilst others cannot; therefore, the domain of application reduces once again the amount of applicable techniques. It is evident, for instance, that if the goal of the analysis is to address the decision process involved in a certain scenario, the method of choice should belong to CTA.

After final goal and domain of application have been considered, there are other aspects to evaluate:

- How much time is available to conduct the analysis and present the results?
- Does the analyst already possess the knowledge to conduct this type of analysis or does he/she need to be trained first?
- How long will the training take to master this technique?
- Does the analyst have an adequate knowledge of the domain of interest in order to understand the task under analysis?
- Will the analyst be able to get in contact with SME to gather relevant data for the analysis?
- Is there any software to support the analyst during his/her work? Does the analyst know how to use the software?

Considering the aim of this work, answers to the previous questions are the following:

- For a beginner, an initial basic training will be required before being able to conduct a TA.
- The initial training should not require too much time before being able to produce a good task analysis.

- Being an aerospace engineer, the knowledge about the domain of interest is adequate to fully understand the task under analysis. Nevertheless, the topic of this work requires some insight from the piloting world and, therefore, certain specific aspects need to be studied.
- The aim of this work is to perform a preliminary analysis of a navigation system, in which the TA is a means to structure and compare the tasks, rather than being used to perform a detailed design. The method should therefore be simple and effective enough in order to fulfill the abovementioned objective.

After pros and cons have been taken into account, it is then possible to make a reasonable choice of which technique should be used to conduct the analysis.
Based on the above explanations, hierarchical task analysis is the method of choice for the aim of this work. HTA allows to break-down the task under analysis through the definition of the single actions that operators need to perform while interacting with a given system. Figure 2.4 summarizes the steps that are required by the HTA:

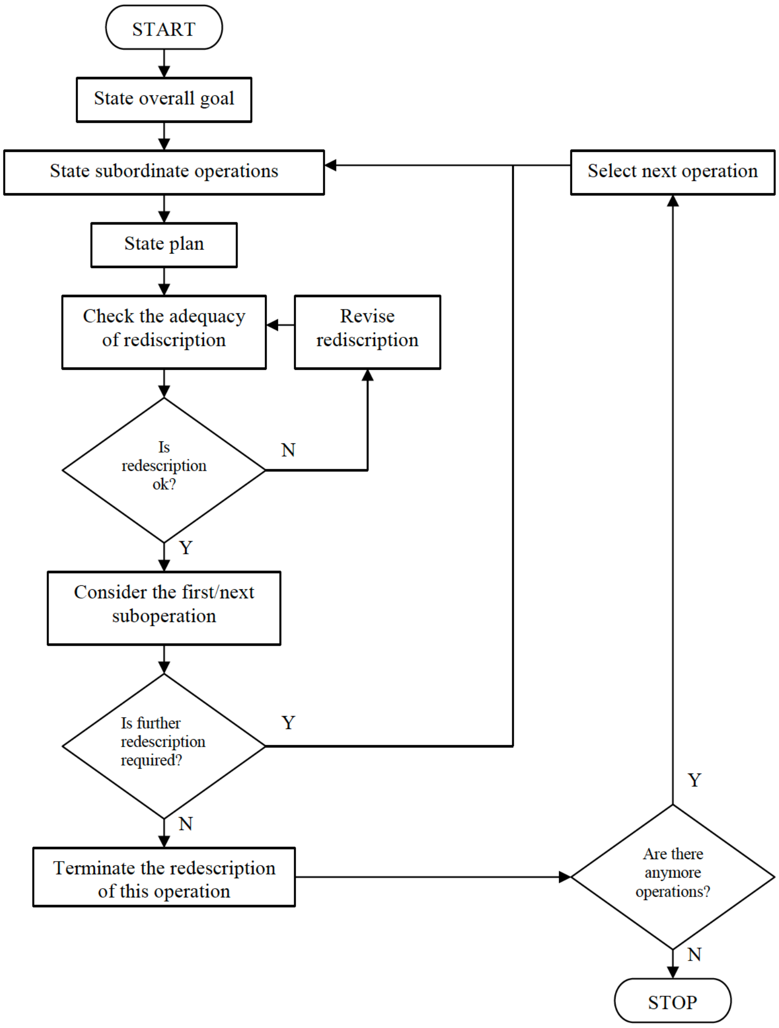


Figure 2.4: HTA flowchart, Human Factors Design Methods Review (P. Salmon, N.A. Stanton, G. Walker, 2003)

3 LEVEL OF AUTOMATION CLASSIFICATIONS

3.1 INTRODUCTION

Before introducing the various scales that can be used to determine the level of automation of a system, it is important to understand what the word automation means. Different definitions have been provided by many authors. Automation can be defined as “*a system or method in which many of the processes of production are automatically performed or controlled by self-operating machines, electronic devices, etc.*” (C. E. Billings, 1996). Another interesting definition is “*automation is the allocation of functions to machines that would be otherwise allocated to humans. The term is also used to refer to the machines which perform those functions. Flight deck automation, therefore, consists of machines on the aircraft flight deck which perform functions otherwise performed by pilots*” (Funk, 1999).

Automation is necessary due to the fact that not all of the functions required for mission accomplishment in today’s complex aircraft are within the capabilities of the unaided human operator, who lacks the sensory capacity to detect much of the information required for flight. Furthermore, the human operator is unable to take certain decisions or make actions based on that information within the time available to accomplish certain critical tasks. Therefore, automation allows to alleviate the pilots from performing tasks that would require increased human attention or effort. From the above definitions, it is a common trait that automation does not exist per se, but it is always used to support/execute tasks performed by human operators; in such a sense, it is a means that, by alleviating the tasks allocated to the operator, modifies the nature of such tasks and, finally, his role within the aircraft under operation.

Another interesting concept is the human-centered automation: “automation *should be designed to work cooperatively with human operators in the pursuit of stated objectives. Automation is considered to be a tool or resource – a device, system or method by which the human can accomplish some tasks that might otherwise be difficult or impossible, or a device or a system which the human can direct to carry out more or less independently a task that would otherwise require increased human attention or effort. The word tool does not foreclose the possibility for the device to have some degree of intelligence - some capacity to learn and then to proceed independently to accomplish a task*” (C. E. Billings, 1996). However, the responsibility for managing and controlling automation and the overall system is retained by the human operator.

According to Billings (1996), three categories of aircraft automation can be described:

- **Control automation:** automation whose functions are the control and direction of an aircraft.
- **Information automation:** automation devoted to the management and presentation of relevant information to flight crew members.
- **Management automation:** automation designed to permit strategic, rather than tactical, control of an operation. When management automation is available, the pilot has the option of acting as a "supervisory controller".

Technology can provide both technical artefacts (tools and means for human problem-solving) and technical agent-based systems (software programs that mimic human properties with behaviors, goals and intentionality). It is the interaction between agent, artefacts and the environmental domains that produces the changes in human roles of interest in the present context. The challenge with new technologies is to understand and predict the influences of these interactions, and the changes that they produce, for future human roles. This understanding is needed so that people remain in control of systems, and for the system functioning to be "human-centric".

Automation is continuously improving in capability, with associated changes in perceptions of appropriate human roles and the suitability of functions for human and/or machine performance. Traditional engineering mostly used the "*left-over*" principle for function allocation, where the technical system was designed to do as much as is feasible from an efficiency point of view, and the rest was left for the operator. HF engineering introduced the *compensatory* principle, where human and machine capabilities are compared on salient criteria and the function allocation is made so that the respective capabilities are used optimally. In 1951, Paul Fitts suggested some simple criteria for allocating functions between people and machines to predict roles in novel air navigation and air traffic control systems (Table 8).

Table 8: Fitt's table, Capability, Cognition and Autonomy (R. M. Taylor, 2002)

What people are better at	What machines are better at
Detecting small amounts of visual, auditory, or chemical energy	Responding quickly to control signals
Perceiving patterns of light or sound	Applying great force smoothly and precisely
Improvising and using flexible procedures	Storing information briefly, erasing it completely
Storing information for long periods of time, and recalling appropriate parts	Reasoning deductively
Reasoning deductively	Doing many complex operations at once
Exercising judgement	

Asking what roles the human can be assigned in future systems, Fitts distinguished among four kinds of control systems:

- Fully automatic control.
- Automatic control with human monitoring.
- Semi-automatic control supplemented by human performance of critical functions.
- Primary control by human operators.

After analyzing issues of alertness, overload, breakdown under stress and human fallibility, Fitts proposed that checking, verifying and monitoring equipment should be devised in ways that make it impossible for a human to violate basic safety rules. As a general rule, Fitts proposed that machines should monitor humans, especially in matters of safety, and prevent them from making serious mistakes. Nevertheless, on the question of who should make decisions, Fitts says that the person who is informed is obviously the best to make decisions.

Automation improves continuously but this comes with risks; increasing automation capability was observed to have the following consequences (Kantowitz and Sorkin, 1987):

- The human must become a monitor of automation, but it is known that humans are poor monitors, unless aided in certain ways.
- Increased automation means increased training requirements.
- Newly automated systems have bugs.
- Failure of automation leads to a loss of credibility and trust.

- Designers tend to not anticipate new problems that automation brings with it.

Different scales and frameworks have been defined with the aim of categorizing the level of automation of a system. A review of a set of recognized scales will be addressed in the following paragraphs of this chapter:

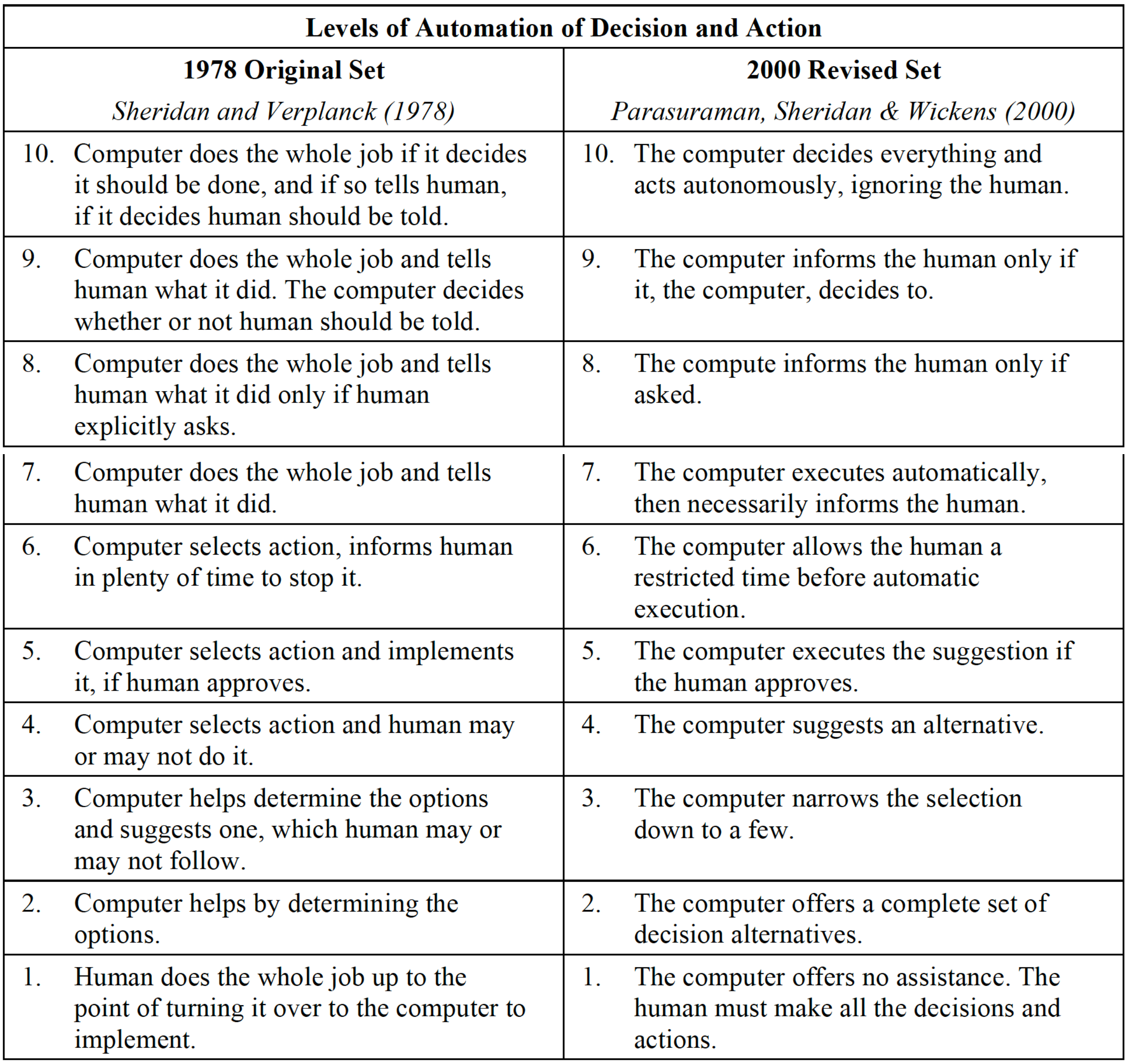
- Sheridan’s original and revised LOA
- ALFUS framework
- Pilot’s associate LOA
- Cognitive cockpit PACT
- Endsley’s LOA

It is noted that the scales analyzed next, sometimes refer to autonomy. Although not considered further along this work, autonomy can be considered as an evolution of an automatic system so that it is capable of making decisions and react to unexpected events without the human intervention.

3.2 SHERIDAN’S ORIGINAL AND REVISED LOA

Sheridan and Verplanck (1978) first proposed 10 possible levels of allocation of decision-making tasks, or levels of automation, between humans and computers. More recently, Parasuraman, Sheridan and Wickens (2000) have considered the application of automation to a four-stage model of independent information processing functions (information acquisition, analysis, decision selection and action implementation). In doing so, they have sought to apply a revised set of LOA. Both the original and revised levels of automation are listed for comparison in Table 9.

Table 9: Sheridan's original and revised LOA, Capability, Cognition and Autonomy (R. M. Taylor, 2002)



Levels of Automation of Decision and Action	
1978 Original Set *Sheridan and Verplanck (1978)*	**2000 Revised Set** *Parasuraman, Sheridan & Wickens (2000)*
10. Computer does the whole job if it decides it should be done, and if so tells human, if it decides human should be told.	10. The computer decides everything and acts autonomously, ignoring the human.
9. Computer does the whole job and tells human what it did. The computer decides whether or not human should be told.	9. The computer informs the human only if it, the computer, decides to.
8. Computer does the whole job and tells human what it did only if human explicitly asks.	8. The compute informs the human only if asked.
7. Computer does the whole job and tells human what it did.	7. The computer executes automatically, then necessarily informs the human.
6. Computer selects action, informs human in plenty of time to stop it.	6. The computer allows the human a restricted time before automatic execution.
5. Computer selects action and implements it, if human approves.	5. The computer executes the suggestion if the human approves.
4. Computer selects action and human may or may not do it.	4. The computer suggests an alternative.
3. Computer helps determine the options and suggests one, which human may or may not follow.	3. The computer narrows the selection down to a few.
2. Computer helps by determining the options.	2. The computer offers a complete set of decision alternatives.
1. Human does the whole job up to the point of turning it over to the computer to implement.	1. The computer offers no assistance. The human must make all the decisions and actions.

3.3 AUTONOMY LEVELS FOR UNMANNED SYSTEMS (ALFUS) FRAMEWORK

The ALFUS is not a specific test or metric, but rather a model of how several different test metrics could be combined to generate an autonomy level. The ALFUS was initially presented at the 2004 International Society for Optics and Photonics (SPIE) Defense and Security Symposium (Huang et al, 2004), and the ALFUS workgroup continues to develop and refine the ALFUS as of writing.

Even though the framework has been developed for Unmanned System (UMS) applications, it is important to describe it because it explicitly refers to the definition of level of automation/autonomy of a complex system and can be tailored to make it applicable to various domains.
ALFUS aims at formulating, through a consensus-based approach, a logical framework for characterizing the UMS autonomy, covering issues of levels of autonomy, mission complexity and environmental complexity. The framework is to provide standard definitions, metrics and processes for the specification, evaluation and development of the autonomous capabilities of the UMSs. The framework is also intended to facilitate communication among the practitioners.

Key definitions were generated in the ALFUS effort to serve as the basis for further framework development:

- **Unmanned System (UMS):** *"A powered physical system, with no human operator aboard the principal components, acts on physical world for the purpose of achieving assigned tasks. May be mobile or stationary. May include any and all associated supporting components. Examples include Unmanned Ground Vehicles (UGV), Unmanned Aerial Vehicles (UAV), Unmanned Underwater Vehicles (UUV), Unmanned Munitions (UM) and Unattended Ground Sensors (UGS)."*

- **Autonomy:** *"A UMS's own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making and acting/executing to achieve its goals as assigned."*

  We further define the stated, integrated "sensing, perceiving, analyzing, communicating, planning, decision-making and acting/executing" as **Root Autonomous Capabilities (RACs)**. Note that the essence of "UMS's own ability" is independent of human interactions.

- **Contextual Autonomous Capability (CAC) model for unmanned systems: "***A UMS's CAC is characterized by the missions that the system is capable of performing, the environments within which the missions are performed and human independence that can be allowed in the performance of the missions. Each of the aspects, or axes, namely Mission Complexity (MC), Environmental*

Complexity (EC) and Human Independence (HI) is further attributed with a set of metrics to facilitate the specification, analysis, evaluation and measurement of the CAC of particular UMSs. This CAC model facilitates the characterization of UMSs from the perspectives of requirements, capability, and levels of difficulty, complexity or sophistication. The model also provides ways to characterize UMS's autonomous operating modes. The three axes can also be applied independently to assess the levels of MC, EC and HI for a UMS."

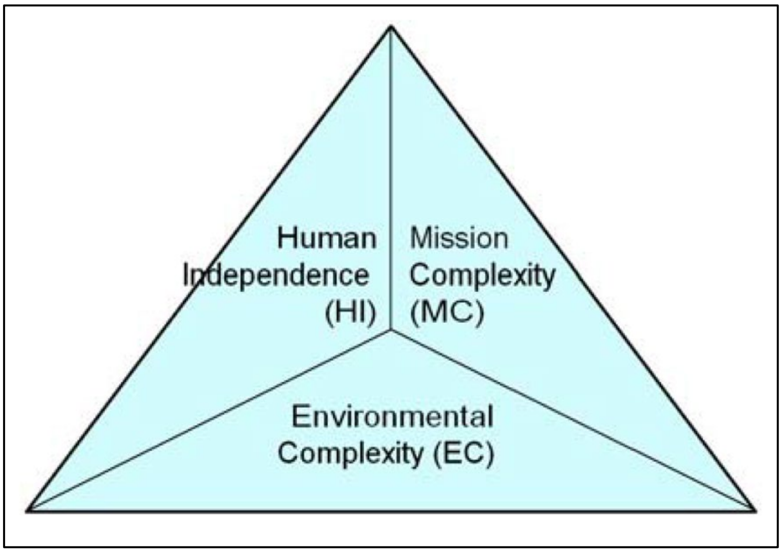


Figure 3.1: The three aspects for ALFUS, ALFUS Framework Volume II (H. Huang, E. Messina, J. Albus, 2007)

- **Level of Autonomy (LOA) or Autonomy Level (AL):** *"A set of progressive indices, typically given in numbers and/or names, identifying a UMS's capability of performing assigned autonomous missions."*

  The autonomy level in ALFUS CAC model refers to the HI aspect or axis, with the other two axes providing the context. The level may be used in a nominal sense while the instantaneous values may be dynamic or adjusting, to the extent of system design, along the course of mission execution depending on the changes in the environmental and operating conditions.

- **High, mid, and low degrees of CAC:** the framework defines the following three CACs to provide a general reference for further CAC investigation.

  - **Highest CAC:** *completes all assigned missions with highest complexity; understands, adapts to, and maximizes benefit/value/efficiency while* *minimizing costs/risks on the broadest scope environmental and operational changes; capable of total independence from operator intervention.*

- **Mid CAC:** *plans and executes tasks to complete an operator specified mission; limited understanding and response to environmental and operational changes and information; limited ability to reduce costs/risks while increase benefit/value/efficiency; relies on about 50% operator input.*
- **Lowest CAC:** *remote control for simple tasks in simple environments.*

These concepts can be further illustrated in Figure 3.2.

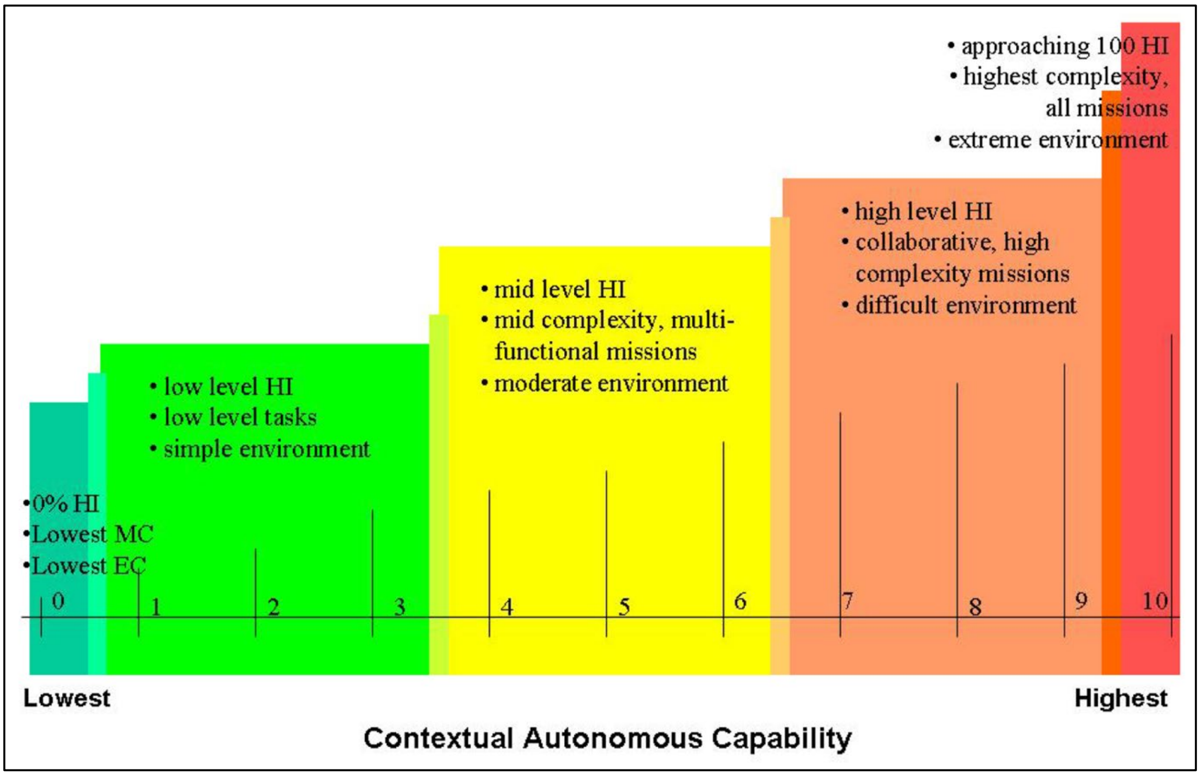


Figure 3.2: CAC illustration, ALFUS Framework Volume II (H. Huang, E. Messina, J. Albus, 2007)

At the leftmost indication, a UMS may operate at the lowest CAC when the UMS performs the simplest mission using Human-Robot Interaction (HRI) 100% of the time in the simplest environment. The general trend may be that CAC increases when the levels of HI, MC, and EC increase, as shown from left to right in the chart.

- **Mode of UMS operation or UMS operational mode:** *"Human operator's ability to interact with a UMS to perform the operator assigned missions. The following are the defined modes of operation: fully autonomous, semi-autonomous, teleoperation, and remote control."*

The CAC definition introduced questions that develop along the framework application, whether related to unmanned or manned systems, and need to be thoroughly understood before the metrics can be developed. The questions are the following:

- What makes a mission complex?
- What makes an environment complex?
- What makes the system human independent?

Being an articulated framework, ALFUS could be applied in the following domains:

- **Defense:** UMSs are well suited for military types of operations. UMSs can replace or support warfighters in extreme operational and environmental conditions.
- **Manufacturing:** robots and unmanned systems can play key roles in manufacturing automation. The challenge is that a manufacturing facility could be very complex and dynamic. Therefore, a framework for performance evaluation and capability characterization could be beneficial.
- **Urban Search and Rescue (US&R):** one of the major concerns in US&R would be the environment. The EC levels might be used to characterize the particular environments. The environments could, in turn, be used to certify UMS for particular US&R operations.
- **Manned aviation automation**

In summary, the ALFUS framework is developed to facilitate articulating, communicating, evaluating, and documenting UMS requirements and capabilities. ALFUS identifies that HI (human independence or levels of autonomy), MC (mission complexity), and EC (environmental complexity) are the three aspects or axes with which the CAC, i.e. contextual autonomous capabilities, for UMSs are specified. Each of the aspects is further elaborated with a set of metrics. The framework is intended to be:

- Generic and covering many UMS domains including air, ground, space, surface, underwater, etc.
- Applicable to the full range of automation, from remote control through full autonomy.
- Extensible, applicable to subsystems, single UMSs, etc.
- Capable of augmenting UMS benefits to human safety and performance enhancement.

3.4 PILOT’S ASSOCIATE LOA

In the 1980’s, the DARPA/USAF Pilot’s Associate (PA) program provided a practical implementation of intelligent pilot aiding based on prime directives and levels of automation. A summary of the PA design approach underpinning the levels of automation is shown in the next page in Table 10. PA design was guided by a top-level operational philosophy based on the pilot being in charge. The goal of the PA was to provide consistently correct information, and to aid the pilot’s decision making by helping to manage workload, reduce confusion, and simplify tasks. This led to the philosophy of the PA as an intelligent subordinate to the pilot, with specific capabilities for decisions and actions.

Table 10: Pilot's associate design approach for LOA, Capability, Cognition and Autonomy (R. M. Taylor, 2002)

Pilot's Associate Design			
Operational Philosophy	**PA Capabilities**	**Operational Relationships**	**Modes for Levels of Autonomy**
The pilot is in charge - i.e. the pilot shall always have the capability to act according to his desires. PA's plans may be: Approved or rejected explicitly with little effort Approved or rejected pre-mission Approved or rejected implicitly by pilot action, or Ignored with predictable results The PA must operate in a predictable manner. The PA is required to monitor the pilot, not the other way around. The PA must notify the pilot of key mission events (as defined and set by the pilot). The effort required of the pilot to control the PA must be less than the effort saved by the PA. PA shall save more effort for the pilot than it creates - it shall be responsive to the pilot and not demanding of his resources.	PA could not act on its own. PA could make recommendations. PA could take actions based on pilot discretion. PA could fly the aircraft tactically on autopilot. PA could take action based on interpreting pilot intent. PA could diagnose malfunctions, identify mis-communications, & determine correct response. PA could deal with ambiguities in human speech in the context of the mission.	OR2. The activity is performed automatically by the PA OR7. PA may perform an action only if various conditions are met. OR6. PA has been given authority to perform, but with pilot consent. OR5. PA may prompt the pilot. OR4. PA may remind the pilot. OR3. PA may remind the pilot, if the pilot asks, or has authorised such. OR1. The pilot must perform the activity	**Associate.** In Associate mode, under full dynamic function allocation (DFA), the proposed system maintains advisory functions and accepts pilot allocated tasks, but also takes over tasks as the context demands. **Assistant.** In Assistant mode, the PA would maintain advisory functions and also assume responsibility for tasks explicitly allocated to it by the pilot. **Advisor** **Standby** **Inactive**

These top levels requirements led to specific Operational Relationships (ORs) for discrete PA sub-functions interactions, with increasing degrees of automation and autonomy. From these ORs, pilot selectable LOA were obtained for groups of functions governed by the required pilot operational relationship and interaction. Five discrete LOA modes were proposed, namely *inactive, standby, advisor, assistant, associate.* Each LOA mode was associated with tailorable functional clusters for flexible responding to avoid too rigid automation imposed by design. These modes were aimed to provide a bounded, communicable structure for delegated levels of authority, minimizing mode confusion, and building trust and confidence. HF research indicates that the required control structure should be cognitively simple, and not complex. Pilots tend to view computer automation simply as automatic (with or without status feedback), semi-automatic telling what will happen and asking permission to proceed or advisory, providing information only.

3.5 COGNITIVE COCKPIT PACT

More recently, the UK MoD *cognitive cockpit* project on technology proof-of-concept, has identified a limited set of four automation assistance levels for integrating knowledge-based decision support with adaptive automation (Taylor et al, 2001). This policy for Pilot Authorization and Control of Tasks, or PACT framework, is used in conjunction with concepts for a *tasking interface manager* whereby mission functions or tasks are assigned for computer automation or computer support. The PACT framework is summarized in Table 11 and illustrated in Figure 3.3.

Table 11: PACT system, Capability, Cognition and Autonomy (R. M. Taylor, 2002)

Primary Modes	Levels	Operational Relationship	Computer Autonomy	Pilot Authority	Adaptation	Information on Performance
AUTOMATIC		**Automatic**	Full	Interrupt	Computer monitored by pilot	On/off Failure warnings Performance only if required.
ASSISTED	**4**	**Direct Support**	Advised action unless revoked	Revoking action	Computer backed up by pilot	Feedback on action. Alerts and warnings on failure of action.
	3	**In Support**	Advice, and if authorised, action	Acceptance of advice and authorising action	Pilot backed up by the computer	Feed-forward advice and feedback on action. Alerts and warnings on failure of authorised action.
	2	**Advisory**	Advice	Acceptance of advice	Pilot assisted by computer	Feed-forward advice
	1	**At Call**	Advice only if requested.	Full	Pilot, assisted by computer only when requested.	Feedforward advice, only on request
COMMANDED		**Under Command**	None	Full	Pilot	None performance is transparent.

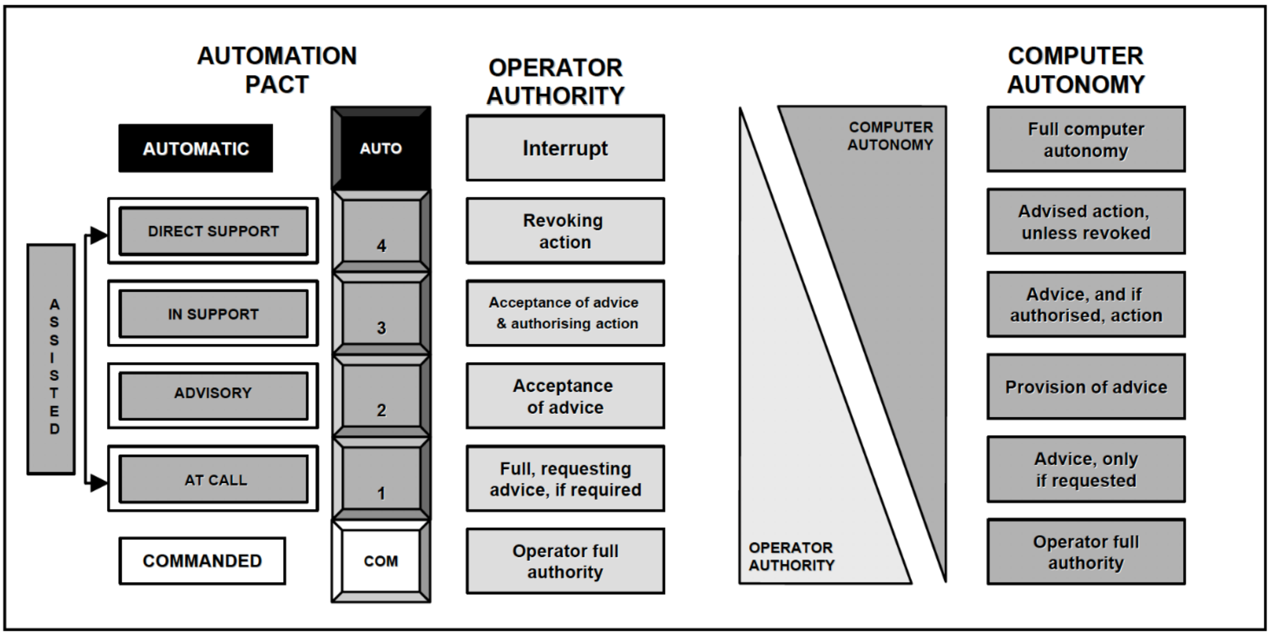


Figure 3.3: Operator authority & computer autonomy, Capability, Cognition and Autonomy (R. M. Taylor, 2002)

The PACT system succeeds in reducing the number of required automation or autonomy modes to three, namely *fully automatic, assisted or pilot commanded,* with a further four secondary levels nested within the semiautomatic assisted mode, which can be changed adaptively or by operator/pilot command.

Mission functions and tasks, at different levels of abstraction allocated individually or grouped in related scripts or plays, can be set to these levels in a number of ways:

- Pre-set operator preferred defaults.
- Operator selection during pre-flight planning.
- Changed by the operator during in-flight re-planning.
- Automatically changed according operator agreed, context-sensitive adaptive rules.

The setting of functions and tasks to PACT levels is described as the creation of personal binding relationships between the operator and the computer. This is to provide the operator with implicit, if not explicit, control and generate trust through understanding of automation functioning.

The PACT system is designed to support the pilot’s cognitive work. The support ranges from providing advice to providing actions.

3.6 ENDSLEY’S LOA

Automated systems have traditionally been explored as binary function allocations: either the human or the machine is assigned to a given task. More recently, intermediary levels of automation have been discussed as a means of maintaining operator involvement in system performance, leading to improvements in situation awareness and reductions in out-of-the-loop performance problems (M. R. Endsley, D. B. Kaber, 1999). A LOA taxonomy applicable to a wide range of cognitive tasks is presented here. The taxonomy comprises various schemes of generic control system function allocations. The functions allocated to a human operator and/or computer included monitoring displays, generating processing options, selecting an “optimal” option and implementing that option.

This taxonomy is composed by ten levels and is intended to have applicability to a wide array of cognitive and psychomotor tasks requiring real-time control within numerous domains including air traffic control, aircraft piloting, advanced manufacturing and teleoperations. All of these domains have many features in common, including:

1. Multiple competing goals.
2. Multiple tasks competing for an operator’s attention, each with different relevance to system goals.
3. High task demands under limited time resources.

Four generic functions intrinsic to these domains have been identified:

1. **Monitoring** – scanning displays to perceive system status.
2. **Generating** – formulating options or strategies for achieving goals.
3. **Selecting** – deciding on a particular option or strategy.
4. **Implementing** – carrying out the chosen option.

Ten levels of automation have been formulated by assigning these functions to the human or computer or a combination of the two, as shown in the taxonomy depicted in the next page in Table 12.

Table 12: Endsley's hierarchy of levels, LOA effects on performance, SA and workload in a dynamic control task (M. R. Endsley, D. B. Kaber, 1999)

Roles Level of automation	Monitoring	Generating	Selecting	Implementing
(1) Manual Control (MC)	H	H	H	H
(2) Action Support (AS)	H/C	H	H	H/C
(3) Batch Processing (BP)	H/C	H	H	C
(4) Shared Control (SHC)	H/C	H/C	H	H/C
(5) Decision Support (DS)	H/C	H/C	H	C
(6) Blended Decision Making (BDM)	H/C	H/C	H/C	C
(7) Rigid System (RS)	H/C	C	H	C
(8) Automated Decision Making (ADM)	H/C	H/C	C	C
(9) Supervisory Control (SC)	H/C	C	C	C
(10)Full Automation (FA)	C	C	C	C

Key: H “Human”, C “Computer”

The ten levels are (M. R. Endsley, D. B. Kaber, 1999):

1. **Manual Control (MC)** – the human performs all tasks including monitoring the state of the system, generating performance options, selecting the option to perform (decision making) and physically implementing it.
2. **Action Support (AS)** – at this level, the system assists the operator with performance of the selected action, although some human control actions are required.
3. **Batch Processing (BP)** – although the human generates and selects the options to be performed, they then are turned over to the system to be carried out automatically. The automation is, therefore, primarily in terms of physical implementation of tasks. Many systems that operate at this fairly low level of automation exist, such as batch processing systems in manufacturing operations or cruise control on a car.
4. **Shared Control (SHC)** – both the human and the computer generate possible decision options. The human still retains full control over the selection of which option to implement; however, carrying out the actions is shared between the human and the system.
5. **Decision Support (DS)** – the computer generates a list of decision options that the human can select from or the operator may generate his/her own options.

Once the human has selected an option, it is turned over to the computer to implement. This level is representative of many expert systems or decision support systems that provide option guidance, which the human operator may use or ignore in performing a task. This level is indicative of a decision support system that is capable of also carrying out tasks, while the previous level (SHC) is indicative of one that is not.

6. **Blended Decision Making (BDM)** – at this level, the computer generates a list of decision options that it selects from and carries out if the human consents. The human may approve of the computer's selected option or select one from among those generated by the computer or the operator. The computer will then carry out the selected action. This level represents a higher-level decision support system that is capable of selecting among alternatives as well as implementing the second option.
7. **Rigid System (RS)** – this level is representative of a system that presents only a limited set of actions to the operator. The operator's role is to select from among this set. He/she may not generate any other options. This system is, therefore, fairly rigid in allowing the operator little discretion over options. However, it will fully implement the selected actions.
8. **Automated Decision Making (ADM)** – at this level, the system selects the best option to implement and carry out that action, based upon a list of alternatives it generates (augmented by alternatives suggested by the human operator). This system, therefore, automates decision making in addition to the generation of options (as with decision support systems).
9. **Supervisory Control (SC)** – at this level the system generates options, selects the option to implement and carries out that action. The human mainly monitors the system and intervenes if necessary. Intervention places the human in the role of making a different option selection (from those generated by the computer or one generated by the operator), thus effectively shifting to the decision support LOA. This level is representative of a typical supervisory control system in which human monitoring and intervention, when needed, is expected in conjunction with a highly automated system.
10. **Full Automation (FA)** – at this level, the system carries out all actions. The human is completely out of the control loop and cannot intervene. This level is representative of a fully automated system where human processing is not deemed to be necessary.

It should be stated that the shown taxonomy represents a range of feasible assignments of the four functions of system(s) monitoring, and options generation, selection and implementation to human, computer and human/computer combinations. While it may be possible to conceive of certain combinations that are not specifically listed here, these were not deemed to be either technically or practically feasible (e.g. it is difficult for either the human or machine to perform any task without directly monitoring the state of the system or inputs from the other); however, other combinations cannot be completely ruled out.

3.7 CRITICAL REVIEW

In the previous paragraphs, several models have been proposed for assessing overall system performance as a function of level of automation. In general, automation/autonomy level frameworks can be divided into two general categories: contextual, i.e. those methods that take into account the system's mission and operational environment, and non-contextual, i.e. those methodologies that do not consider outside factors.

The most commonly referenced contextual model for assessing autonomous performance is the ALFUS framework. The complete model was primarily envisioned to satisfy the need of accurately assessing the autonomy level of a UMS. It uses the three-axis method of the contextual autonomous capability model. Each axis refers to a metric group, which can be MC, EC or HI. For a given mission and environment, metrics are measured and combined to form a level of automation/autonomy. However, this methodology still has some drawbacks that prevent its direct implementation. ALFUS does not provide the tools to:

- Decompose the tasks in a commonly agreed-upon, standard way.
- Assess the interdependency between the metrics, as some of the subtasks can apply to more than one metric.
- Allow metrics to be standardized in scoring scales: this will cause subjective evaluation and criteria to influence the results across different users or competing companies.
- Integrate the metrics for a concise set of indices for the autonomy levels.

While the ALFUS framework is continuing to be refined and applied to a limited extent, progress has been slow, and many challenges still remain to be addressed before the ALFUS can become a useful measure of LOA. These shortcomings of the ALFUS suggest that, for the aim of this work, it would be better to use a simpler non-contextual automation levels framework.

A simpler method for allocating a system's (e.g. UMS or manned platform) autonomy/automation level is desirable, because such allocation could be derived without first performing extensive operational-level assessment.

What is needed for the analysis object of this work, in order to allocate a level of automation, is a general scale that can be applied to various tasks or actions. PACT and PA designs are interesting concepts but the number of levels that they propose might be limiting for characterizing in detail a specific function.

Endsley's taxonomy provides several advantages in that it considers a wide range of options describing the way in which core functions can be divided between a human and a computer to achieve task performance. The functions it is based upon are generic enough to be applicable to a wide variety of domains and task types. The levels listed in the taxonomy represent a means of systematically examining the effect of automation, as implemented incrementally, on different aspects of a central task.

For the analysis object of this work, Sheridan's revised scale could be a valid candidate to allocate a LOA to the different tasks but, for all the above-mentioned reasons, Endsley's taxonomy is considered to be the most appropriate to support this work.

4 DESCRIPTION OF AIRCRAFT NAVIGATION SYSTEMS AND SCENARIO BASED HTA

The aim of this chapter is to outline the results of a task analysis related to a navigation system, and in particular to the Flight Management System (FMS). In order to achieve this goal, in the first part of the chapter basic notions of air navigation techniques, together with a brief introduction regarding the FMS, are reviewed. Given the complexity of the FMS, it has been decided to focus the analysis on a number of operational scenarios: the second part of this chapter provides their detailed description. Next, after explaining the framework used to perform the analysis, the main results of the HTA will be outlined.

4.1 CONCEPTS OF AIR NAVIGATION TECHNIQUES

Navigation has been an ever-present component of humankind's exploitation of the capability of flight. While the principles of navigation have not changed since the early days of sail, the increased speed of flight, particularly with the advent of the jet age, has placed an increased emphasis upon accurate navigation.

Navigation consists of a complex sequence of activities performed both pre-flight and during flight allowing to get safely from a departure to an arrival location while separating from other traffic, reducing trajectory deviations, keeping tight flight plan schedules and maximizing fuel efficiency. This section summarizes some of the modern methods of navigation, leading to more detailed descriptions of how each technique operates. The main methods of navigation as practiced today may be summarized as follows:

- **Radio navigation** using navigation aids - ground-based radiofrequency beacons and airborne receiving and processing equipment.
- **Inertial navigation** using a combination of air data and Inertial Navigation (IN) or Doppler.
- **Satellite navigation** using a Global Navigation Satellite System (GNSS), more usually a Global Positioning System (GPS).
- **Multiple-sensor navigation** using a combination of all the above.

The basic navigation parameters are shown in Figure 4.1 and may be briefly summarized as follows:

1. An aircraft will be flying at a certain altitude relative to a barometric datum (barometric altitude) or terrain (radar altitude).
2. The aircraft may be moving with velocity components in the aircraft $X(V_x), Y(V_y)\ and\ Z(V_z)$ axes. Its speed through the air may be characterized as Indicated Airspeed (IAS) or Mach number (M). Its speed relative to the ground is determined by the Ground Speed (GS).
3. The aircraft will be flying on a certain heading; however, the prevailing wind speed and direction will modify this to the aircraft track. The aircraft track represents the aircraft path across the terrain and will lead to the destination or next waypoint of the aircraft.
4. The aircraft heading will be defined by a bearing to magnetic (compass) north or to true north relating to earth-related geographic coordinates.
5. The aircraft will be flying from its present position, defined by latitude, longitude and altitude, to a waypoint also characterized by latitude and longitude.
6. A series of flight legs, defined by waypoints, will determine the aircraft designated flight path from the departure airfield to the destination airfield.

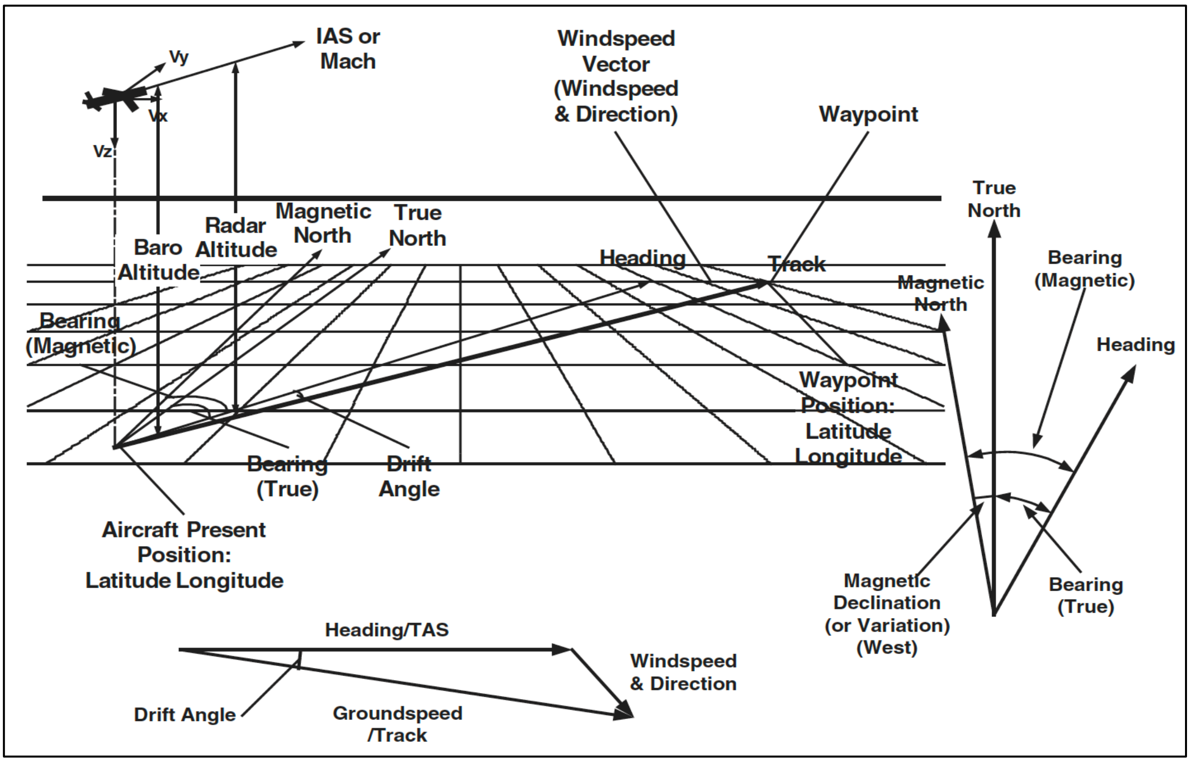


Figure 4.1: Basic navigation parameters, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

The classic method of navigation which has been used for many years is to use a combination of magnetic and inertial directional gyros used together with airspeed information derived from the air data sensors to navigate in accordance with the parameters shown in Figure 4.1. This is subjected to errors mainly related to the effects of en-route winds which can cause along-track and across-track errors. In the 1930s it was recognized that the use of radio beacons and navigation aids could significantly reduce these errors by providing the flight crew with navigation assistance related to precise points on the ground. In the following, the different methods of navigation will be described.

- **Radio navigation**
  Since the 1930s, the primary means of navigation over land was by means of radio aids that evolved in VHF Omni-Ranging/Distance Measuring Equipment (VOR/DME) beacons as shown in Figure 4.2. By arranging the location of these beacons at major navigation or crossing points, and in some cases airfields, it was possible to construct an entire airway network that could be used by the flight crew to define the aircraft flight from takeoff to touchdown. Other radiofrequency aids include DME and Non-Directional Beacons (NDB).

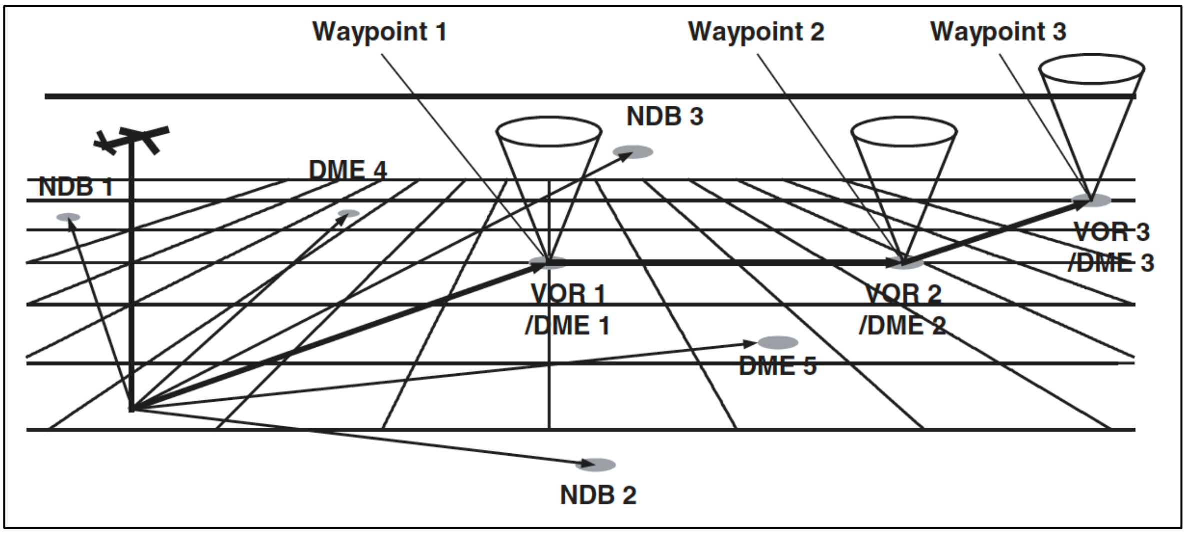


Figure 4.2: Radio navigation using VOR/DME, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

Figure 4.2 shows:

1. Three VOR/DME beacon pairs: VOR 1/DME 1, VOR 2/DME 2 and VOR 3/DME 3 which define waypoints 1 to 3. These beacons represent the intended waypoints 1, 2 and 3 as the aircraft proceeds down the intended flight plan route, most likely an identified airway. When correctly tuned, the VOR/DME pairs automatically so to present the flight crew with bearing to and distance from the next waypoint.
2. Off-route DME beacons, DME 4 and DME 5, may be used as additional means to locate the aircraft position by means of the DME fix obtained where the two DME 4 and DME 5 range circles intersect.
3. Off-route NDB beacons may be used as an additional means to determine the aircraft position by obtaining a cross-fix from the intersection of the bearings from NDB 1 and NDB 2.

A major limitation of the radio beacon navigation technique results from line-of-sight propagation limitations at the frequencies at which both VOR and DME operate. This navigation technique, still available nowadays, is therefore, mainly usable overland or in regions where the beacon coverage is sufficiently comprehensive. The referred issue was tackled in the past by introducing low frequency radio beacons (e.g. LORAN or OMEGA) that did allow long range navigation: their usage was however complex and did not allow to achieve very precise positioning. The advent of satellite-based navigation systems brought to their complete dismissal.

- **Inertial navigation**

  In the 1960s, the availability of Inertial Navigation Systems (INS) to the aviation community added another dimension (i.e. time) to the navigation equation. Flight crew were able to navigate by autonomous means using an onboard INS with inertial sensors. The principles of inertial navigation depend upon the arrangement of inertial sensors such as gyroscopes and accelerometers in a predetermined orthogonal axis set. The gyroscopes may be used to define attitude or body position and rates. The output from the accelerometer sensor is integrated to provide velocities, and then integrated again to provide travelled distance. First in the military field and then in commercial marketplace, inertial navigation systems became a preferred method for achieving long-range navigation. For reasons of both availability and accuracy, systems were developed with dual and triple INS installations.

By aligning the platform to earth-referenced coordinates and present position during initialization, it was then possible to fly for long distances without relying upon VOR/DME beacons. Waypoints could be specified in terms of latitude and longitude as arbitrary points on the globe, more suited to the aircraft's intended flight path rather than a specific geographic feature or point in a radio beacon network (Figure 4.3).

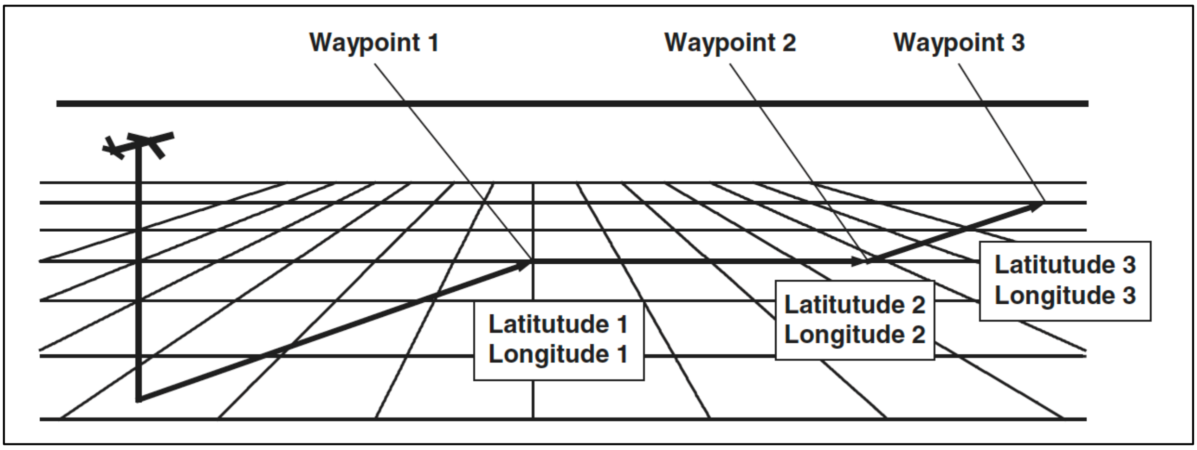


Figure 4.3: Fundamentals of inertial navigation, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

There are limitations on the latitudes at which the ground alignment could be performed – 76° north or south – as attaining satisfactory alignment becomes progressively more difficult due to the significant increase in magnetic variation occurring near the poles. Furthermore, despite being accurate in short term, IN accumulates errors over time and requires to be re-aligned; this issue impacts long-range flights.

- **Satellite navigation**

  Global navigation techniques came into being from the 1980s through the 1990s when satellites became commonly available. The use of global navigation satellite systems, to use the generic name, offers a cheap and accurate navigational means to anyone who possesses a suitable receiver. Although the former Soviet Union developed a system called GLONASS and the European Union developed the GALILEO, it is the US GPS that is most widely used. GPS is a US satellite-based radio navigational, positioning and time reference system operated by the Department of Defense (DoD). The system provides highly accurate position and velocity information and precise time on a continuous global basis to an unlimited number of properly equipped users. The system is unaffected by weather and provides a worldwide common grid reference system based on the earth-fixed coordinate system. The principles of satellite navigation using GPS are illustrated in Figure 4.4.

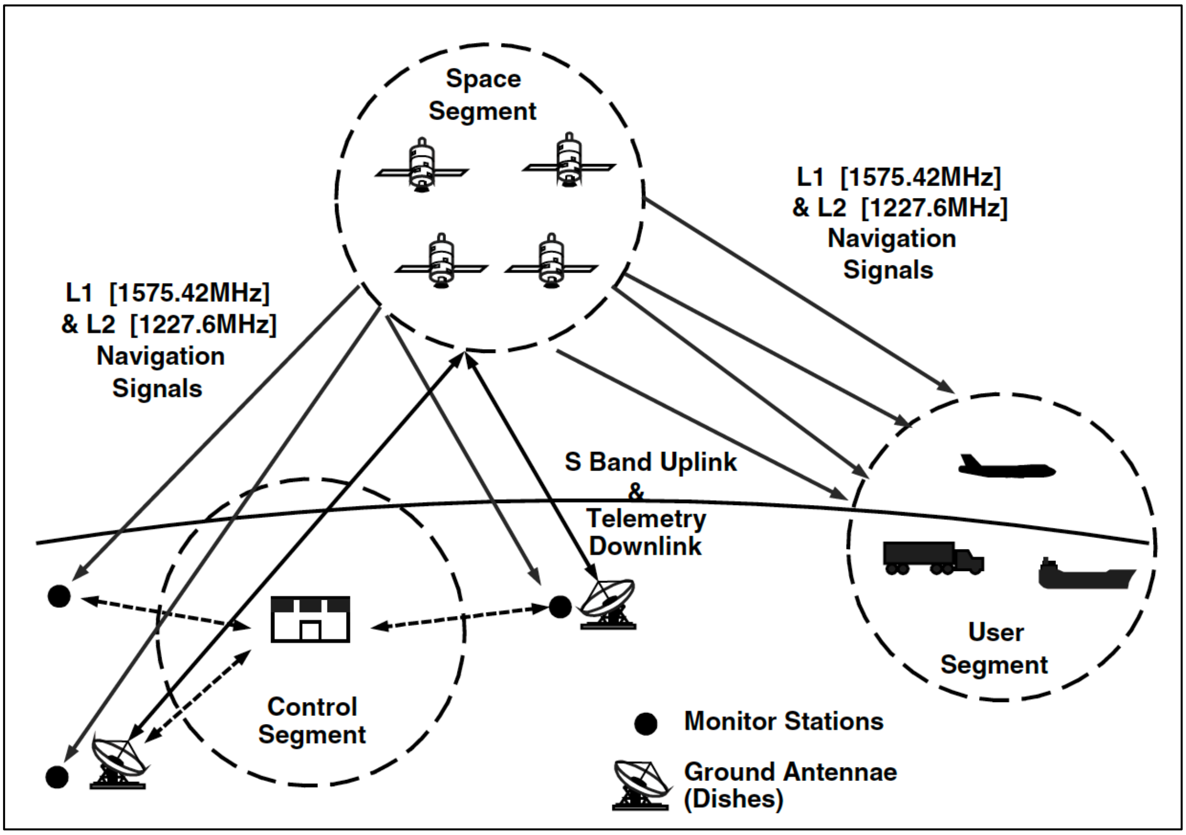


Figure 4.4: Principles of GPS satellite navigation, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

GPS comprises three major components as characterized in the figure:

1. The **control segment** embraces the infrastructure of ground control stations, monitor stations and ground-based satellite dishes that exercise control and maintenance over the system.
2. The **space segment** includes the satellite constellation that forms the basis of the network.
3. The **user segment** includes all the users: ships, trucks, automobiles, aircraft and hand-held sets. In fact, anyone in possession of a GPS receiver is part of the user segment.

GPS operation is based on the concept of ranging and triangulation from a group or constellation of satellites in space which act as precise reference points. A GPS receiver measures distance from a satellite using the travel time of a radio signal. Each satellite transmits specific codes (or portions of them), namely Coarse/Acquisition (CA) and Precision (P), which contain information on the position of the satellite, the GPS system time and the health and accuracy of the transmitted data. Knowing the speed at which the signal travelled and the exact broadcast time, the distance travelled by the signal can be computed from the arrival time. The receiver uses data from a minimum of four satellites in direct line of sight. GPS receivers match the CA code of each satellite with an identical copy of the code contained in the receiver database. By shifting its copy of the satellite code in a matching process, and by comparing this shift with its internal clock, the receiver can calculate how long it took the signal to travel from the satellite to the receiver (pseudorange). Each satellite transmits information about its exact orbital location and the GPS receiver uses the latter to precisely establish the position of the satellite. Using the calculated pseudorange and position information supplied by the satellite, the GPS receiver mathematically determines its position by triangulation. The GPS receiver needs at least four satellites to yield a three-dimensional position (latitude, longitude and altitude) and time solution. A major drawback of this technology is the noisy nature of the signal in the acquisition phase.

- **Multiple-sensor navigation**

  Integrated navigation, as the name suggests, employs all the features and systems described so far. An integrated navigation solution using a multi-sensor approach blends the performance of all the navigation techniques already described together with GPS to form a totally integrated system. In this case, the benefits of the GPS and IN derived data are blended to provide more accurate data fusion, in the same way as barometric and IN data are fused (Figure 4.5). A key prerequisite to achieving a multi-sensor system is the installation of a high-grade flight management system to perform the integration of all the necessary functions and provide a suitable interface with the flight crew.

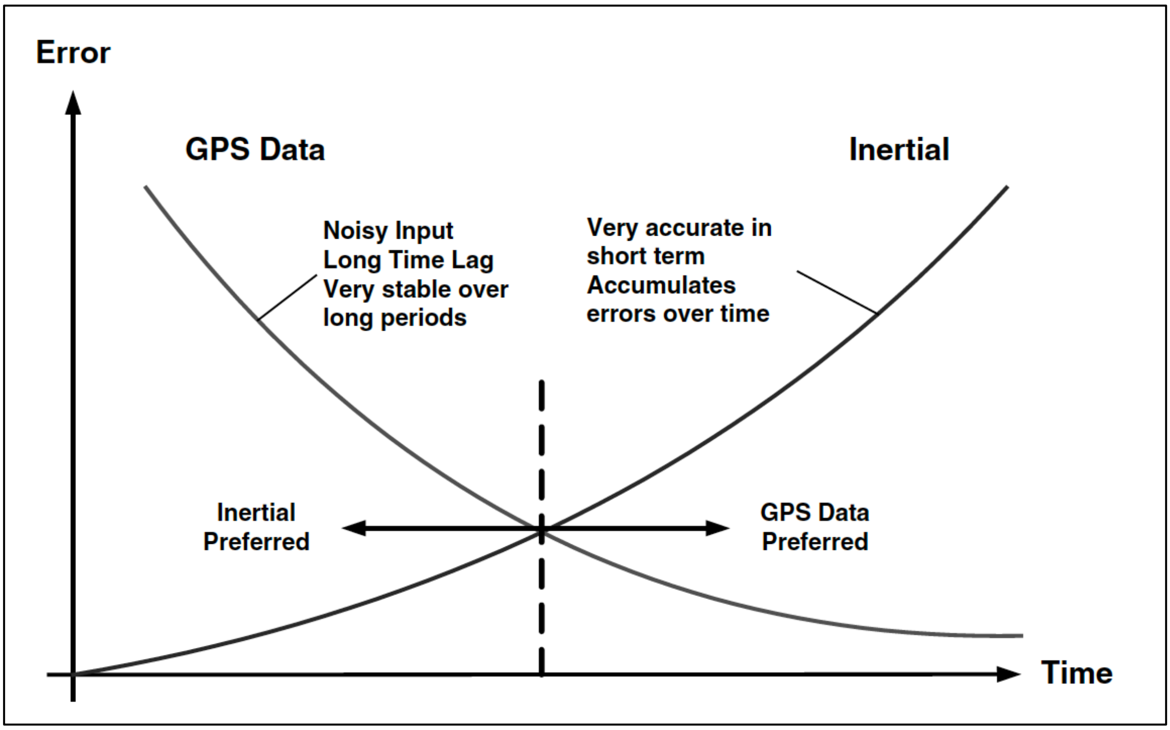


Figure 4.5: Integrated GPS and inertial navigation, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

Integrated navigation allowed the introduction of the Performance-Based Navigation (PBN) concept. PBN aims to ensure global standardization of RNAV (Area Navigation) and RNP (Required Navigation Performance) specifications and to limit the proliferation of navigation specifications in use world-wide. PBN can be defined as "*area navigation based on performance requirements for aircraft operating along an ATS route, on an instrument approach procedure or in a designated airspace".*

4.2 FLIGHT MANAGEMENT SYSTEM

In order to facilitate the execution of the navigation task, and thanks to the advent of digital computers, from the 1970s the FMS has been introduced and continuously developed. FMS functionality can be summarized in:

- **LNAV** – the ability to navigate laterally in two dimensions.
- **VNAN** – the ability to navigate laterally in two dimensions plus the ability to navigate in the vertical plane. When combined with LNAV, this provides three-dimensional navigation.

- **Four-dimensional navigation** – the ability to navigate in three dimensions plus the addition of time constraints for the satisfaction of time arrival at a waypoint.
- **Full performance-based navigation** – the capability of four-dimensional navigation together with the addition of an aircraft specific performance model. By using cost indexing techniques, full account may be made of the aircraft performance in real time during flight, allowing optimum use of fuel and aircraft energy to achieve the necessary flight path.

The development of the FMS went along with the evolution of the processing capability of the avionics and has been mainly based on:

- Added functionalities to improve flight's efficiency.
- Improvement of the HMI based on many years of experience or even errors.

A typical FMS will embrace dual computers and dual Multifunction Control and Display Units (MCDUs) as shown in Figure 4.6. In transport aircraft the system implementation is likely to be in the form portrayed in this figure. For military fighter aircraft the functions will be similar but embedded in the avionics system navigation computers and mission computers in accordance with peculiar operational requirements. Figure 4.6 is key to depicting the integration of the navigation functions described above.

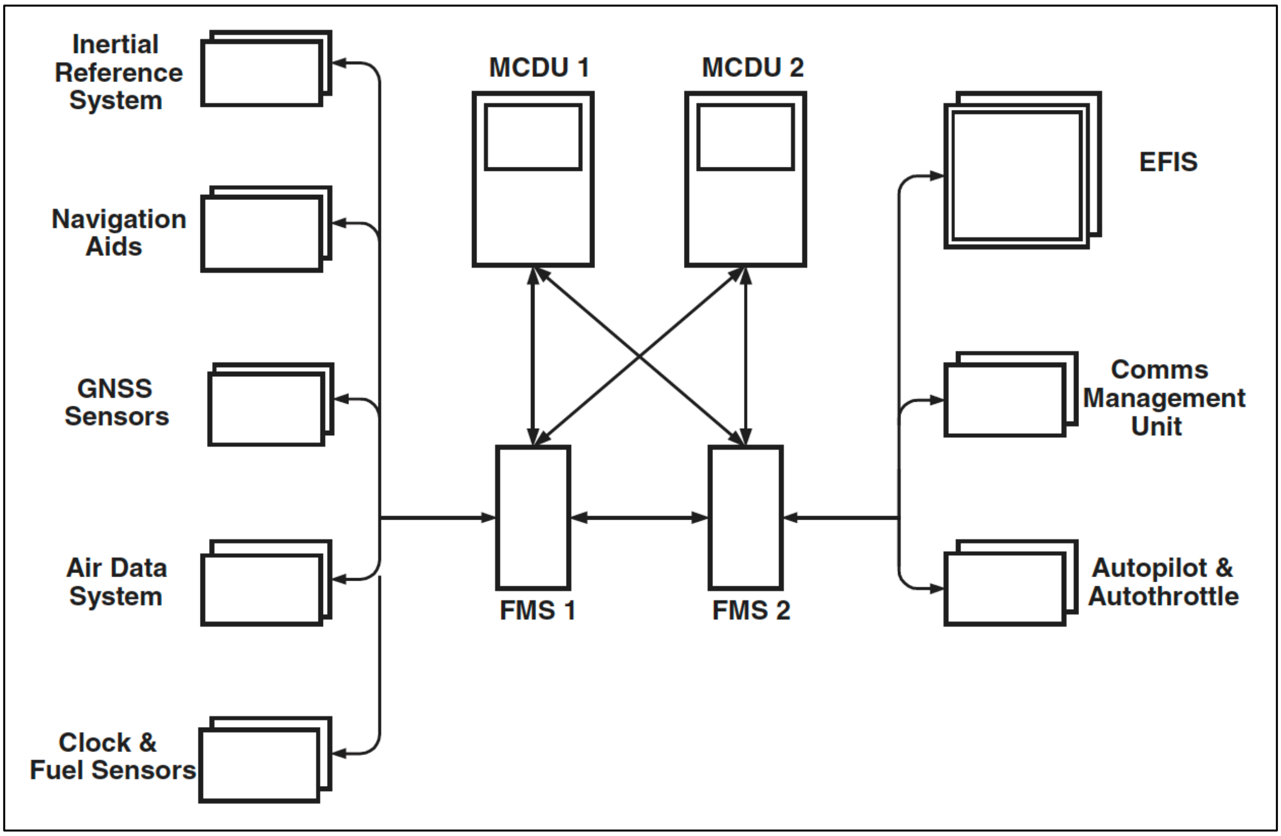


Figure 4.6: Typical FMS, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

System sensor inputs, usually in dual-redundant form for reasons of availability and integrity are shown on the left. These are:

- Dual INS/IRS (Inertial Reference System).
- Dual navigation sensors: VOR/DME, DME/DME, etc.
- Dual GNSS sensors – usually GPS.
- Dual air data sensors.
- Dual inputs from onboard sensors relating to fuel and time.

These inputs are used by the FMS to perform necessary navigation calculations and provide information to the flight crew via a range of display units:

- Electronic Flight Instrument System (EFIS).
- Communications control system.
- Interface with the autopilot/flight director system to provide the flight crew with flight direction or automatic flight control in a number of predefined modes.

The FMS-crew interface typical of a civilian aircraft implementation is shown in Figure 4.7.

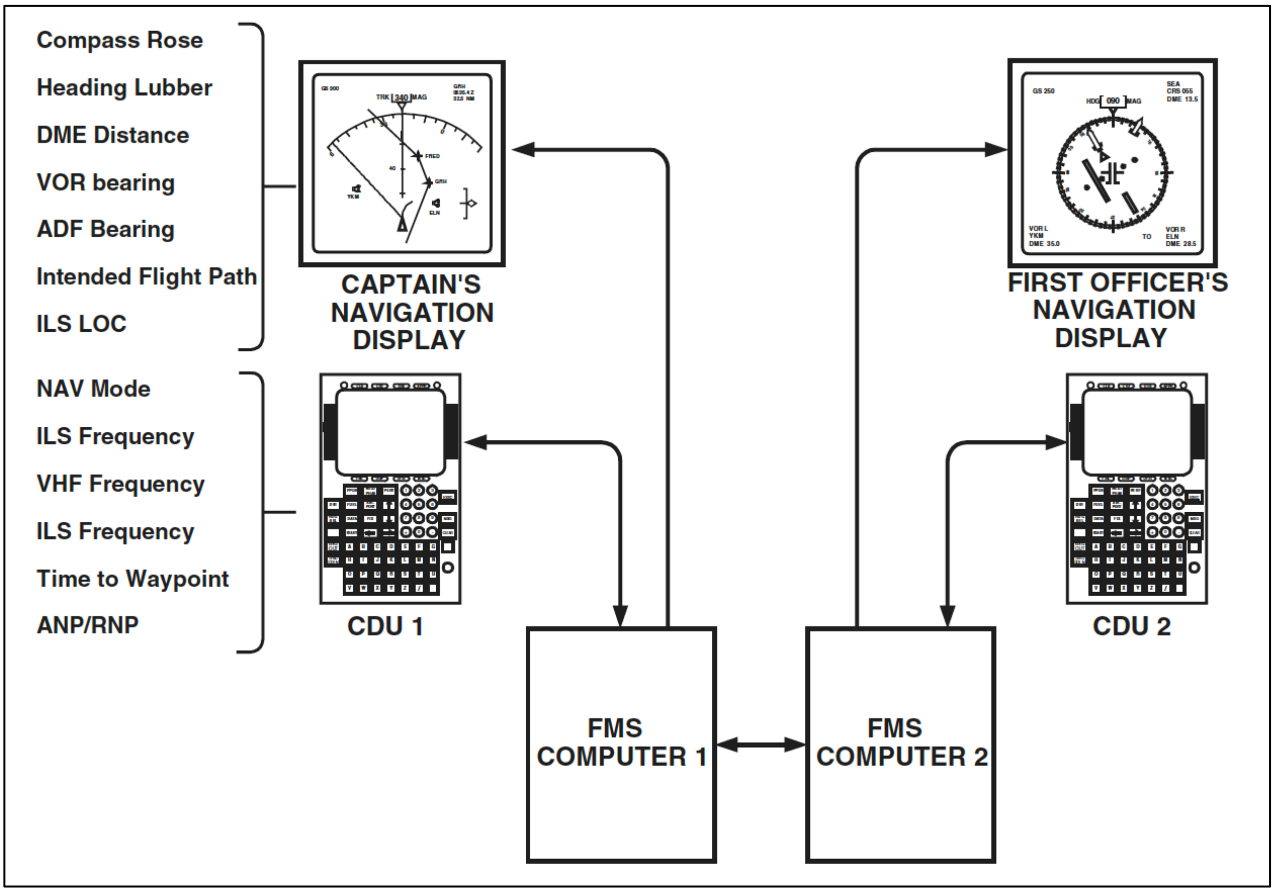


Figure 4.7: FMS control and display interface, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

The key interface with the flight crew is via the following displays:

- Captain’s and first officer’s Navigation Displays (NDs), part of the EFIS. These are color displays that provide the pilots with phase of flight-dependent navigation and steering information necessary to fly the intended route.
- Multifunction control and display units 1 and 2, part of the FMS. Both MCDUs display information and act as means for the flight crew to manually enter data.

The FMS computers perform all the necessary computations and show the appropriate navigation and performance parameters on the appropriate display.
The functions of the FMS at a top level are shown in Figure 4.8. These may be summarized as follows:

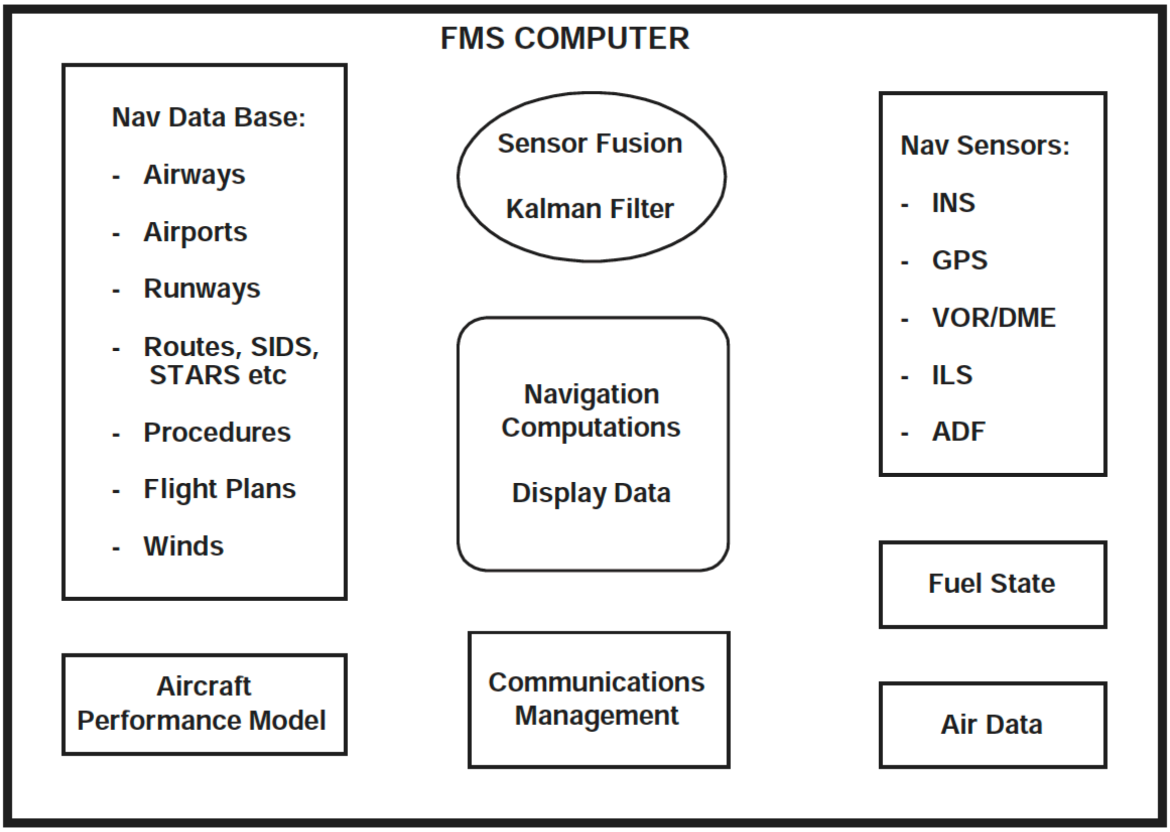


Figure 4.8: Top-level FMS functions, Military Avionics Systems (I. Moir & A. G. Seabridge, 2006)

1. Navigation computations and display data. All the necessary navigation computations are undertaken to derive the navigation or guidance information according to the phase of flight and the employed sensors. This information is displayed on the EFIS navigation display or the FMS CDU.
2. Navigation sensors. INS, GPS, VOR, ILS, ADF, TACAN and other navigation aids provide dual sensor (i.e. redundant) information to be used for various navigation modes.
3. Air data. The Air Data Computers (ADCs) provide the FMS with high-grade corrected air data parameters and attitude information for use in the navigation computations.
4. Fuel state. The fuel quantity measurement system and the engine-mounted fuel flowmeters provide information on the aircraft fuel quantity and engine fuel flow. The calculation of fuel use and total fuel consumption is used to derive aircraft and engine performance during the flight. When used together with a full aircraft performance model, optimum flight guidance may be derived.

5. Sensor fusion and Kalman filter. The sensor information is fused and validated against other sources to determine the validity and degree of fidelity of the data. By using a tailored Kalman filter, the computer is able to determine the accuracy and integrity of the navigation sensor and navigation computations and determine the actual navigation performance (ANP) of the system in real time.
6. Communications management. The system passes information to the communication control system regarding the communication and navigation aid channel selections that have been initiated by the FMS in accordance with the requirements of the flight plan.
7. Navigation database. The navigation base contains a wide range of data that are relevant to the flight legs and routes the aircraft may expect to use. This database will include the normal flight plan information for standard routes that the aircraft will fly together with normal diversions. It will be regularly updated and maintained. A comprehensive list of these items includes:

    a) Airways;
    b) Airports – approach and departure information, airport and runway lighting, obstructions, limitations, airport layout, gates, etc.;
    c) Runways including approach data, approach aids, category of approach and decision altitudes;
    d) Routes, clearance altitudes, Standard Instrument Departures (SIDs), Standard Terminal Arrival Routes (STARSs) and other defined navigation data;
    e) Procedures including notification of short-term airspace restrictions or special requirements;
    f) Flight plans with standard diversions;
    g) Wind data – forecast winds and actual winds derived throughout flight.

8. Aircraft performance model. The inclusion of a full performance model adds to the system's ability to compute four-dimensional (*x, y, z, time)* flight profiles and at the same time make optimum use of the aircraft energy to optimize fuel consumption. By using the aircraft velocity and other dynamic parameters, it is possible to compute the performance of the aircraft over very small-time increments. By using this technique, and provided that the sensor data are sufficiently accurate, the future dynamic behavior of the

aircraft may be accurately predicted. Using this feature and knowing the four-dimensional trajectory and gate speeds that are detailed in the flight plan, the aircraft can calculate the optimum trajectory to meet all these requirements.

The FMS provides the essential integration of all of these functions to ensure that the overall function of controlling the navigation of the aircraft is attained. The flight plan that resides within the FMS memory will be programmed for the entire route profile, for all eventualities, including planned diversions.

The FMS MCDU is the key flight crew interface with the navigation system, allowing the flight crew to enter data as well as having vital navigation information displayed. Figure 4.9 is an example of an MCDU installed on the Airbus A320-200.

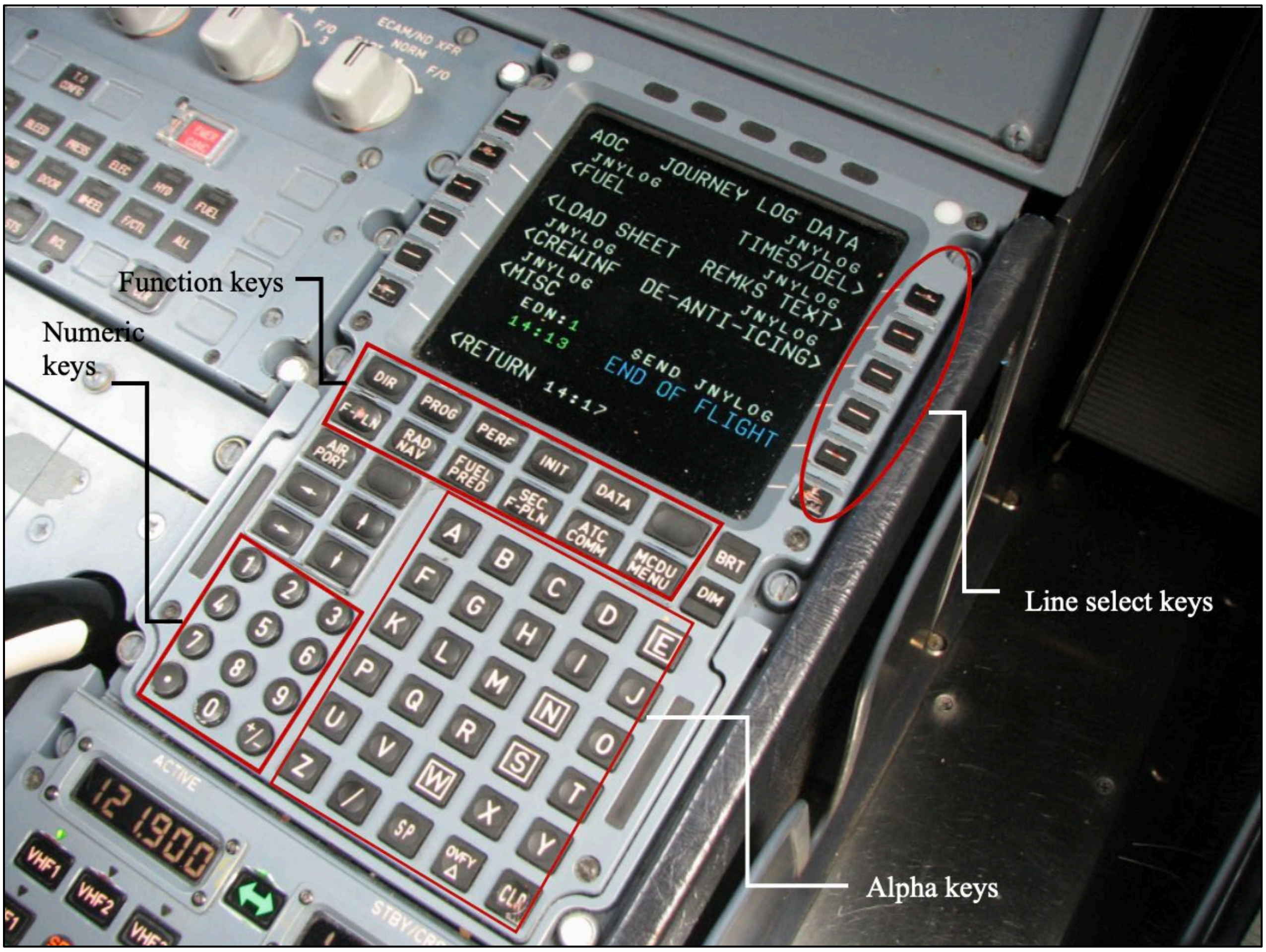


Figure 4.9: Airbus A320-200 MCDU, https://it.wikipedia.org/wiki/Flight_Management_System

The MCDU has a screen on which alphanumeric information is displayed, in contrast to the pictorial information displayed on the EFIS navigation displays. The tactile keyboard has alphanumeric keys in order to allow manual entry of navigation data, as well as various function keys by which specific navigation modes may be selected. The line keys at the side of the display are soft keys that allow the flight crew to enter a menu-driven system of subpages to access more detailed information. On many aircraft the MCDU is also used to portray maintenance status and to execute test procedures using the soft keys and the menu-driven feature. Finally, there are various annunciator lights and lighting control system.

4.3 DESCRIPTION OF THE SCENARIOS UNDER ANALYSIS

Two different scenarios will be analyzed in this paragraph. First, a description of both scenarios will be provided and subsequently the related task analysis will be presented in the next paragraph.

Scenario 1, flight from Grottaglie to Bologna with route modification request

The first scenario consists in a flight from Grottaglie to Bologna. The route passes through Pescara and then proceeds to destination. For the aim of this work, it is assumed that halfway through the flight, prior to reaching Pescara, an occurrence, either from the Air Traffic Control (ATC) or from e.g. environmental conditions, requires a diversion towards the sea, continue to Ancona and then finally fly towards Bologna. Further to the request, the pilot has to modify the current flight plan and determine whether the onboard fuel will be enough to comply with the diversion. Furthermore, the pilot should check for any change in the Top of Descent (TOD) point. After these evaluations the pilot can decide on the feasibility of the diversion. Assuming a cruise altitude around FL200, the route is composed by the SID segments, 10 waypoints and the STAR segments to destination for a total distance of 375 NM. Table 13 provides detailed information concerning waypoint name (ID), leg track (TRK), leg distance (DIST), and coordinates of the waypoints in terms of latitude and longitude:

Table 13: Route details from Grottaglie to Bologna

TARANTO/GROTTAGLIE (LIBG, LI) to **BOLOGNA/BORGO PANIGALE** (LIPE, LI): 12 fixes, 374.9 Nautical Miles [NM]

ID	TRK	DIST	Coordinates	Name/Remarks
LIBG	0	0	N40°31'02.13" E017°23'59.20"	TARANTO/GROTTAGLIE
ROBOT	18	12	N40°42'35.00" E017°28'10.00"	ROBOT
LUXIL	287	28	N40°49'09.00" E016°52'15.00"	LUXIL
DIVKU	314	62	N41°30'00.00" E015°50'15.99"	DIVKU
URIPI	311	37	N41°52'32.99" E015°11'05.00"	URIPI
PES	310	56	N42°26'08.99" E014°11'02.99"	PESCARA
AMGOK	319	18	N42°39'17.99" E013°53'45.99"	AMGOK
GUDPO	318	13	N42°48'28.99" E013°41'33.99"	GUDPO
IVMEP	336	31	N43°16'21.99" E013°22'05.00"	IVMEP
LIKNO	308	54	N43°47'37.99" E012°20'53.99"	LIKNO
PELEG	317	37	N44°13'39.99" E011°44'07.00"	PELEG
LIPE	316	26	N44°31'51.01" E011°17'49.01"	BOLOGNA

LIBG (0.0nm) -SID-> **ROBOT** (12.0nm) -L995-> **LUXIL** (40.0nm) -M872-> **DIVKU** (102.0 NM) -M872-> **URIPI** (139.0 NM) -M872-> **PES** (194.8 NM) -M872-> **AMGOK** (213.1 NM) -M872-> **GUDPO** (226.0 NM) -M872-> **IVMEP** (257.3 NM) -M872-> **LIKNO** (311.6 NM) -Q95-> **PELEG** (348.7 NM) -STAR-> **LIPE** (374.9 NM)

Tracks are magnetic, distances are in Nautical Miles. The codes in bold capital letters are the various waypoints along the route (but first and last on the list are the departure and arrival airports).

The alphanumeric codes between -> represent the airways linking the various waypoints.

The diversion will impact the route, which will now be composed by the SID segments, 17 waypoints and the STAR segments to destination for a total distance of 455 NM. Table 14 provides detailed information concerning waypoint name (ID), leg track (TRK), leg distance (DIST), and coordinates of the waypoints in terms of latitude and longitude. The waypoints marked in red are the new ones, consequence of the modification of the route.

Table 14: Modified route details

ID	TRK	DIST	Coordinates	Name/Remarks
LIBG	0	0	N40°31'02.13" E017°23'59.20"	TARANTO/GROTTAGLIE
ROBOT	18	12	N40°42'35.00" E017°28'10.00"	ROBOT
LUXIL	287	28	N40°49'09.00" E016°52'15.00"	LUXIL
DIVKU	314	62	N41°30'00.00" E015°50'15.99"	DIVKU
URIPI	311	37	N41°52'32.99" E015°11'05.00"	URIPI
PES	310	56	N42°26'08.99" E014°11'02.99"	PESCARA
ESODU	89	7	N42°26'34.00" E014°19'52.99"	ESODU
ERPOG	89	39	N42°28'41.99" E015°12'09.00"	ERPOG
ARSOB	315	18	N42°40'45.00" E014°53'45.99"	ARSOB
NUTRO	314	44	N43°09'35.99" E014°08'56.99"	NUTRO
LAPVO	314	16	N43°20'00.00" E013°52'32.99"	LAPVO
MASEG	313	7	N43°24'46.00" E013°44'58.00"	MASEG
ANC	313	16	N43°35'11.00" E013°28'16.00"	ANCONA
BIDMA	287	18	N43°39'42.99" E013°04'17.00"	BIDMA
SORUG	287	4	N43°40'42.99" E012°58'56.99"	SORUG
ASDOR	287	26	N43°47'04.99" E012°23'58.99"	ASDOR
LIKNO	286	2	N43°47'37.99" E012°20'53.99"	LIKNO
PELEG	317	37	N44°13'39.99" E011°44'07.00"	PELEG
LIPE	316	26	N44°31'51.01" E011°17'49.01"	BOLOGNA

LIBG (0.0 NM) -SID-> **ROBOT** (12.0 NM) -L995-> **LUXIL** (40.0 NM) -M872-> **DIVKU** (102.0 NM) -M872-> **URIPI** (139.0 NM)-M872-> **PES** (194.8 NM) -M169-> **ESODU** (201.3 NM) -M169-> **ERPOG** (240.0 NM) -L612-> **ARSOB** (258.1 NM) -L612-> **NUTRO** (301.8 NM) -L612-> **LAPVO** (317.6 NM) -L612-> **MASEG** (324.9 NM) -L612-> **ANC** (340.9 NM) -M730-> **BIDMA** (358.9 NM) -M730-> **SORUG** (362.9 NM) -M730-> **ASDOR** (388.9 NM) -M730-> **LIKNO** (391.2 NM) -Q95-> **PELEG** (428.4 NM) -STAR-> **LIPE** (454.6 NM)

Tracks are magnetic, distances are in Nautical Miles. The codes in bold capital letters are the various waypoints along the route (but first and last on the list are the departure and arrival airports).

The alphanumeric codes between -> represent the airways linking the various waypoints.

As can be seen from the previous tables, the original route is around 375 nautical miles whilst the modified one is approximately 455 nautical miles. Assuming:

- Cruise altitude: FL200
- Final descent altitude for Bologna: FL160

- Cruise speed: 260 knots (CAS)
- Final descent speed: 200 knots (CAS)

The TOD point is approximately 18 NM before the last point of the route and is not affected by the modification of the latter.

For both the original and modified route, the departure follows the SID linked to runway 17. Figure 4.10 shows the entire route from Grottaglie to Bologna.

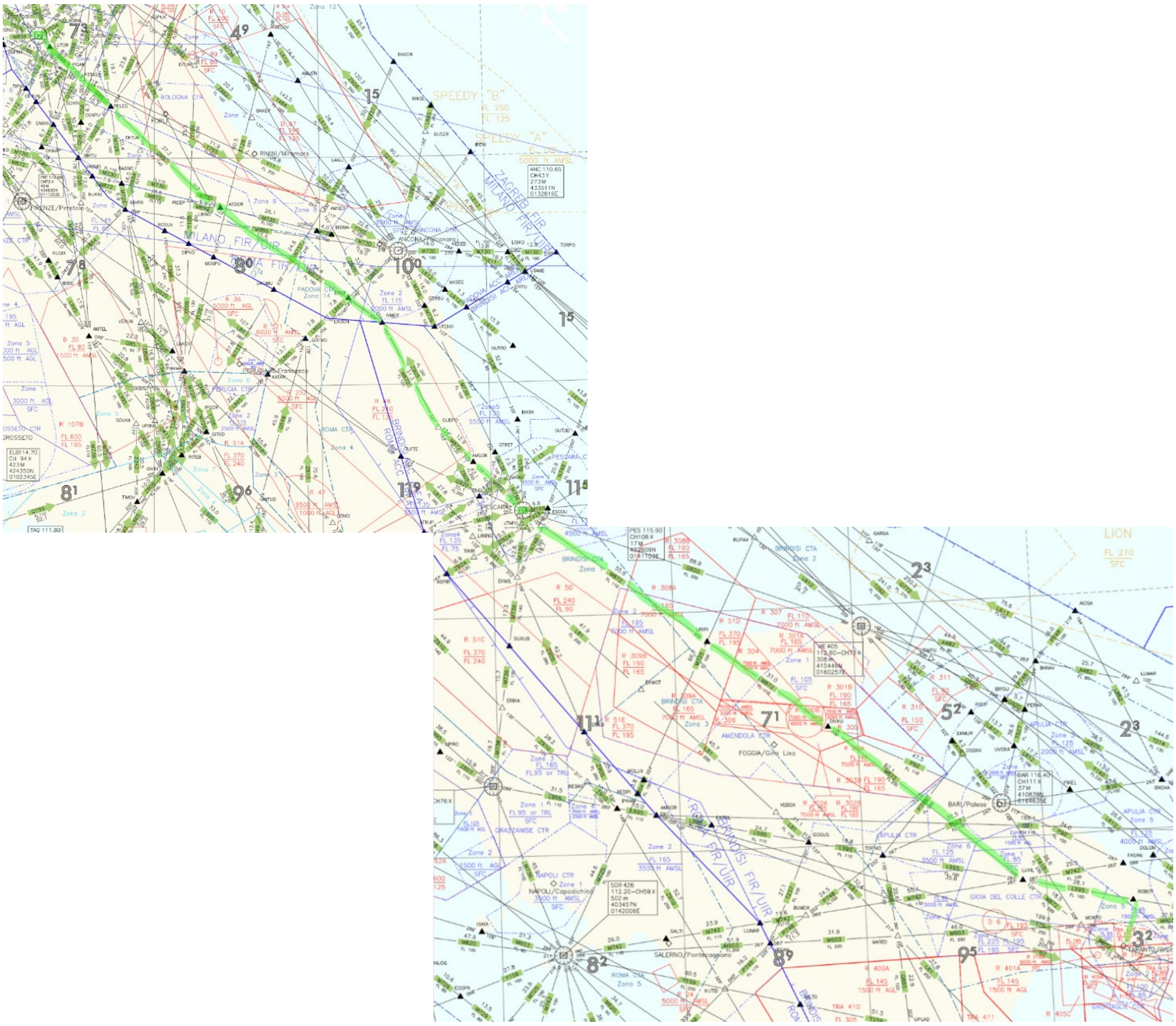


Figure 4.10: Route from Grottaglie to Bologna, ENAV (2019)

Figure 4.11 shows how the route would be affected by the diversion. In the figure, the original route is highlighted in green whilst the modified portion is depicted in red.

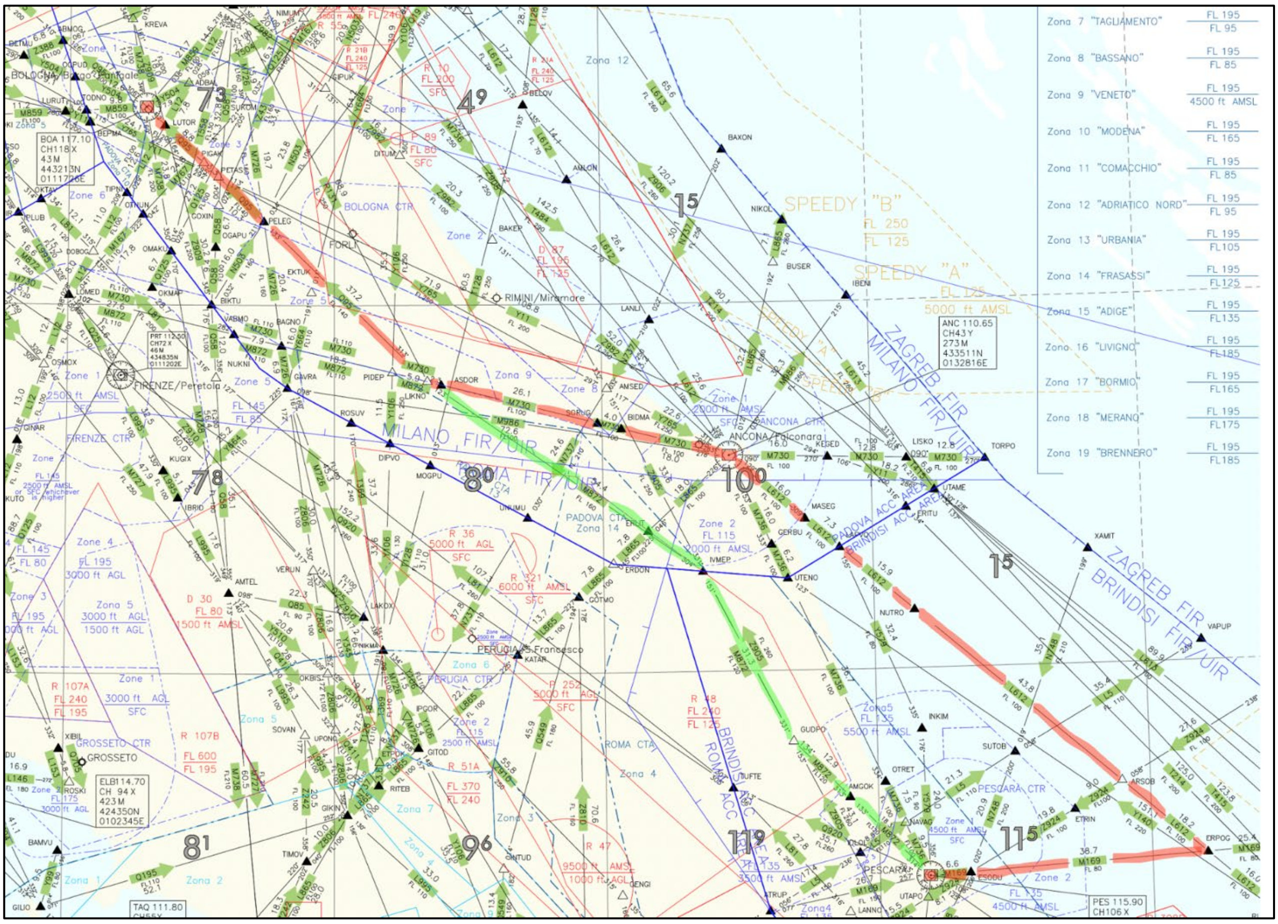


Figure 4.11: Modified route, ENAV (2019)

Scenario 2, flight from Grottaglie to Bologna with diversion to Forlì

The second scenario consists again of a flight from Grottaglie to Bologna and like the previous case the route passes through Pescara and then deviates to Bologna. This scenario considers that around the IVMEP waypoint, the ATC informs the pilot that the airport has been closed and requires to land the aircraft in Forlì. This request will require the pilot to modify the current flight plan, select a dedicated STAR and check for impacts on the TOD point. This situation is more critical than the previous scenario because the flight is almost at its end, while the previously planned trajectory results to be significantly affected. Nevertheless, there should not be any issues with the fuel since the route to Forlì is slightly shorter than the one to Bologna. Assuming a cruise altitude around FL200, the route is composed by the SID segments, 10 waypoints and the STAR segments to destination for a total distance of 375 NM. Table 15 provides detailed information concerning waypoint name (ID), leg track (TRK), leg distance (DIST), and coordinates of the waypoints in terms of latitude and longitude:

Table 15: Route details from Grottaglie to Bologna

TARANTO/GROTTAGLIE (LIBG, LI) to **BOLOGNA/BORGO PANIGALE** (LIPE, LI): 12 fixes, 374.9 Nautical Miles [NM]

ID	TRK	DIST	Coordinates	Name/Remarks
LIBG	0	0	N40°31'02.13" E017°23'59.20"	TARANTO/GROTTAGLIE
ROBOT	18	12	N40°42'35.00" E017°28'10.00"	ROBOT
LUXIL	287	28	N40°49'09.00" E016°52'15.00"	LUXIL
DIVKU	314	62	N41°30'00.00" E015°50'15.99"	DIVKU
URIPI	311	37	N41°52'32.99" E015°11'05.00"	URIPI
PES	310	56	N42°26'08.99" E014°11'02.99"	PESCARA
AMGOK	319	18	N42°39'17.99" E013°53'45.99"	AMGOK
GUDPO	318	13	N42°48'28.99" E013°41'33.99"	GUDPO
IVMEP	336	31	N43°16'21.99" E013°22'05.00"	IVMEP
LIKNO	308	54	N43°47'37.99" E012°20'53.99"	LIKNO
PELEG	317	37	N44°13'39.99" E011°44'07.00"	PELEG
LIPE	316	26	N44°31'51.01" E011°17'49.01"	BOLOGNA

LIBG (0.0nm) -SID-> **ROBOT** (12.0nm) -L995-> **LUXIL** (40.0nm) -M872-> **DIVKU** (102.0 NM) -M872-> **URIPI** (139.0 NM) -M872-> **PES** (194.8 NM) -M872-> **AMGOK** (213.1 NM) -M872-> **GUDPO** (226.0 NM) -M872-> **IVMEP** (257.3 NM) -M872-> **LIKNO** (311.6 NM) -Q95-> **PELEG** (348.7 NM) -STAR-> **LIPE** (374.9 NM)

Tracks are magnetic, distances are in Nautical Miles. The codes in bold capital letters are the various waypoints along the route (but first and last on the list are the departure and arrival airports).

The alphanumeric codes between -> represent the airways linking the various waypoints.

The modification required from the ATC will impact the route, which will now be composed by the SID segments, 10 waypoints and the STAR segments to destination for a total distance of 342 NM. Table 16 provides detailed information concerning waypoint name (ID), leg track (TRK), leg distance (DIST), and coordinates of the waypoints in terms of latitude and longitude. The waypoints marked in red are the new ones, consequence of the modification of the route.

Table 16: Route details from Grottaglie to Forlì

ID	TRK	DIST	Coordinates	Name/Remarks
LIBG	0	0	N40°31'02.13" E017°23'59.20"	TARANTO/GROTTAGLIE
ROBOT	18	12	N40°42'35.00" E017°28'10.00"	ROBOT
LUXIL	287	28	N40°49'09.00" E016°52'15.00"	LUXIL
DIVKU	314	62	N41°30'00.00" E015°50'15.99"	DIVKU
URIPI	311	37	N41°52'32.99" E015°11'05.00"	URIPI
PES	310	56	N42°26'08.99" E014°11'02.99"	PESCARA
AMGOK	319	18	N42°39'17.99" E013°53'45.99"	AMGOK
GUDPO	318	13	N42°48'28.99" E013°41'33.99"	GUDPO
IVMEP	336	31	N43°16'21.99" E013°22'05.00"	IVMEP
LIKNO	308	54	N43°47'37.99" E012°20'53.99"	LIKNO
ASDOR	106	2	N43°47'04.99" E012°23'58.99"	ASDOR
LIPK	332	28	N44°11'43.68" E012°04'10.61"	FORLI'

LIBG (0.0nm) -SID-> **ROBOT** (12.0nm) -L995-> **LUXIL** (40.0nm) -M872-> **DIVKU** (102.0 NM) -M872-> **URIPI** (139.0 NM) -M872-> **PES** (194.8 NM) -M872-> **AMGOK** (213.1 NM) -M872-> **GUDPO** (226.0 NM) -M872-> **IVMEP** (257.3 NM) -M872-> **LIKNO** (311.6 NM) -M730-> **ASDOR** (313.9 NM) -STAR-> **LIPK** (342.4 NM)

Tracks are magnetic, distances are in Nautical Miles. The codes in bold capital letters are the various waypoints along the route (but first and last on the list are the departure and arrival airports).

The alphanumeric codes between -> represent the airways linking the various waypoints.

Figure 4.12 shows how the route is affected by the modification requested by the ATC. In the figure, the original route is highlighted in green whilst the modified portion is depicted in red. Assuming:

- Cruise altitude: FL200
- Final descent altitude for Bologna: FL160
- Final descent altitude for Forlì: FL100
- Cruise speed: 260 knots (CAS)
- Final descent speed: 200 knots (CAS)

The TOD point is approximately 18 NM before the last point of the route for the original one and 36 NM for the modified route and, therefore, the pilot needs to start the descent earlier than expected.

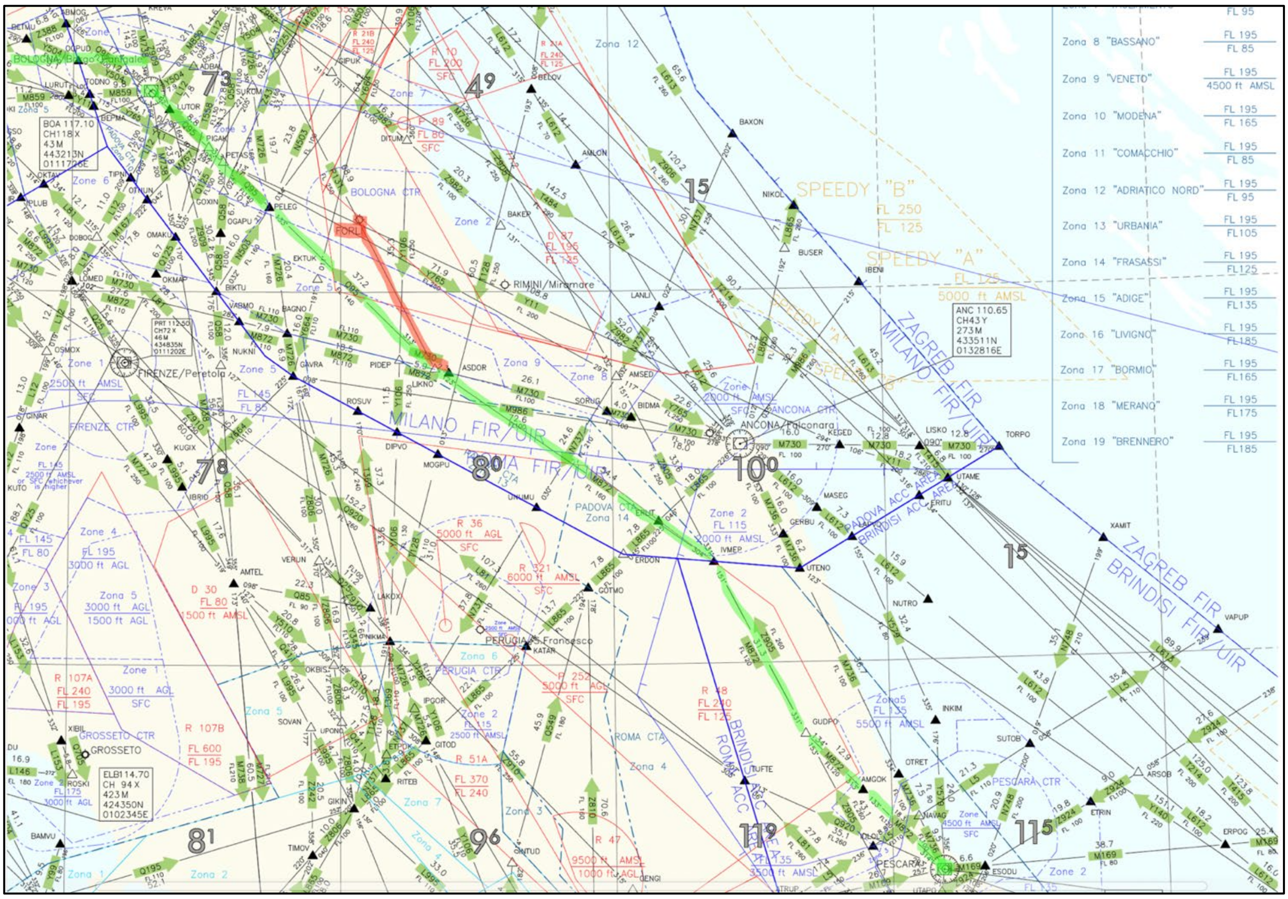


Figure 4.12: Modified route to Forlì, ENAV (2019)

4.4 TASK ANALYSIS

In the first part of this paragraph, the high-level tasks that pilots carry during the flight are described. Next, the structure of the task analysis will be outlined and finally the results of the TA applied to the scenarios defined in paragraph 4.3 will be presented.

High-level tasks

The main tasks that are to be conducted during a flight are *aviate, navigate, communicate and manage*. These tasks can be defined in the following way:

- **Aviate:** fly the aircraft by using the flight controls and flight instruments to direct the airplane’s attitude, airspeed and altitude.

- **Communicate:** during any phase of the flight pilots are in contact with ATC and/or other entities, so they always need to pay attention to possible requests while carrying the other tasks.
- **Navigate:** even while carrying other tasks, the pilot should always be aware of the aircraft's present position and he/she has to keep it on the expected route.
- **Manage:** this activity is relatively recent and involves the management of aircraft systems (e.g. fuel management, diversion management, etc.) and the application, if needed, of emergency or abnormal procedures.

Pilots have to carry various tasks simultaneously and this results in an important workload. In commercial aircrafts there are two pilots that share these tasks but there are many other situations in which there is only one pilot in charge, and he/she has the responsibility to conduct a safe flight.

Prioritization between the different tasks is a very important aspect concerning the flight's safety, for either normal or emergency conditions. Effective prioritization does not only relate to critical matters and/or periods of high workload but also to low workload situations.

Prioritization for pilots is a dynamic process intimately connected and interwoven with many other issues, such as: decision making, airmanship, situation awareness, pilot perception, pilot memory aids, pilot workload and crew resource management.

Effective prioritization can be a balance between speed and accuracy and there will often be a tradeoff between the two:

- When speed (or immediacy) is essential then failure to prioritize effectively can lead to an increase in risk by delaying essential tasks beyond a point of usefulness (or recovery).
- When accuracy is essential then failure to prioritize effectively can lead to latent errors based on false analyses or assumptions.

Effective prioritization rests on accurate knowledge, sufficient practice, and use of resources. The importance of being both accurate and timely with prioritization of tasks depends on the size and immediacy of potential risk, so a working understanding and application of risk assessment is essential when managing operational threats. These aspects can be addressed through the adoption of a professional attitude whereby vigilance, attention and focus are used to maintain effective situation awareness.

A pilot’s ability to prioritize task effectively may be directly affected by workload, the nature and number of threats, and the availability of resources. Flight deck automation (and the associated automatic flight control and aircraft systems) has undoubtedly impacted how tasks are prioritized and, as a consequence, helped to reduce pilots’ workload. However, understanding, monitoring and managing flight deck automation takes time and effort and, in many cases, they become priority tasks. In emergency conditions, prioritization becomes even more important.

Task analysis structure

In order to analyze the scenarios that have been described in the previous paragraph, hierarchical task analysis was the chosen methodology.

HTA is a systematic method used to describe how an activity is organized in order to meet the overall objective. It involves identifying in a top down fashion the overall goal of the task, the various sub-tasks and the conditions under which they should be carried out in order to achieve that goal. By doing this, it is possible to represent complex tasks as a hierarchy of goals, operations and plans:

- *Goals*: the unobservable task goals associated with the task in question;
- *Operations*: the observable behaviors or activities that the operator has to perform in order to accomplish the goal of the task in question;
- *Plans*: the unobservable decisions and planning made on behalf of the operator.

The standard method to execute an HTA has here been expanded so to describe tasks in a comprehensive and structured way. Each goal, sub-goal and operation has been characterized by means of four specific elements:

- A list of “command verbs” has been introduced in order to define operations in a consistent way. The list is presented in Table 17.

Table 17: Command verbs and their definition

COMMAND VERBS	DEFINITION
Press	Physical action to interact with the keys of the interface
Check	Control of the interface to see if the presented data are correct
Decide	To find a solution by following a set of procedures
Terminate	To end a procedure or a specific phase of the interaction
Enter	To fill data fields with relevant information
Correct	To modify data fields if the provided information is incorrect
Select	To choose the right data/information among the available choices
Execute	To perform an activity or to enable a system performing an activity
Receive	To get or to be given a piece of information
Recall	To activate a specific function by pronouncing its name
Process	To perform a particular series of operations on the information

- Tasks have been characterized by the **OODA Loop** step they belong to, in order to distinguish between manual/repetitive tasks and cognitive/decisional ones.
- Salience of the visual cues that guide the operator's actions.
- Execution time determined by means of the Keystroke-Level Model (KLM).

Colonel John Boyd (United States Air Force, retired) coined the term and developed the concept of the OODA Loop (Observation, Orientation, Decision, Action), as a means to describe decision-making processes. The first node of the loop, **observe**, reflects the need for situation awareness. A pilot must be aware of those things around him/her that may impact the flight. Continuous monitoring of aircraft controls, weather, etc., provides a constant reference point by which the pilot knows his/hers starting point in the loop. **Orient**, the second node of the loop, focuses the pilot's attention on one or more discrepancies in the flight. For instance, assume that there is a low oil pressure reading. The pilot is aware of this deviation and considers the available options in view of potential hazards to the flight. The pilot then moves to the third node, **decide**, in which he/she makes a positive determination about a specific effect. This decision is based upon experience and knowledge of potential results, and to make sure that the particular action will produce the expected result. The pilot then **acts** on that decision, making a physical action to cause the aircraft to react in the desired fashion. Once the loop has been completed, the pilot is once again in the observe position. The assessment of the resulting action is added to the previously perceived aspects of the flight to further define its progress. The structure of the OODA loop is outlined in Figure 4.13.

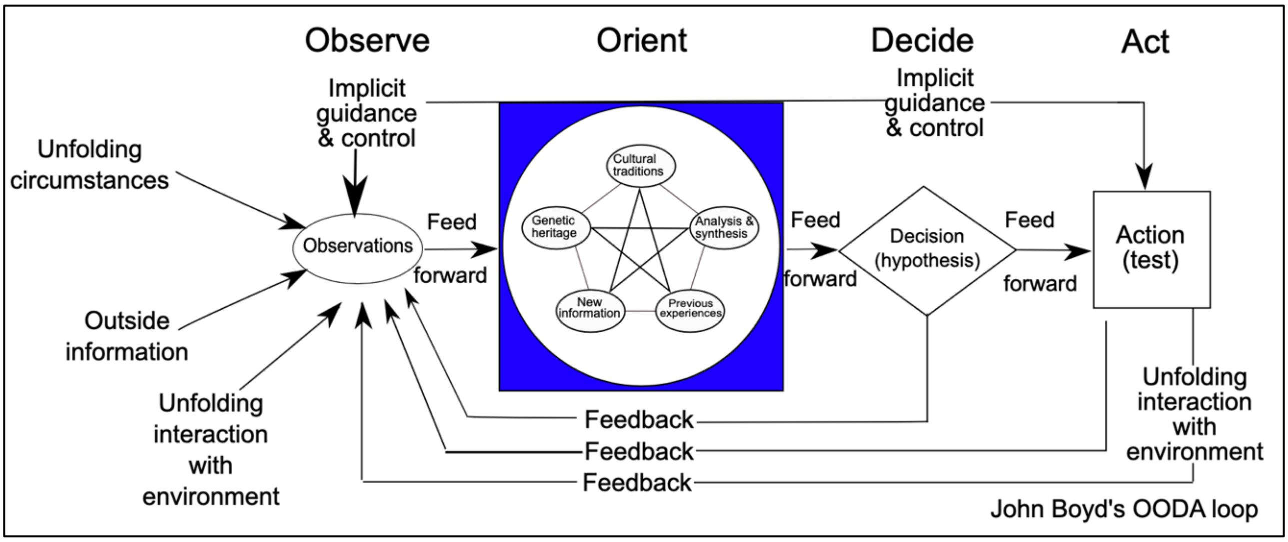


Figure 4.13: John Boyd's OODA loop, https://en.wikipedia.org/wiki/OODA_loop

The salience of the visual cues guides the operator’s actions and as such can be a useful element to characterize and discriminate different types of interaction. Figure 4.14 outlines the decision tree used to perform the assessment. A visual cue is assessed as (Sherry et al, 2010):

- *“None”* – when there is no visual cue, or there is a visual cue that has no semantic similarity to the goal to complete the task, or there are multiple visual cues (or headings) with equal semantic similarity.
- *“Partial”* – when the only visual cue is ambiguous, or when competing visual cues cannot be easily distinguished from one another.
- *“Exact”* – when the correct label has semantic similarity to the task and there are no competing cues.

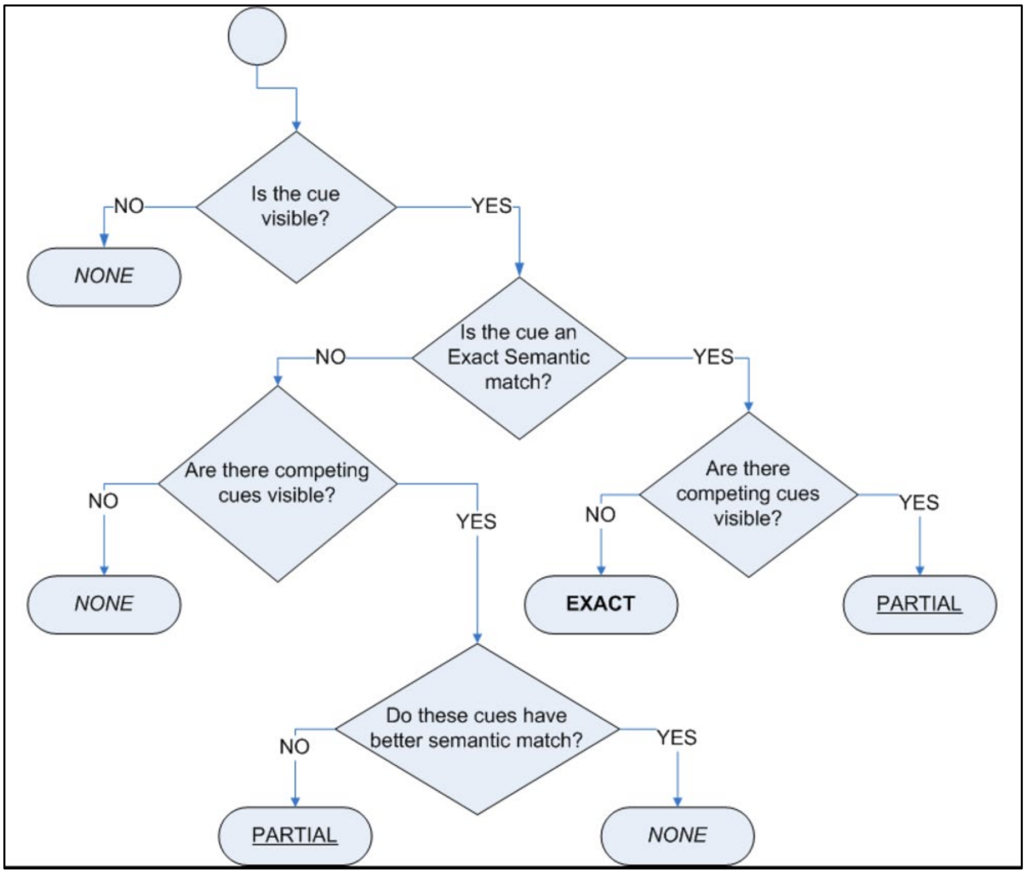


Figure 4.14: Visual cue assessment, System Design and Analysis: Tool for Automation Interaction Design and Evaluation Methods (NASA, 2010)

The KLM, proposed by Card, Moran, & Newell, predicts task execution time from a specified design and specific task scenario. Basically, the sequence of keystroke-level actions that the user must perform to accomplish a task is listed, and then the times required by the actions are added up. It is not necessary to have an implemented or mocked-up design. The KLM requires only that the user interface is specified in enough detail to dictate the sequence of actions required to perform the tasks of interest (Kieras, 2001).

The actions are termed *keystroke level* if they consist in operations like pressing keys, moving the mouse, pressing buttons and so forth. The KLM requires to describe how the user would do the task in terms of actions at this keystroke level. The basic actions are called *operators*, and there exist a standard set for use in the KLM, whose execution times have been estimated from experimental data. The following list includes the operators relevant for the analysis and their estimated times. The overall KLM features additional operators that are not mentioned because out of scope:

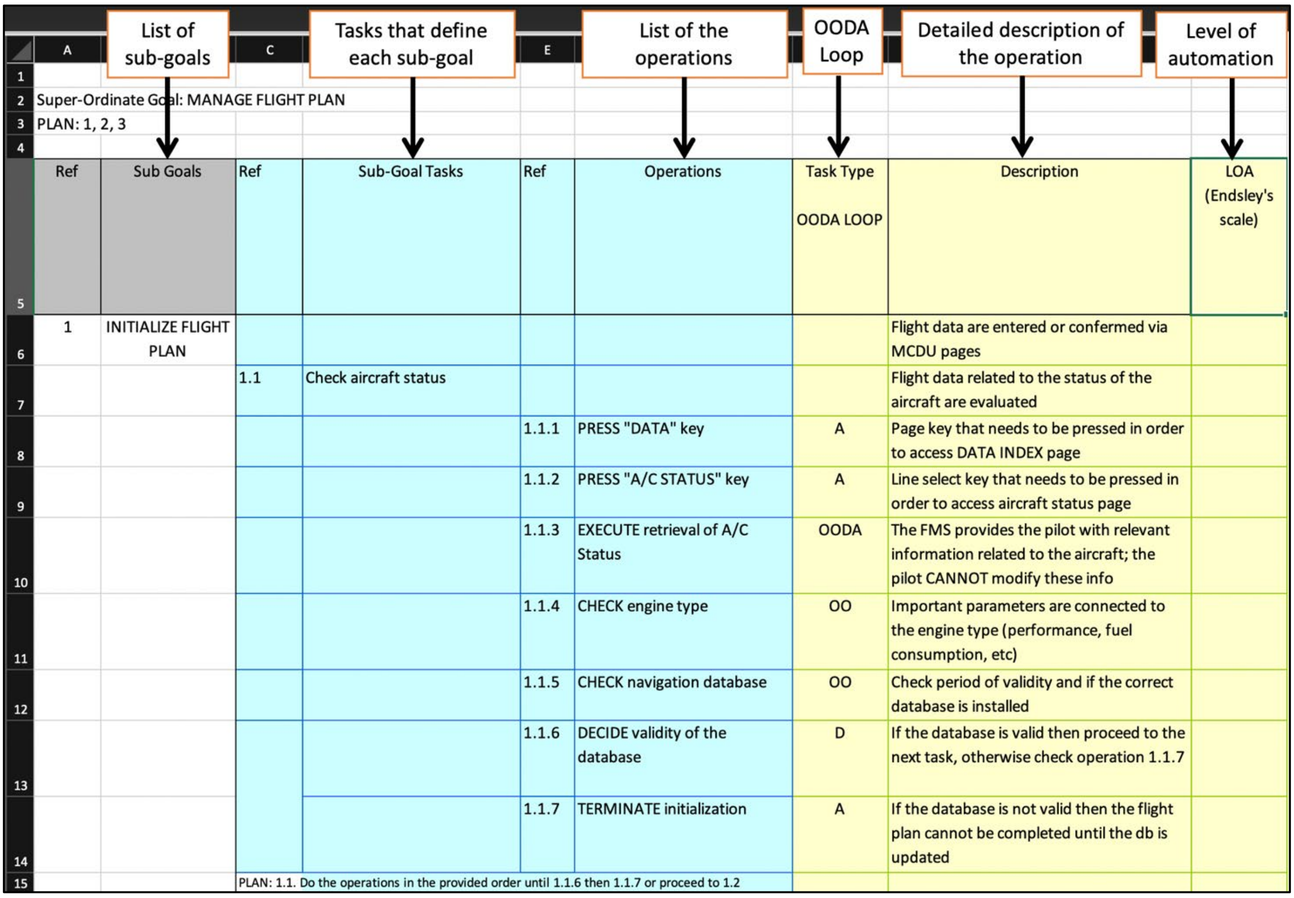
- **K – Keystroke (1.35 sec):** this operator consists in pressing a key or button on the keyboard.
- **T(n) – Type a sequence of *n* characters on a keyboard (n∗K sec):** this operator is simply a shortcut for a series of K operators, and would normally be used when the user is typing a string of characters that is a single “chunk”, such as a filename.
- **H – Home hands to keyboard or mouse (0.6 sec):** since the targets are pretty large, and the movement well practiced, moving the hand between keyboard and mouse (and vice-versa) is relatively fast.
- **M – Mental act of routine thinking or perception (0.6 – 1.35 sec):** how long it takes to perform a mental act depends on what cognitive processes are involved and is highly variable from situation to situation or person to person. The M operator is intended to represent routine thinking, not complex, lengthy, problem-solving operations. Based on the available results, a good overall estimate for the duration of an M is 1.2 sec.
- **W(t) – Waiting for the system to respond (time *t* must be determined):** this is the time that the user must wait on the system before he/she can proceed.

The reason for expanding HTA by adding OODA Loop, salience and the assessment of execution times is twofold: it allows to better describe the pilot interaction and will be useful for the next phase of the work, in which an analysis of how the interaction could be improved will be made.

The results of the HTA will be presented both in a written/descriptive fashion and in spreadsheet form (in the annexes of this document). Starting from left, the spreadsheet has the following structure:

- The first column includes the list of sub-goals.
- The second column outlines the tasks that define each sub-goal.
- The third column includes the list of the operations that need to be made in order to fulfill the sub-goal tasks.
- The fourth column characterizes each operation according to the OODA Loop decision model.
- The fifth column provides a detailed description of each operation/sub-goal/task.
- The last column contains the allocation of the LOA for each operation.

The structure of the spreadsheet is outlined in Figure 4.15. In this example, the first sub-goal is shown along with the sub-goal tasks and operations that are needed to fulfill it. The last column of the spreadsheet, LOA, will be the topic of the next chapter and therefore is left blank in this example.



List of sub-goals

Tasks that define each sub-goal

List of the operations

OODA Loop

Detailed description of the operation

Level of automation

Super-Ordinate Goal: MANAGE FLIGHT PLAN

PLAN: 1, 2, 3

Ref	Sub Goals	Ref	Sub-Goal Tasks	Ref	Operations	Task Type OODA LOOP	Description	LOA (Endsley's scale)
1	INITIALIZE FLIGHT PLAN						Flight data are entered or conferned via MCDU pages	
		1.1	Check aircraft status				Flight data related to the status of the aircraft are evaluated	
				1.1.1	PRESS "DATA" key	A	Page key that needs to be pressed in order to access DATA INDEX page	
				1.1.2	PRESS "A/C STATUS" key	A	Line select key that needs to be pressed in order to access aircraft status page	
				1.1.3	EXECUTE retrieval of A/C Status	OODA	The FMS provides the pilot with relevant information related to the aircraft; the pilot CANNOT modify these info	
				1.1.4	CHECK engine type	OO	Important parameters are connected to the engine type (performance, fuel consumption, etc)	
				1.1.5	CHECK navigation database	OO	Check period of validity and if the correct database is installed	
				1.1.6	DECIDE validity of the database	D	If the database is valid then proceed to the next task, otherwise check operation 1.1.7	
				1.1.7	TERMINATE initialization	A	If the database is not valid then the flight plan cannot be completed until the db is updated	
		PLAN: 1.1. Do the operations in the provided order until 1.1.6 then 1.1.7 or proceed to 1.2						

Figure 4.15: TA structure

Description of the HTA

The object of this work is the interaction that the pilot has with the FMS and therefore the task analysis will particularly focus on the "manage" task. Nevertheless, the pilot interacts with this system while he/she is already busy doing all the other tasks. Considering the high-level tasks previously introduced, along with the identified scenarios, the pilot will also cater for:

- **Aviate:** fly the aircraft, with or without the use of autopilot, and monitor main flight parameters (speed, altitude, attitude and engine performance).

- **Communicate:** it is essential that the pilot is able to receive important communications from the ATC and/or other entities, so he/she always needs to pay attention while carrying other tasks.
- **Navigate:** even while carrying other tasks, the pilot should always be aware of the aircraft's present position and he/she has to keep it on the expected route.
- **Manage:** management of aircraft systems (e.g. fuel management, diversion management, etc.)

For the aim of this work, the following assumptions are considered:

- The autopilot is active.
- There are no emergency conditions.
- The level of detail of the task description will not consider operations such as pressing a single letter/number to form a word but will generally regard these inputs as "data entry".

Considering the two scenarios that have been described in paragraph 4.3, the super-ordinate goal of the HTA is: **MANAGE FLIGHT PLAN**. In order to accomplish this goal, three sub-goals have been defined:

1. **INITIALIZE FLIGHT PLAN**
2. **EDIT FLIGHT PLAN**
3. **MODIFY FLIGHT PLAN**

Both scenarios share almost the same structure and content of the HTA, especially for what concerns the first and second sub-goals. The major difference between the two is that the first scenario requires the insertion of several new waypoints along the route (and hence this modification will require a specific "*route revision method")* whilst the second requires the change of the arrival airport, which is performed in a different way if compared to what is needed for the first scenario. In the spreadsheet form of the HTA all the operations required to accomplish the sub-goals are outlined in detail.
The three sub-goals can be described in the following way:

1. **INITIALIZE FLIGHT PLAN:** before the pilot can actually insert the flight plan in the FMS, several checks have to be performed in order to make sure that the

information loaded by the FMS is the one related to the current aircraft. This is important because it impacts different performance calculations. In order to accomplish this sub-goal, the pilot usually:

   a. Checks the stored navigation database and decides whether it is correct or not. This is an important control that pilots perform because they cannot fly the aircraft if the validity of the database is expired.
   b. Inserts relevant information related to the aircraft.
   c. Sets departure and arrival airport.
   d. Checks the indicated present position and decides if it needs to be corrected or not.

Once these operations have been carried out, the pilot can proceed to enter the intended flight plan.

2. **EDIT FLIGHT PLAN:** in order to accomplish this sub-goal, the pilot usually:

   a. Enters the full departure information (runway, SID, etc.).
   b. Enters the various waypoints along the route: depending on whether they are linked by airways or not, two different procedures can be employed to enter in the system the different waypoints.
   c. Enters the full arrival information (STAR, runway, etc.).
   d. Computes and evaluates aircraft performance.
   e. Once all the information has been entered in the FMS, the pilot reviews the entire flight plan and decides whether it needs to be integrated with other relevant information.

3. **MODIFY FLIGHT PLAN:** depending on the modifications that need to be applied, the pilot has several ways to update the route. With respect to the identified scenarios, the possible modifications are:

   a. Enter new waypoints and update the current route.
   b. Delete existing waypoints and either replace them or not.
   c. Delete long segments and update the current route.
   d. Change the arrival airport.

First scenario, flight from Grottaglie to Bologna with route modification request

The pilot receives a route modification request and based on it he/she needs to decide which strategy needs to be adopted in order to update the active flight plan in relation to the options offered by the FMS. The modifications that need to be implemented in the first scenario will require the pilot to start by deleting the waypoints AMGOK, GUDPO, IVMEP and this can be done by either following the procedure outlined in Figure 4.16 (sub-goal task 3.4 "Route revision, method 2") or the one presented in Figure 4.17 (sub-goal task 3.5 "Route revision, method 3").

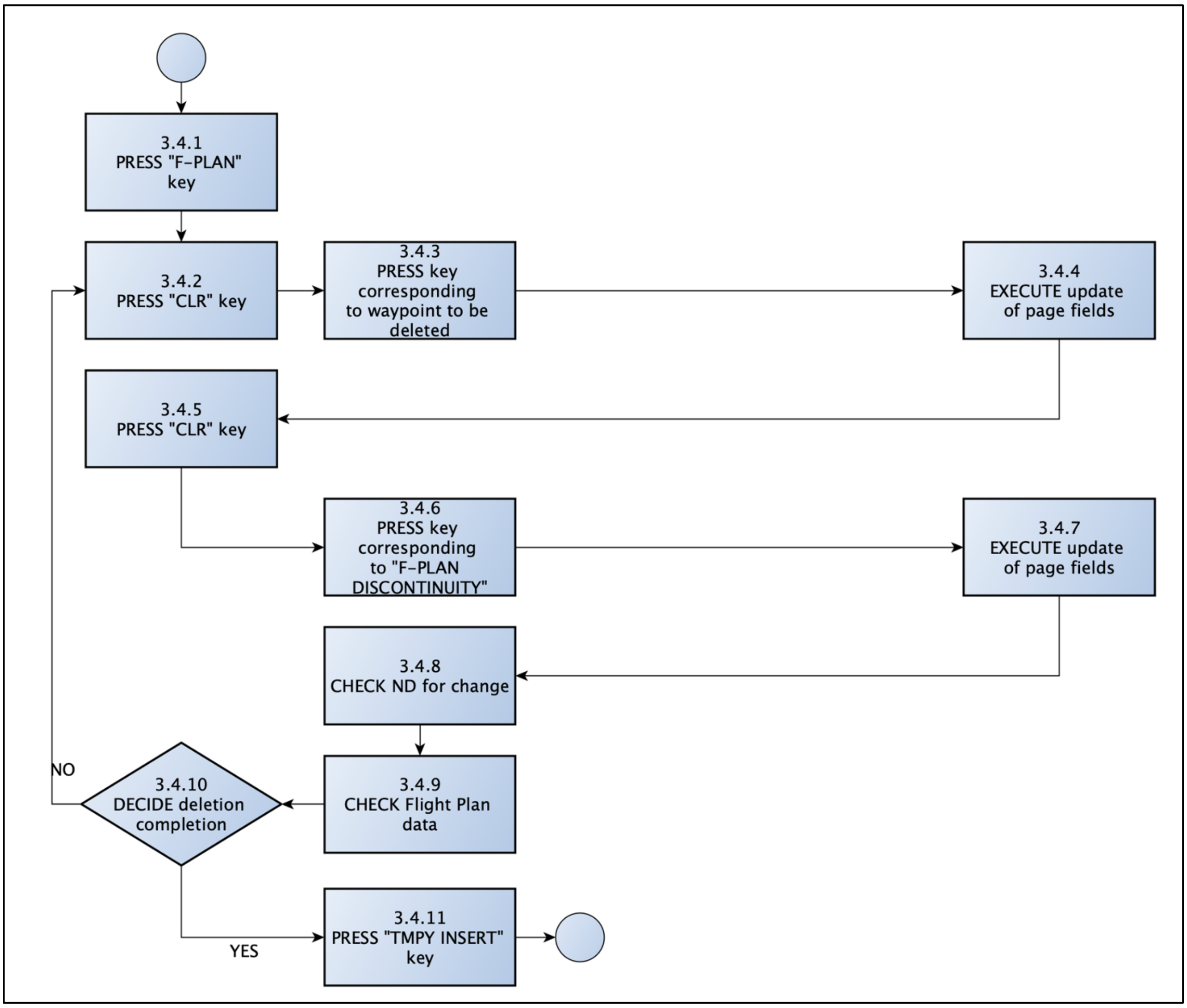


Figure 4.16: Waypoint deletion procedure, Route revision method 2

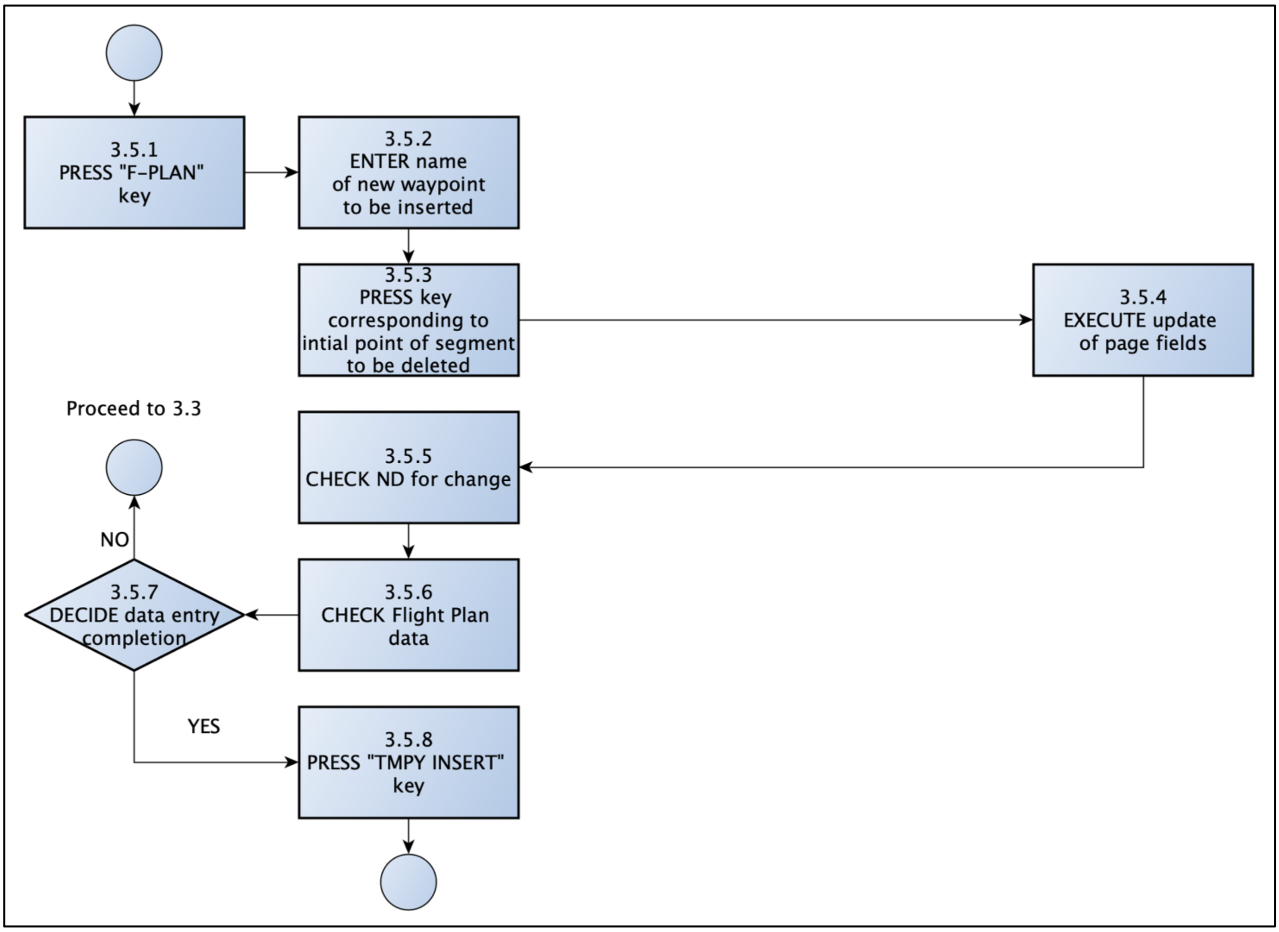


Figure 4.17: Waypoint deletion procedure, Route revision method 3

The pilot will then add the new waypoints following the procedure outlined in Figure 4.18 (sub-goal task 3.3 “Route revision, method 1”). It is noted that, when executing the tasks of the subject scenario, the first operation of “Route revision, method 1” is skipped since it has been already executed as part of the waypoint deletion procedure.

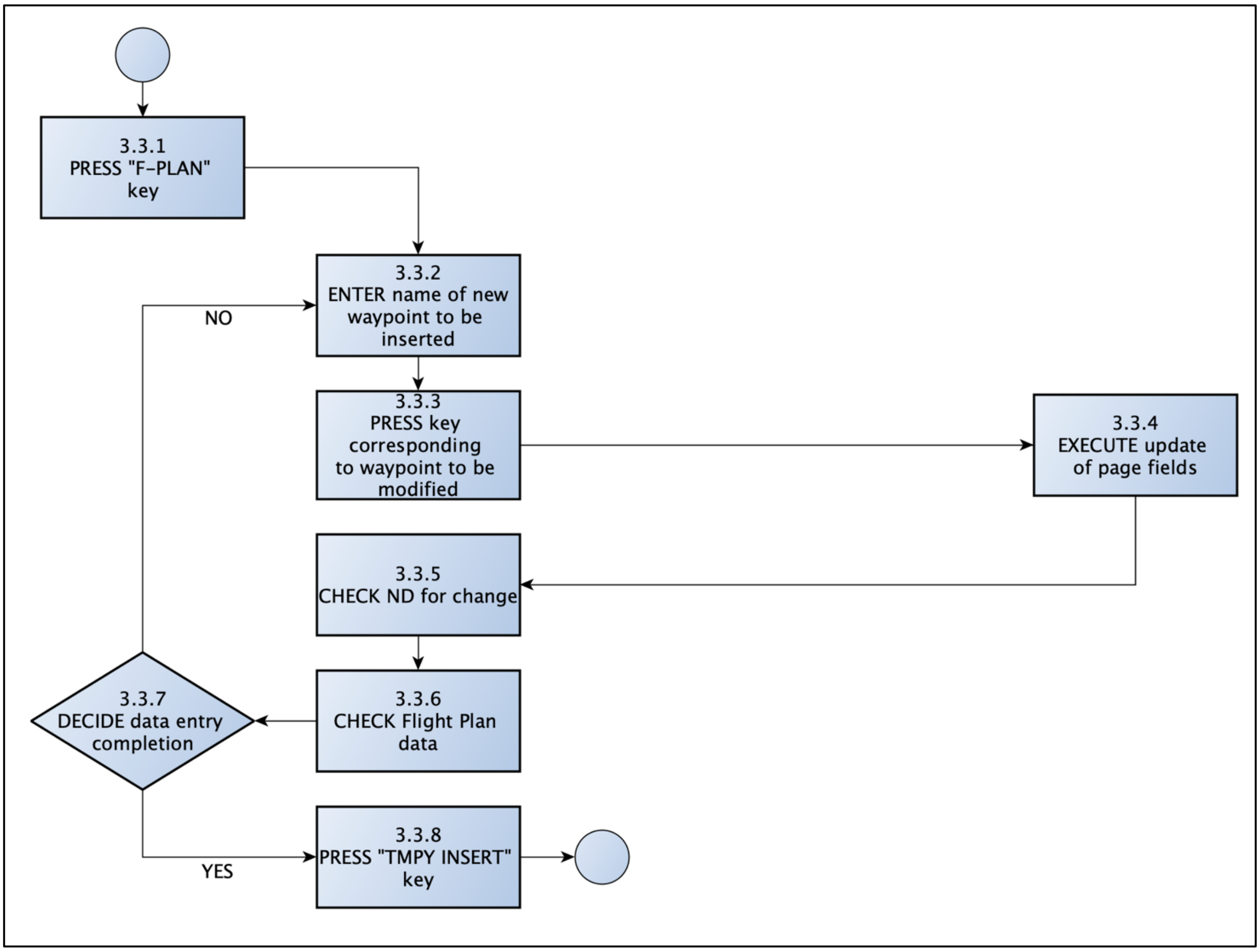


Figure 4.18: Waypoint insertion procedure, Route revision method 1

Lastly, the pilot needs to check aircraft performance computations such as TOD point and estimated fuel at destination, following the procedure presented in Figure 4.19 (sub-goal task 3.6 “Assess aircraft performance”). This is essential in order to assess the feasibility of the modifications.

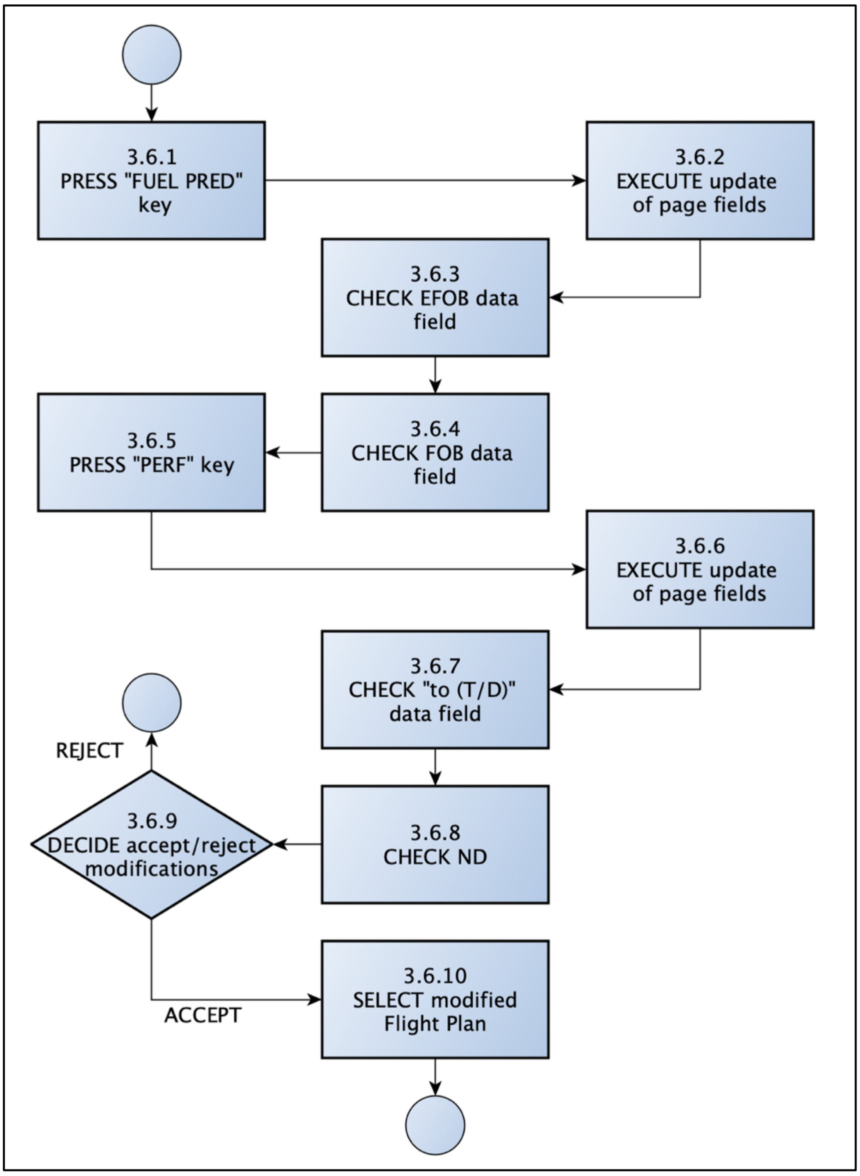


Figure 4.19: Assess aircraft performance procedure

Second scenario, flight from Grottaglie to Bologna with diversion to Forlì

For this scenario the pilot first modifies the destination airport, and this will cause to automatically delete all the waypoints after the diversion point (LIPE and PELEG in this specific case). Then he/she needs to add the new waypoints that link the diversion point with the new destination airport.

The procedure to modify the destination airport is outlined in Figure 4.20 (sub-goal task 3.2 “Change destination airport”). New waypoints are added following the procedure presented in Figure 4.18 (sub-goal task 3.3 “Route revision, method 1”).

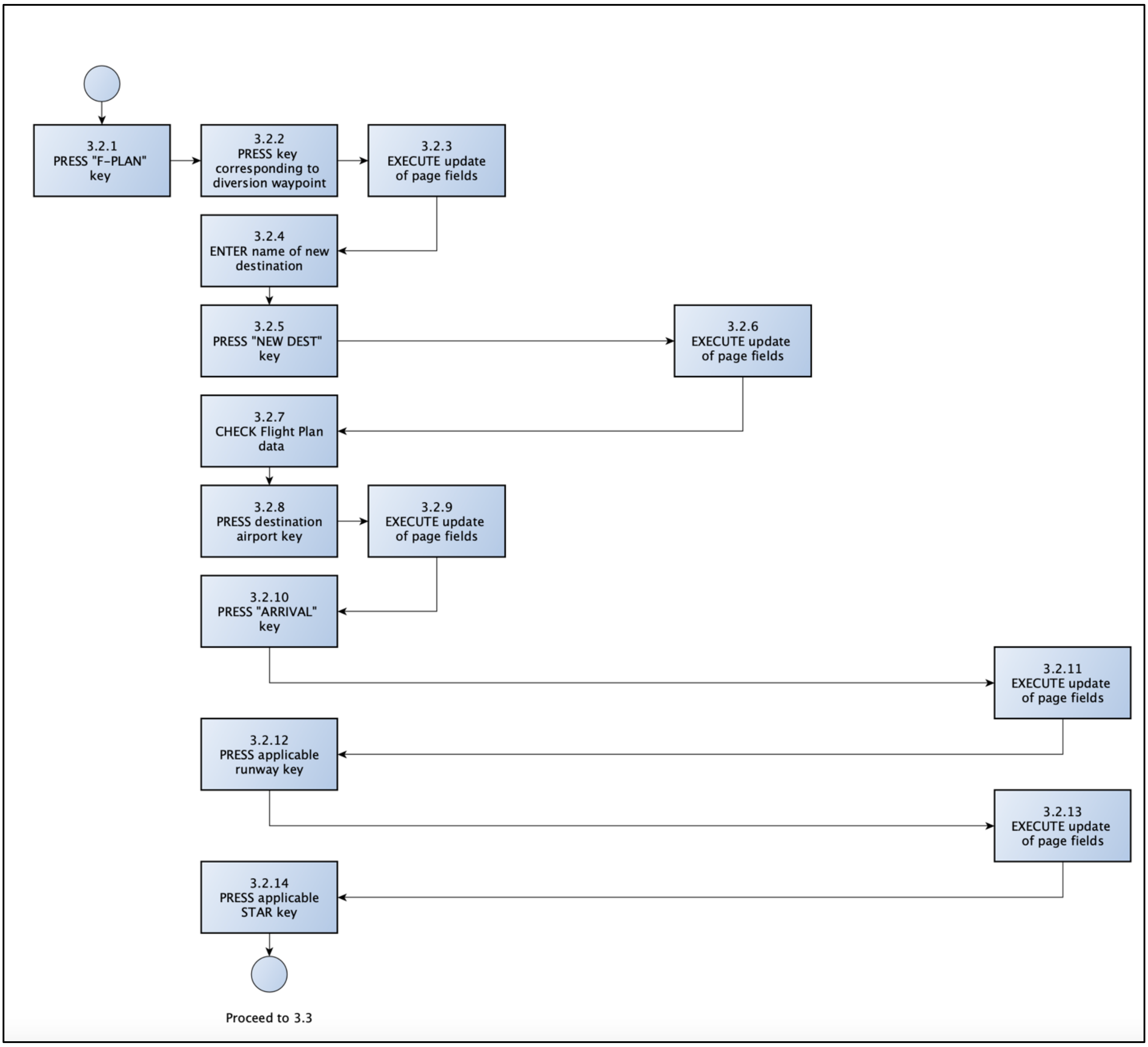


Figure 4.20: Destination airport change procedure

Also in this case, it is important to check the position of the TOD point so to assess any impact on fuel and preparation of the need to anticipate the descent maneuver and hence, the procedure outlined in Figure 4.19 (sub-goal task 3.6 “Assess aircraft performance”) needs to be followed.

5 MCDU-BASED FMS VS. IMPROVEMENT HYPOTHESES: LOA ANALYSIS AND COMPARISON

The aim of this chapter is to first analyze the traditional MCDU-based FMS by allocating a LOA to the operations outlined in the TA of chapter 4, and then to investigate possible interaction improvements in relation to the scenarios' specific tasks. In order to achieve this goal, in the first paragraph a LOA allocation is performed using the Endsley's scale that has been chosen in chapter 3, and the results are presented in a diagram form. The second part of this chapter analyses possible improvement hypotheses. Each hypothesis is preliminarily assessed in terms of technological feasibility and worked out by studying impacts on task sequences, assigning a LOA and assessing interactions. Finally, a comparison between the MCDU-based FMS and the implementation of the improvement hypotheses is performed. A summary of the analysis is provided in the last paragraph of this chapter. While the complete LOA allocation is presented in the annexes of this document, this chapter will focus on the two scenarios that have been described in chapter 4.

5.1 LOA ANALYSIS OF MCDU-BASED FMS

This analysis is based on the TA that has been presented in chapter 4 and consists in the allocation of a LOA to every operation that makes up the tasks under analysis.
As discussed in chapter 3, the scale selected for this purpose is Endsley's taxonomy, whose ten levels are summarized below (M. R. Endsley, D. B. Kaber, 1999):

1. **Manual Control (MC)**
2. **Action Support (AS)**
3. **Batch Processing (BP)**
4. **Shared Control (SHC)**
5. **Decision Support (DS)**
6. **Blended Decision Making (BDM)**
7. **Rigid System (RS)**
8. **Automated Decision Making (ADM)**
9. **Supervisory Control (SC)**
10. **Full Automation (FA)**

The allocation has been performed by analyzing every operation and by choosing an appropriate LOA consistently with the abovementioned taxonomy. Furthermore, considering the specific characteristics of the FMS, the following assumptions have been made:

- To PRESS a key can have two different levels of automation depending on how the FMS aids the pilot:
    - LOA 1 when the pilot presses a page select key (like DATA, INIT, AIRPORT, F-PLAN…) to access a menu, because the referred keys can be identified through engraved labels, i.e. no computation is performed by the FMS.
    - LOA 2 when the pilot presses a line select key, because the referred keys can be identified through labels presented on screen, i.e. the FMS performs a computation to aid him/her by showing what pages could be accessed by selecting the corresponding key.

- To ENTER data using the keyboard is considered a LOA 2 because, as the pilot presses the different keys, the FMS shows them, further to an internal process, on the scratchpad and therefore the pilot has a feedback of what has been typed.
- To EXECUTE update of page fields can have three different levels of automation depending on what the FMS performs when updating a page and on how the pilot can interact with the latter:
    - LOA 3 when the FMS just executes a command/presents data but does not provide options.
    - LOA 5 when the FMS executes a command/presents data, checks for errors and prompts the pilot (e.g. after a waypoint is deleted, the FMS adds a “flight plan discontinuity” between the cleared and the subsequent waypoint).
    - LOA 7 when the FMS executes a command/presents data, checks for errors and presents only a limited set of options to the pilot that are dependent on a specific situation (e.g. when the pilot sets the departure airport, he/she can select only from the runways that the FMS presents).

- To DECIDE is considered a LOA 1 because it is an operation that is performed solely by the pilot even though it could be based on parameters shown by the FMS. In the frame of this analysis, it is assumed that the system cannot take decisions.
- To CHECK is considered a LOA 2 because it is an operation that is performed by the pilot aided by data presented by the FMS.

Considering the two scenarios under analysis (the complete allocation is based on the spreadsheet and is presented in the annexes), the LOA allocation produced the following results.

First scenario, flight from Grottaglie to Bologna with route modification request

The pilot receives a route modification request and based on it he/she needs to decide which strategy needs to be adopted in order to update the active flight plan in relation to the options offered by the FMS. The modifications that need to be implemented in the first scenario will require the pilot to start by deleting the waypoints AMGOK, GUDPO, IVMEP and this can be done by either following the procedure outlined in Figure 5.1 (sub-goal task “Route revision, method 2”) or the one presented in Figure 5.2 (sub-goal task “Route revision, method 3”).

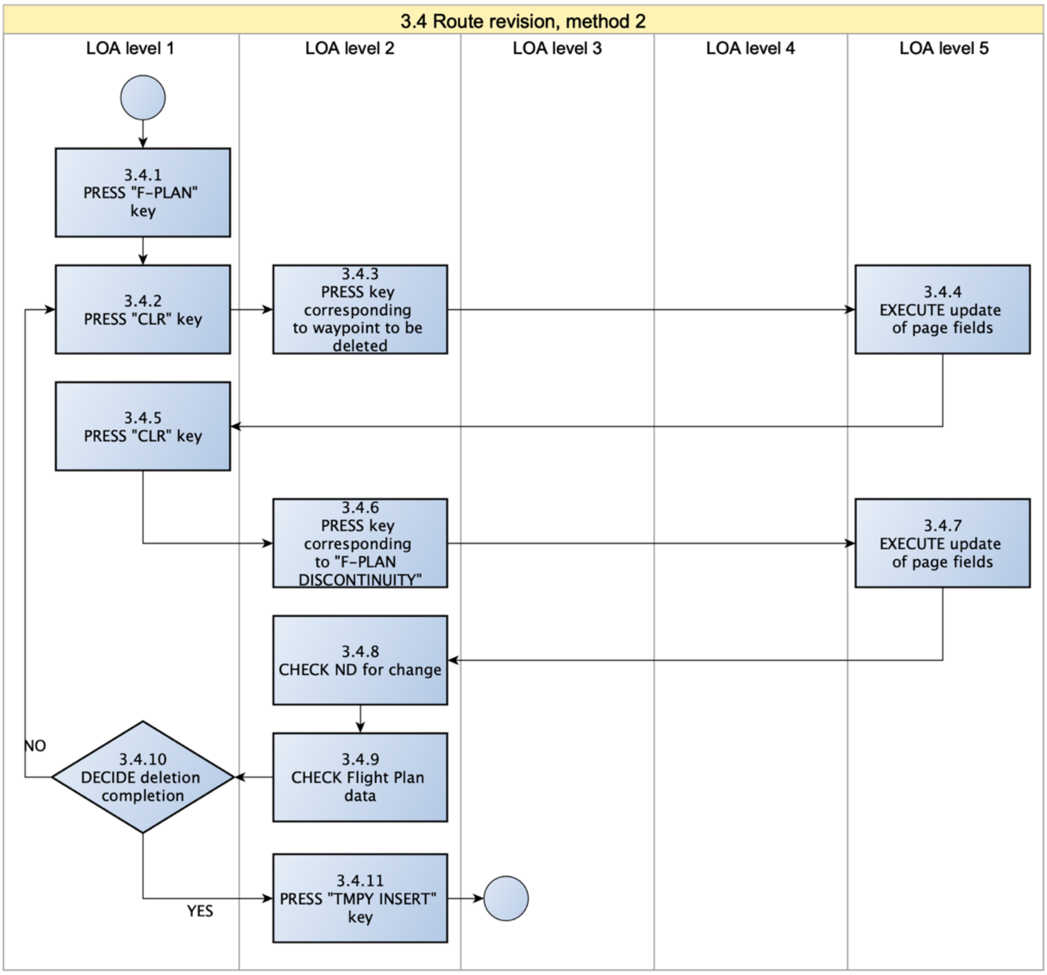


Figure 5.1: Waypoint deletion procedure 1, LOA analysis

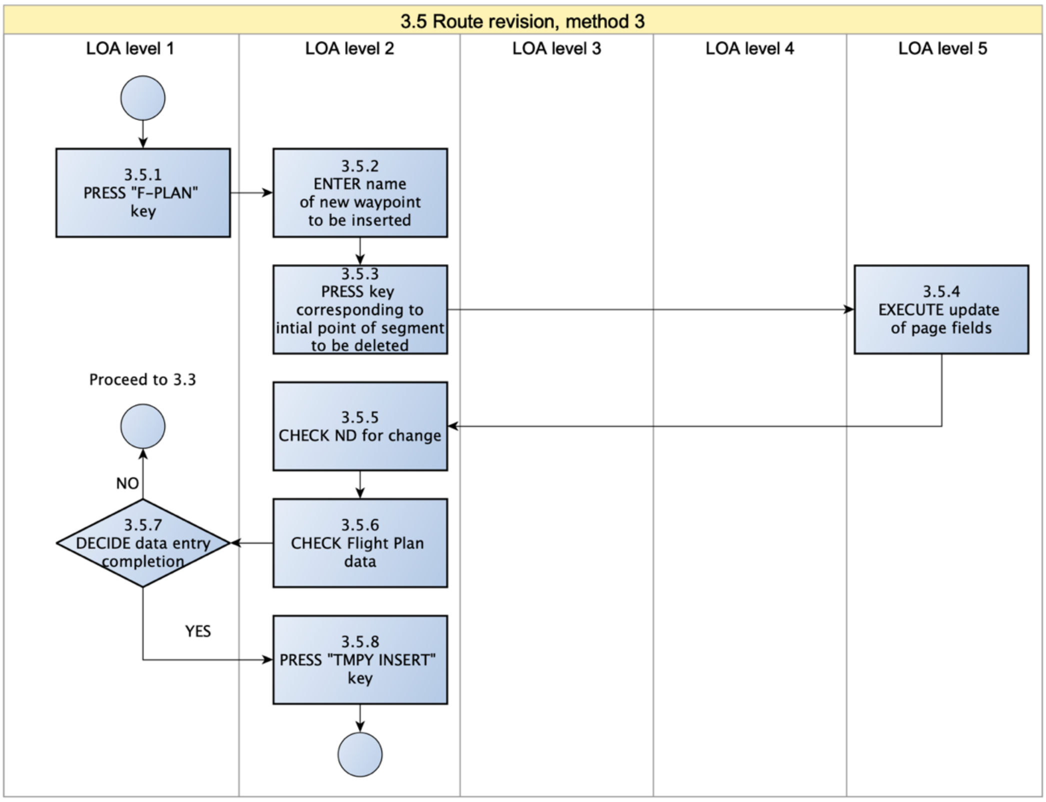


Figure 5.2: Waypoint deletion procedure 2, LOA analysis

The pilot will then add the new waypoints following the procedure outlined in Figure 5.3 (sub-goal task "Route revision, method 1"). It is noted that, when executing the tasks of the subject scenario, the first operation of "Route revision, method 1" is skipped since it has been already executed as part of the waypoint deletion procedure.

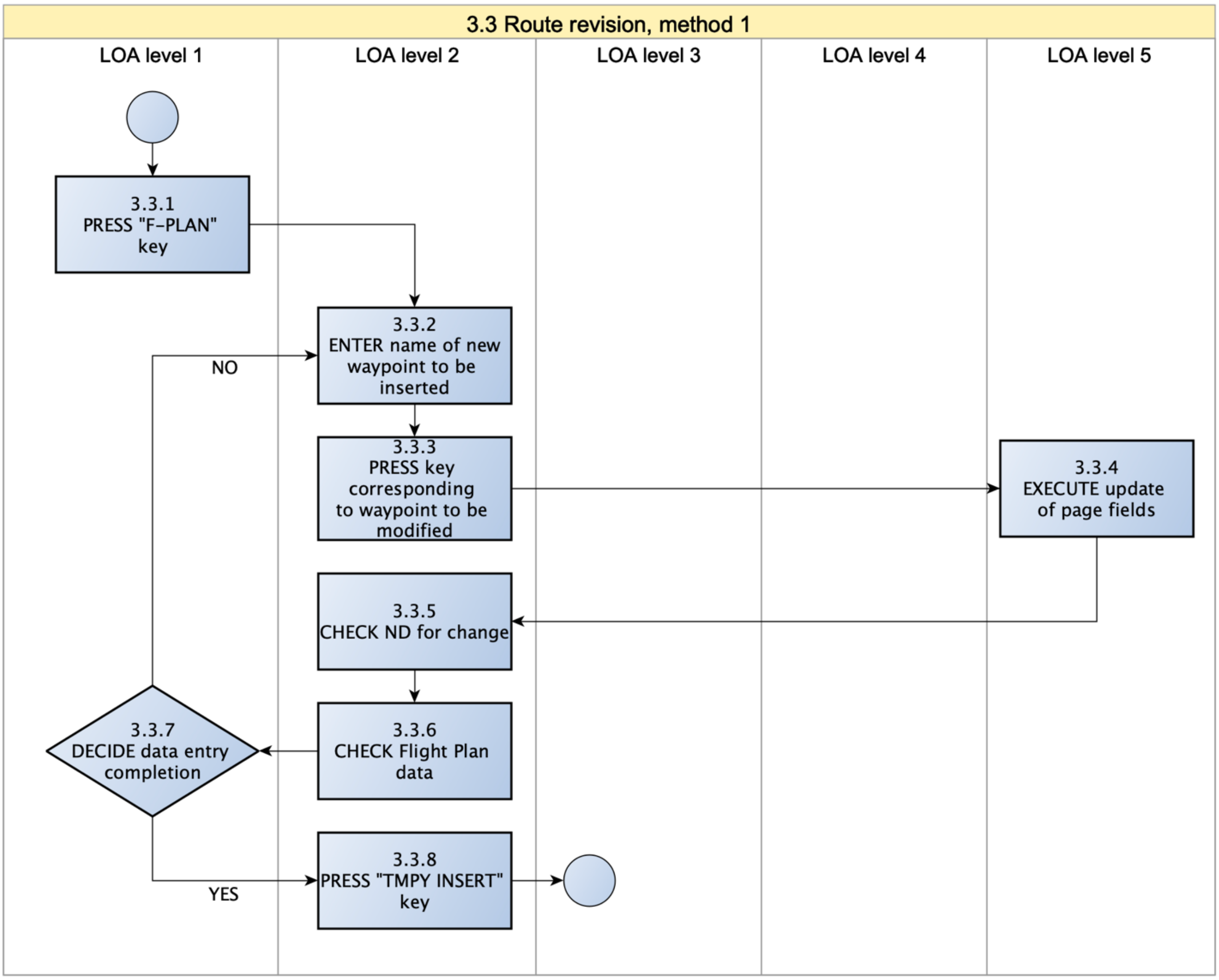


Figure 5.3: Waypoint insertion procedure, LOA analysis

Lastly, the pilot needs to check aircraft performance computations such as TOD point and estimated fuel at destination, following the procedure presented in Figure 5.4 (sub-goal task 3.6 "Assess aircraft performance"). This is essential in order to assess the feasibility of the modifications.

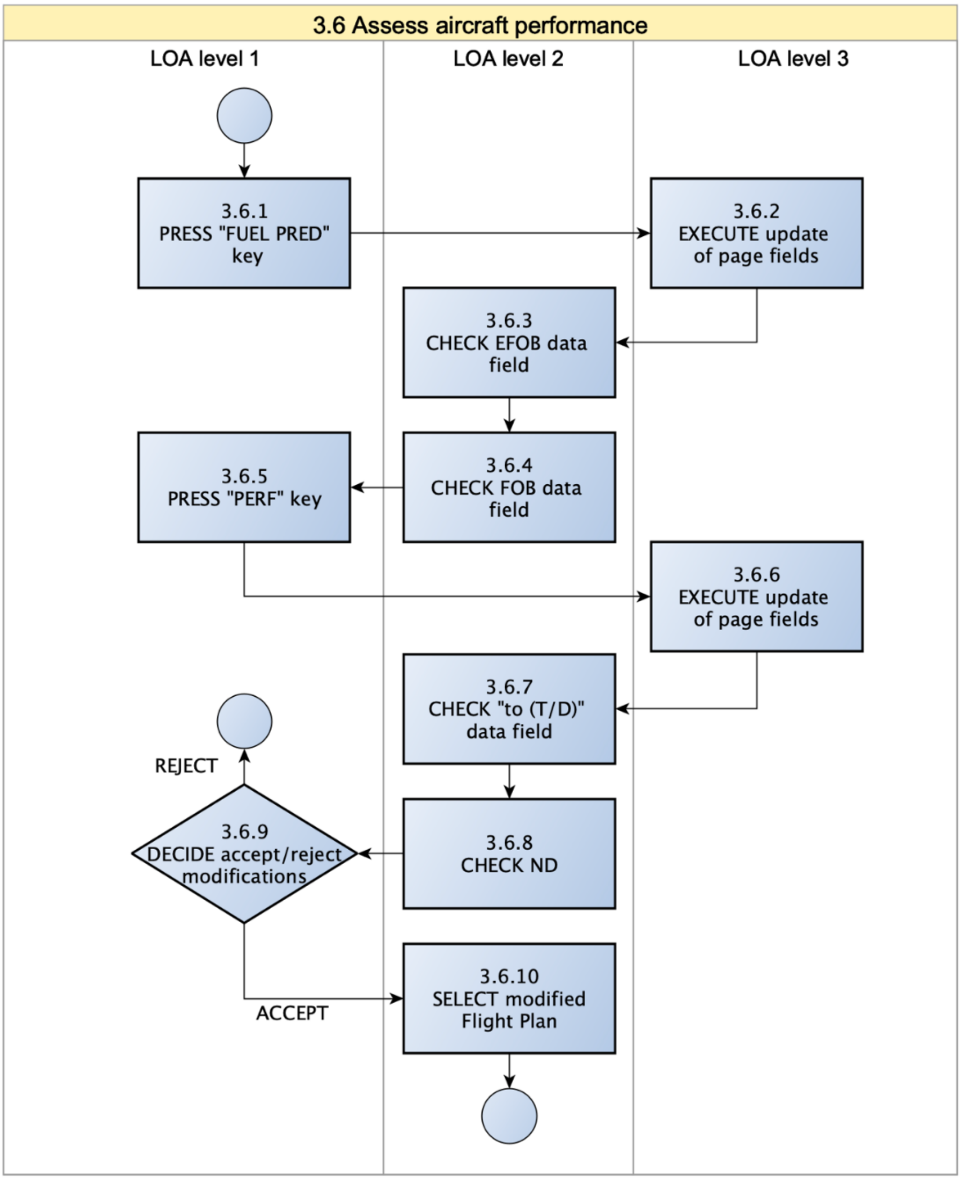


Figure 5.4: Assess aircraft performance procedure, LOA analysis

Second scenario, flight from Grottaglie to Bologna with diversion to Forlì

For this scenario the pilot first modifies the destination airport, and this will cause to automatically delete all the waypoints after the diversion point (LIPE and PELEG in this specific case). Then he/she needs to add the new waypoints that link the diversion point with the new destination airport.

The procedure to modify the destination airport is outlined in Figure 5.5 (sub-goal task 3.2 “Change destination airport”). New waypoints are added following the procedure presented in Figure 5.3 (sub-goal task 3.3 “Route revision, method 1”).

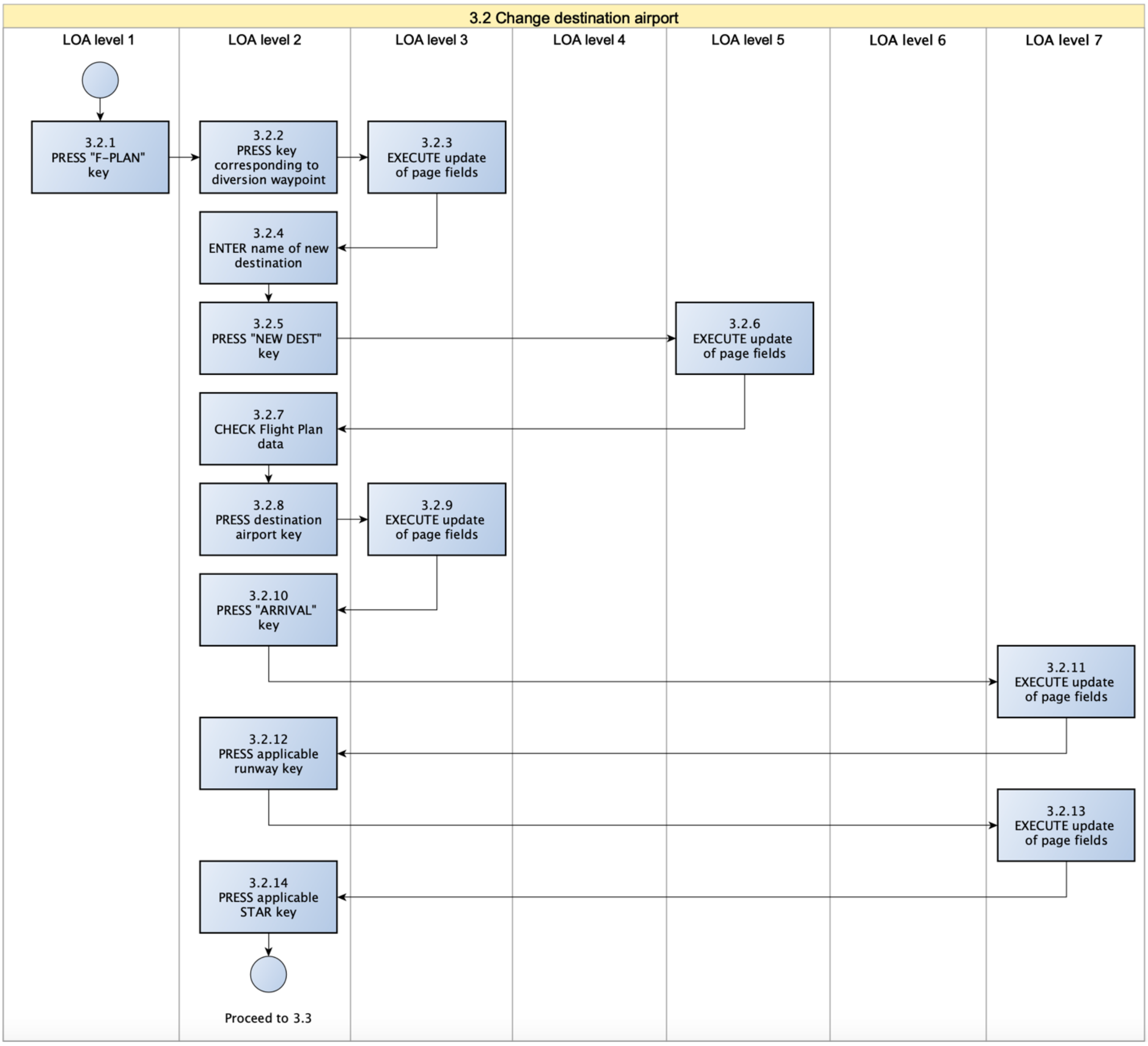


Figure 5.5: Destination airport change procedure, LOA analysis

In contrast with the previous scenario, the pilot now has to mandatorily comply with the request of the ATC, but it is still important to check the position of the TOD point so to assess any impact on fuel and preparation of the need to anticipate the descent maneuver and hence, the procedure outlined in Figure 5.4 (sub-goal task 3.6 “Assess aircraft performance”) needs to be followed.

5.2 IMPROVEMENT HYPOTHESES

In order to propose possible interaction improvement hypotheses, it has been decided to refer to a well-established automation philosophy and downselect the following elements, appropriate for driving the generation of the improvement hypotheses.

1. Apply automation as a tool to aid, not replace the pilot.
2. Use new technologies and functional capabilities only when:
    a. They result in a clear and distinct operational or efficiency advantages, and
    b. There is no adverse effect to the human-machine interface.

The proposed hypotheses evolve from being “aircraft centric”, i.e. the modifications would mainly impact the equipment installed on-board, to become “ATC-system centric”, in the sense that these modifications would impact both the aircraft and the related ATC infrastructures/procedures that manage air traffic.
The possible improvement hypotheses consist in:

- **Touch screen interaction:** the majority of pilots of large commercial aircraft still interact with on-board avionic systems using conventional interfaces, such as the Flight Control Unit (FCU) for autopilot control and the MCDU for flight management. The idea is to introduce new modes of interaction to the flight deck, in order to simplify the latter. There are several advantages associated with this technology (Zammit-Mangion et al, 2017), such as the ability to manage avionic systems in a more intuitive manner, and to control systems and view their status from the same display. Considering that touchscreen technology is consolidated and can be ruggedized for flight deck applications, this option could be implemented by working on a software that manages interaction aspects.
- **Voice interaction:** also known as Direct Voice Input (DVI), voice control has many potential benefits. For instance, pilots could issue commands “hands-

free", thus allowing them to use their hands for other tasks. Furthermore, pilots would reduce their look down times and could therefore increase their focus on concurrent tasks. Cockpit voice recognition technology has been in development for over a couple of decades. Nevertheless, it is recognized that this kind of interaction cannot substitute the MCDU-based FMS but could be used as a backup, or to aid pilots during busy periods.
Possible advantages of this blended interaction (Baber & Noyes, 2002):

- A reduction of workload, particularly in system's management, hence allowing the pilot to pay more attention to the flying tasks.
- Ease of operation.
- Benefit to single-seat aircraft.
- Speech's real advantage comes when the pilot is busy.
- Easier interaction.
- Single word can be used to replace navigation through nested page trees.
- Possible input time decrease depending on the required interaction: recalling different pages could benefit by this type of interaction but data entry could take the same time if not more.
- Improves head-up attention.

Possible issues:

- Noise in the cockpit.
- Syntax errors.
- Activation method.
- Required training.
- Recognition rate.
- Response time of the system.

- **Data link:** this technology could be used to improve the way pilots interact with the ATC and with the FMS when they have to modify a route**.** Nevertheless, this option cannot supersede an on-board means of control of the FMS due e.g. connectivity (availability and stability of the link) issues. Instead of modifying waypoints manually, the idea is to employ a data link message that includes every modification of the route and can be directly loaded into the FMS. As of today, data link technology is already in use for simpler transactions with the

ATC; industrial research and development is ongoing to expand capabilities and operational use up to exchange of flight plan updates.

In the following, considering only the procedures related to the two operational scenarios under analysis, the possible improvement hypotheses in relation to applicable sub-goals, are described in more details:

- 3.2 CHANGE DESTINATION AIRPORT
    - **Touch screen interaction:** it is assumed that the pilot has a touch display at his/her disposal, with the active route shown on it (upon pilot selection, elements like waypoints, airports, radio aids from the navigation database can be displayed on the map). The pilot receives a modification request which requires the change of the destination airport, and this could be done by first localizing and then clicking on the new airport ⇒ a menu appears with the available options ⇒ replace destination airport. Then, using a similar type of interaction, the waypoints to destination, STAR and approach procedures can be added.
    - **Voice interaction:** it is assumed to employ a specialized jargon to recall specific functions, like for instance “CHANGE destination airport”. The pilot can recall the function either by, e.g., pressing a specific button installed on his cloche and then speak or a microphone installed in the cockpit can detect the use of the specialized jargon (an appropriate means, informs the pilot when his message has been successfully detected). Therefore, the pilot first recalls the flight plan page, then recalls the “change destination airport” function and enters its name by spelling it. Then, using a similar type of interaction, the waypoints to destination, STAR and approach procedures can be added.

- 3.3 ROUTE REVISION, METHOD 1 (ADD WPT)
    - **Touch screen interaction:** it is assumed that the pilot has a touch display at his/her disposal, with the active route shown on it (upon pilot selection, elements like waypoints, airports, radio aids from the navigation database can be displayed on the map). The pilot receives a modification request which requires the addition of certain waypoints,

and this could be done by first localizing and then clicking on the waypoint of interest ⇒ a menu appears with the available options ⇒ add WPT. Then, the FMS updates the route and sequences the modified flight plan. Finally, the pilot has to determine whether other waypoints need to be added to the route.

  - **Voice interaction:** it is assumed to employ a specialized jargon to recall specific functions, like for instance "ADD waypoint". The pilot can recall the function either by, e.g., pressing a specific button installed on his cloche and then speak or a microphone installed in the cockpit can detect the use of the specialized jargon (an appropriate means, informs the pilot when his message has been successfully detected). Therefore, the pilot first recalls the flight plan page, then recalls the "add waypoint" function and enters its name by spelling it. Then, the FMS updates the route and sequences the modified flight plan. Finally, the pilot has to determine whether other waypoints need to be added to the route.

- 3.4 ROUTE REVISION, METHOD 2 (DELETE WPT)

  - **"Smarter FMS":** the aim is to decrease the number of keypresses by introducing a "multiple CLR function", select all the waypoints to be deleted and clear the discontinuity in the flight plan. Then the FMS automatically updates and sequences the flight plan (otherwise asks the pilot to intervene and informs him/her if the flight plan cannot be sequenced automatically).
  - **Touch screen interaction:** it is assumed that the pilot has a touch display at his/her disposal, with the active route shown on it (upon pilot selection, elements like waypoints, airports, radio aids from the navigation database can be displayed on the map). The pilot receives a modification request which requires the deletion of certain waypoints, and this could be done by first localizing and then clicking on the waypoint of interest ⇒ a menu appears with the available options ⇒ delete WPT. Then, the FMS updates the route and sequences the modified flight plan. Finally, the pilot has to determine whether other waypoints need to be deleted from the route.
  - **Voice interaction:** it is assumed to employ a specialized jargon to recall specific functions, like for instance "DELETE waypoint". The pilot can

recall the function either by, e.g., pressing a specific button installed on his cloche and then speak or a microphone installed in the cockpit can detect the use of the specialized jargon (an appropriate means, informs the pilot when his message has been successfully detected). Therefore, the pilot first recalls the flight plan page, then recalls the "delete waypoint" function and enters its name by spelling it. Subsequently, the FMS updates the route and sequences the modified flight plan. Finally, the pilot has to determine whether other waypoints need to be deleted from the route.

- 3.6 ASSESS AIRCRAFT PERFORMANCE
    - **Voice interaction:** it is assumed to employ a specialized jargon to recall specific functions, like for instance "CHECK fuel" or "PERF". The pilot can recall the function either by, e.g., pressing a specific button installed on his cloche and then speak or a microphone installed in the cockpit can detect the use of the specialized jargon (an appropriate means, informs the pilot when his message has been successfully detected). Therefore, the pilot first recalls the function, and then the FMS loads the correct page allowing the pilot to make his/her checks. This assessment is essential before accepting/rejecting the modifications required by the ATC.
- DATA LINK: assuming that the content of the ATC data link message includes every modification of the current route until final destination, this option could be used to replace the entire modification procedure. Therefore, the tasks 3.2, 3.3, and 3.4 could be blended into one single task called "MODIFY CURRENT ROUTE". It is assumed that the ATC sends a modified flight plan by means of a two-way data link system; information is forwarded to the FMS and then presented to the pilot. By doing so, there is no need to manually change the destination airport, delete waypoints or add them. Thus, the pilot is asked to review the modified route, acknowledge the receipt, confirm ability to comply and finally select the modified flight plan.

Table 18 summarizes the options that have been presented and links them to the operational scenarios.

Table 18: Improvement options

Sub-goals	3.2			3.3			3.4				3.6
Scenario	T/S	VI	D/L	T/S	VI	D/L	S	T/S	VI	D/L	VI
Route revision				✓	✓	✓	✓	✓	✓	✓	✓
Change destination	✓	✓	✓	✓	✓	✓					✓

Key: T/S “Touchscreen”, VI “Voice Interaction”, D/L “Data Link”, S “Smarter”.

5.3 ANALYSIS AND COMPARISON

The analysis of the improvement hypotheses is based on the structure outlined in Figure 5.6. Starting from the task analysis and the previously defined scenarios, both the original procedures and the improvement hypotheses have been analyzed in terms of number of keypresses, salience of the visual cues and execution times (by means of the Keystroke Level Model, KLM).

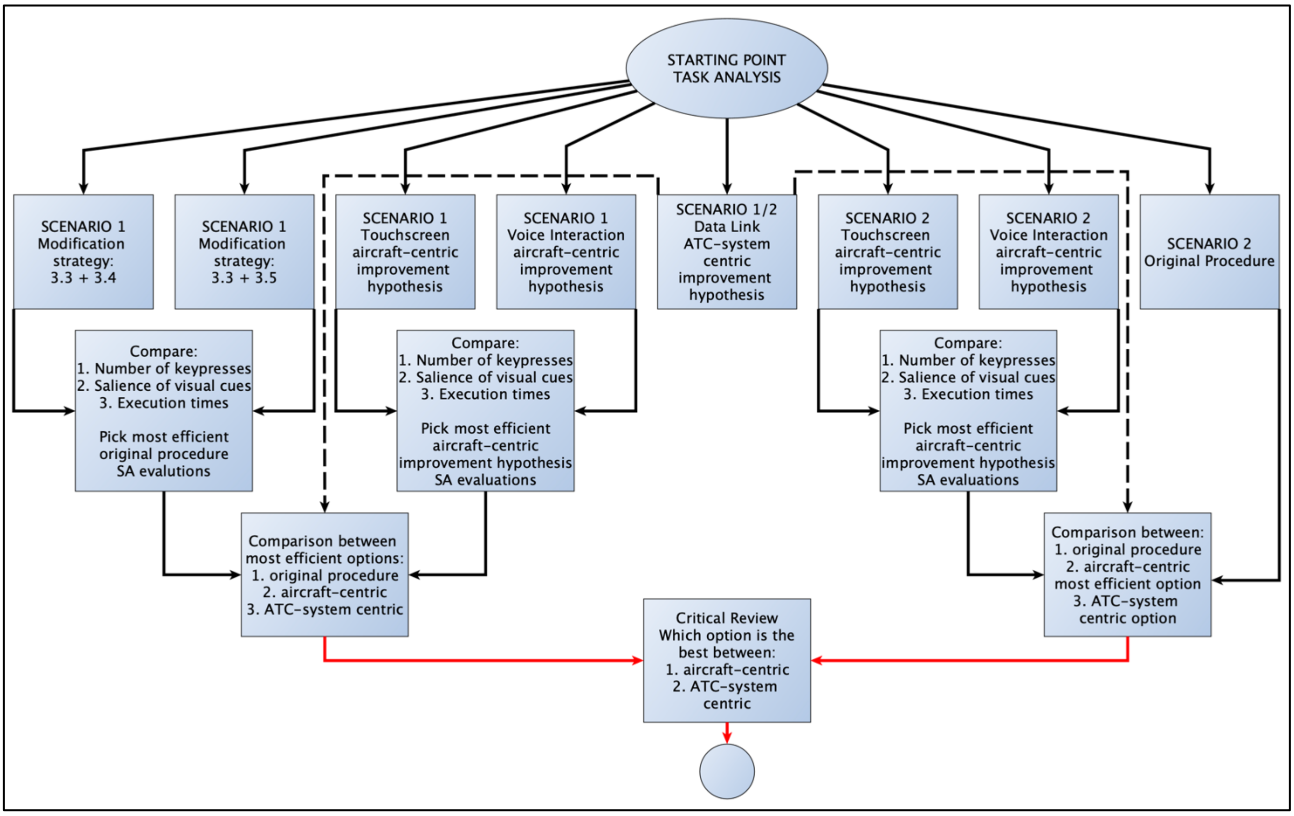


Figure 5.6: Structure of the analysis

The outcome of each single assessment has been compared as follows:

1. Comparison, based on the two operational scenarios, between MCDU-based procedures (if there is more than one option available, like for the first scenario) in order to determine the most efficient one.
2. Comparison between the aircraft centric improvement hypotheses in order to determine the most efficient one.
3. Final comparison between the most efficient options that have been determined in the previous steps and the ATC-system centric improvement hypothesis.

Within the comparison, the KLM (Kieras, 2001) is applied considering the following adaptations with respect to the baseline:

- The operator W (t), namely “waiting for the system to respond” is assumed to have the same value in all of the alternative designs and therefore will not be included in the KLM analysis.
- The operator K* is used to indicate a voice command as opposed to K which represents a keystroke. Voice commands execution times have been determined experimentally by evaluating the time needed to pronounce the exact command (Desmarais et al, 2007).
- The execution times for the operators K, H and T are taken to be: K = 1.35 sec, H = 0.6 sec and T = n*K, where n is the number of characters in a sequence (K. H. Miller, 1976). These execution times are better suited to be used for the analysis subject of this work.
- The estimate of the execution times for the improvement hypotheses is preliminary because a detailed concept of the HMI goes beyond the scope of this work.

5.3.1 FLIGHT FROM GROTTAGLIE TO BOLOGNA WITH ROUTE MODIFICATION REQUEST, SCENARIO ANALYSIS

MODIFICATION STRATEGY 1 (3.3+3.4)

Figure 5.1 presents the procedure to delete a waypoint. The procedures to add a waypoint and to assess aircraft performance have been outlined previously in Figures 5.3 and 5.4 respectively.

The characteristics of this procedure are:

- Number of keypresses: 75.
    - Delete waypoints AMGOK, GUDPO, IVMEP: 13 keypresses (approximately 4 per waypoint, plus F-PLAN key).
    - Add waypoints ESODU, ERPOG, ARSOB, NUTRO, LAPVO, MASEG, ANC, BIDMA, SORUG, ASDOR: 59 keypresses (approximately 6 per waypoint, except for ANC, plus TMPY INSERT key).
    - Assess aircraft performance: 3.
- Salience of the visual cues: partial because most operations present competing visual cues. The FMS proposes various pages that can be accessed by pressing the corresponding line select keys, and therefore the pilot has to search for the desired one.
- Execution times (evaluation based on KLM model):

Table 19: Waypoint deletion execution time, strategy 1

Steps	Description	Operator	Operator Time	Elapsed Time
1	CLR key	K	1.35	1.35
2	Search for waypoint in list	M	1.2	2.55
3	Press key corresponding to waypoint to be deleted	K	1.35	3.9
4	CLR key	K	1.35	5.25
5	Search for “F-PLAN DISCONTINUITY”	M	1.2	6.45
6	Press key corresponding to “F-PLAN DISCONTINUITY”	K	1.35	7.8
7	Check ND	M	1.2	9

9 seconds represent the time needed to delete a single waypoint and hence, considering the three waypoints that need to be deleted, the total is 27

seconds. There are two more steps that need to be added which are not included in the table because they take place only once:

- Hand to FMS, 0.6 sec
- F-PLAN key, 1.35 sec

Therefore, the total amount of time that is needed to fulfill this task is 28.95 seconds.

Table 20: Waypoint addition execution time, strategy 1

Steps	Description	Operator	Operator Time	Elapsed Time
1	Enter waypoint name	T (5)	1.35*5 = 6.75	6.75
2	Verify name correctness on scratchpad	M	1.2	7.95
3	Search for correct waypoint position in list	M	1.2	9.15
4	Press corresponding line select key	K	1.35	10.5
5	Verify correct placement	M	1.2	11.7

11.7 seconds represent the time needed to add a single waypoint and hence, considering the ten waypoints that need to be added, the total is 117 seconds. There is one final step that needs to be added which is not included in the table because it takes place only once: TMPY INSERT key, 1.35 sec. Therefore, the total amount of time that is needed to fulfill this task is 118.35 seconds.

Table 21: Assess aircraft performance execution time, strategy 1

Steps	Description	Operator	Operator Time	Elapsed Time
1	FUEL PRED key	K	1.35	1.35
2	Search for EFOB data field	M	1.2	2.55
3	Search for FOB data field	M	1.2	3.75
4	PERF key	K	1.35	5.1
5	Search for (T/D) data field	M	1.2	6.3

6.3 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance in order to decide whether to accept/reject the proposed modifications.

Summary: **TOTAL TIME MODIFICATION STRATEGY 1 (3.3+3.4+3.6)** = 28.95 + 118.35 + 6.3 = **153.6** seconds.

MODIFICATION STRATEGY 2 (3.3+3.5)

Figure 5.2 presents the procedure to delete a segment. The procedures to add a waypoint and to assess aircraft performance have been outlined previously in Figures 5.3 and 5.4 respectively.

The characteristics of this procedure are:

- Number of keypresses: 63.

    - Delete segment composed by AMGOK, GUDPO, IVMEP by adding the waypoint ESODU: 7 keypresses.
    - Add waypoints ERPOG, ARSOB, NUTRO, LAPVO, MASEG, ANC, BIDMA, SORUG, ASDOR: 53 keypresses (approximately 6 per waypoint, aside ANC, plus TMPY INSERT key).
    - Assess aircraft performance: 3.

- Salience of the visual cues: partial because most operations present competing visual cues. The FMS proposes various pages that can be accessed by pressing the corresponding line select keys, and therefore the pilot has to search for the desired one.
- Execution times (evaluation based on KLM model):

Table 22: Segment deletion execution time, strategy 2

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to FMS	H	0.6	0.6
2	F-PLAN key	K	1.35	1.95
3	Enter new waypoint name	T (5)	1.35*5 = 6.75	8.7
4	Verify name correctness on scratchpad	M	1.2	9.9
5	Search for correct waypoint position in list	M	1.2	11.1
6	Press corresponding line select key	K	1.35	12.45
7	Verify correct placement	M	1.2	13.65

13.65 seconds represent the time needed to delete the entire segment.

Table 23: Waypoint addition execution time, strategy 2

Steps	Description	Operator	Operator Time	Elapsed Time
1	Enter waypoint name	T (5)	1.35*5 = 6.75	6.75
2	Verify name correctness on scratchpad	M	1.2	7.95
3	Search for correct waypoint position in list	M	1.2	9.15
4	Press corresponding line select key	K	1.35	10.5
5	Verify correct placement	M	1.2	11.7

11.7 seconds represent the time needed to add a single waypoint and hence, considering the nine waypoints that need to be added, the total is 105.3 seconds.

There is one final step that needs to be added which is not included in the table because it takes place only once: TMPY INSERT key, 1.35 sec. Therefore, the total amount of time that is needed to fulfill this task is 106.65 seconds.

Table 24: Assess aircraft performance execution time, strategy 2

Steps	Description	Operator	Operator Time	Elapsed Time
1	FUEL PRED key	K	1.35	1.35
2	Search for EFOB data field	M	1.2	2.55
3	Search for FOB data field	M	1.2	3.75
4	PERF key	K	1.35	5.1
5	Search for (T/D) data field	M	1.2	6.3

6.3 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance in order to decide whether to accept/reject the proposed modifications.

Summary: **TOTAL TIME MODIFICATION STRATEGY 2 (3.3+3.5+3.6)** = 13.65 + 106.65 + 6.3 = **126.6** seconds.

COMPARISON BETWEEN MCDU-BASED MODIFICATION STRATEGIES

From the analysis of the previous two procedures, the following preliminary conclusions can be drawn:

- Modification strategy 2 appears to be more efficient because it requires less keypresses (63 vs. 75) and less time to complete the task (126.6 sec vs. 153.6 sec).
- The salience of the visual cues is partial for both modification strategies and hence there is no major difference between them. However, the overall effort in finding applicable cues is less in the latter case because of the lower number of keypresses.
- For both strategies the pilot has to work “head-down” but, considering that modification strategy 2 requires less time to be completed, the latter gives the opportunity of keeping better SA on other tasks and external scenario.

Therefore, based on the previous considerations, **MODIFICATION STRATEGY 2 (3.3 + 3.5)** appears to be the most efficient**.**

TOUCHSCREEN INTERACTION

Figures 5.7 outlines the possible procedure to delete a waypoint by using a touchscreen interface whilst the strategy to add a waypoint is presented in Figure 5.8. The procedure to assess aircraft performance has been outlined previously in Figure 5.4 and would not be impacted by using touchscreen interaction.

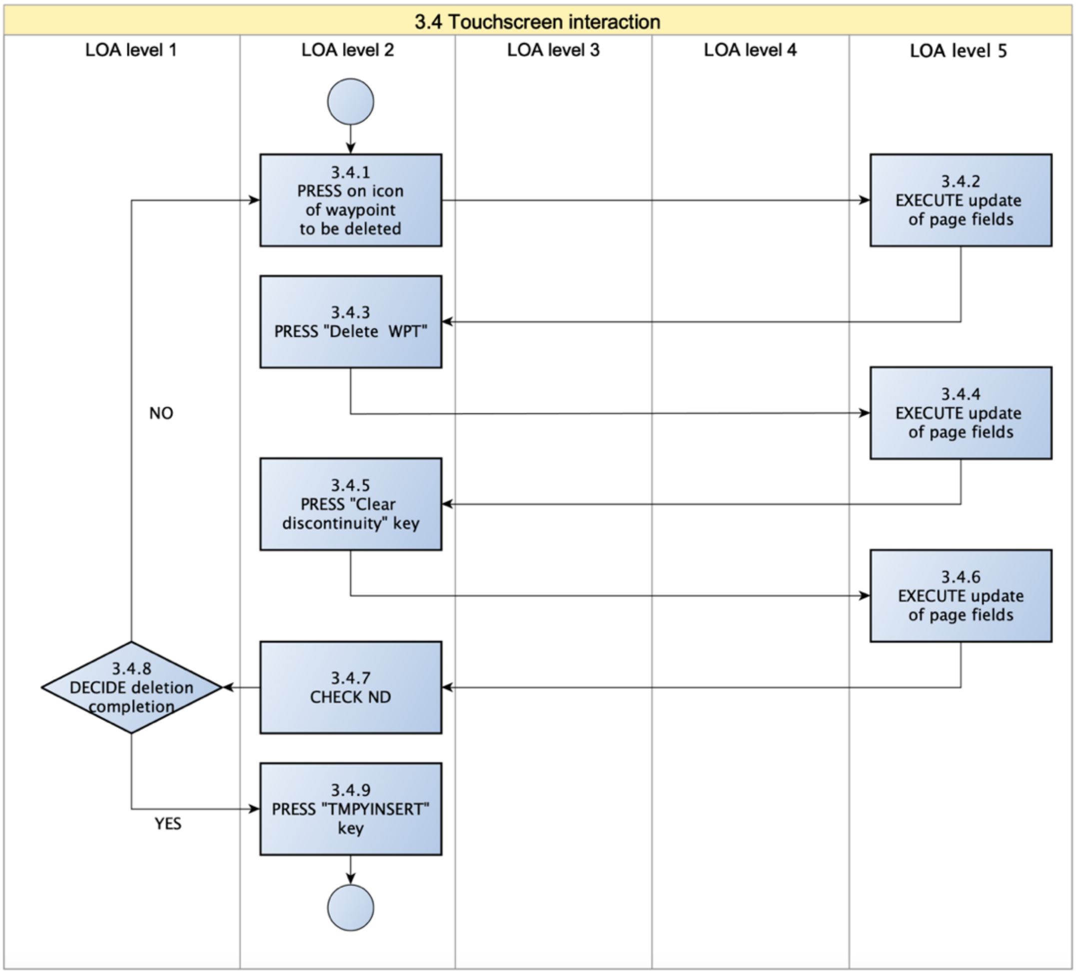


Figure 5.7: Touchscreen waypoint deletion procedure, LOA analysis

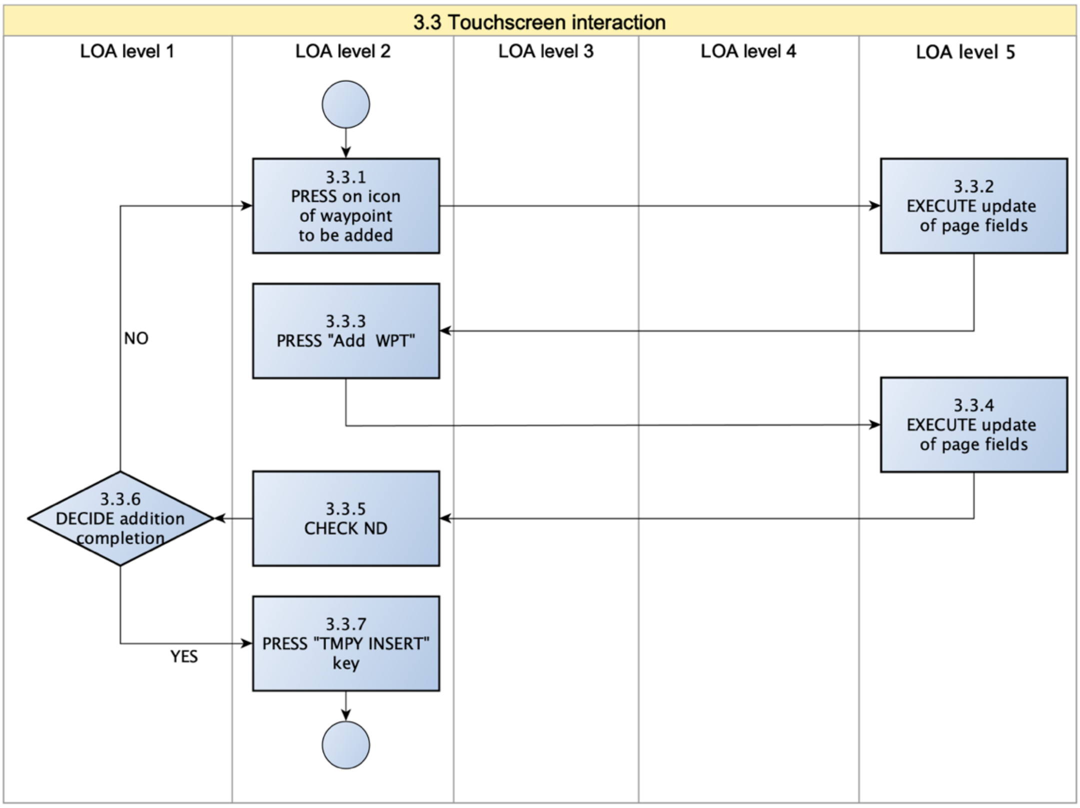


Figure 5.8: Touchscreen waypoint addition procedure, LOA analysis

The characteristics of this procedure are:

- Number of keypresses: 33.
  - Delete waypoints AMGOK, GUDPO, IVMEP: 9 keypresses (approximately 3 per waypoint).
  - Add waypoints ESODU, ERPOG, ARSOB, NUTRO, LAPVO, MASEG, ANC, BIDMA, SORUG, ASDOR: 21 keypresses (approximately 2 per waypoint, plus key to insert modification).
  - Assess aircraft performance: 3.

- Salience of the visual cues: partial because most operations present competing visual cues. The touchscreen shows on the map various waypoints that could be added by clicking on them, and therefore the pilot has to search for the desired ones. It is assumed that the scale of the map is optimized for the area of interest.
- Execution times (evaluation based on KLM model):

Table 25: Waypoint deletion execution time, touchscreen

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to touch screen	H	0.6	0.6
2	Search for waypoint on map	M	1.2	1.8
3	Press on waypoint to be deleted	K	1.35	3.15
4	Press on “delete waypoint”	K	1.35	4.5
5	Press on “clear discontinuity”	K	1.35	5.85
6	Verify correct deletion	M	1.2	7.05

7.05 seconds represent the time needed to delete a single waypoint and hence, considering the three waypoints that need to be deleted, the total is 21.15 seconds.

Table 26: Waypoint addition execution time, touchscreen

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to touch screen	H	0.6	0.6
2	Search for waypoint on map	M	1.2	1.8
3	Press on waypoint to be added	K	1.35	3.15
4	Press on "add waypoint"	K	1.35	4.5
5	Verify correct addition	M	1.2	5.7

5.7 seconds represent the time needed to add a single waypoint and hence, considering the ten waypoints that need to be added, the total is 57 seconds. There is one final step that needs to be added which is not included in the table because it takes place only once: TMPY INSERT key, 1.35 sec. Therefore, the total amount of time that is needed to fulfill this task is 58.35 seconds.

Table 27: Assess aircraft performance execution time, touchscreen

Steps	Description	Operator	Operator Time	Elapsed Time
1	FUEL PRED key	K	1.35	1.35
2	Search for EFOB data field	M	1.2	2.55
3	Search for FOB data field	M	1.2	3.75
4	PERF key	K	1.35	5.1
5	Search for (T/D) data field	M	1.2	6.3

The performance of the aircraft is assessed in the standard way and 6.3 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance in order to decide whether to accept/reject the proposed modifications.

Summary: **TOTAL TIME TOUCHSCREEN INTERACTION** = 21.15 + 58.35 + 6.3 = **85.8** seconds.

VOICE INTERACTION

Figure 5.9 presents the possible procedure to delete a waypoint by using a vocal interaction. The procedures to add a waypoint and to assess aircraft performance are outlined in Figures 5.10 and 5.11 respectively.

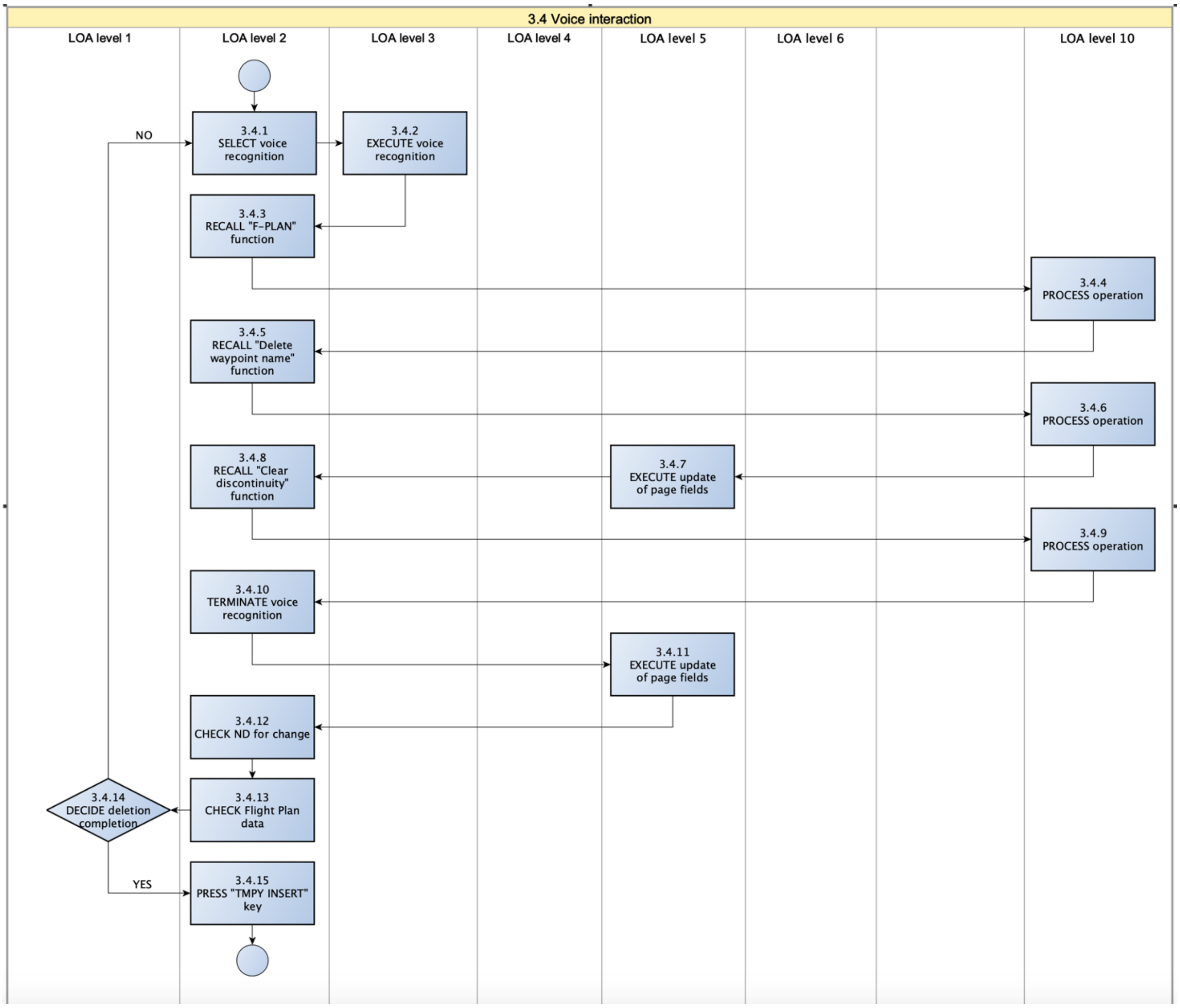


Figure 5.9: Voice interaction waypoint deletion procedure, LOA analysis

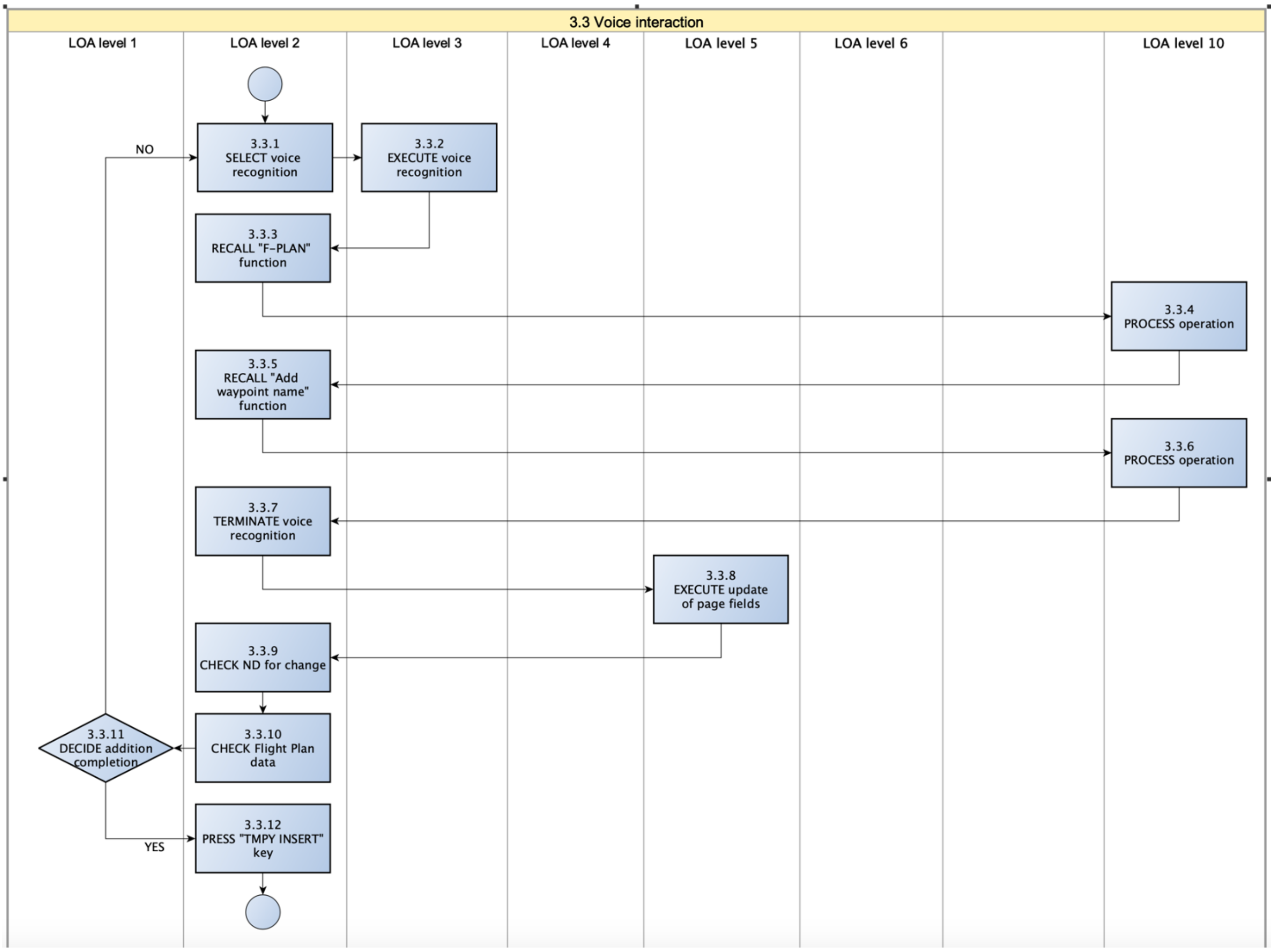


Figure 5.10: Voice interaction waypoint addition procedure, LOA analysis

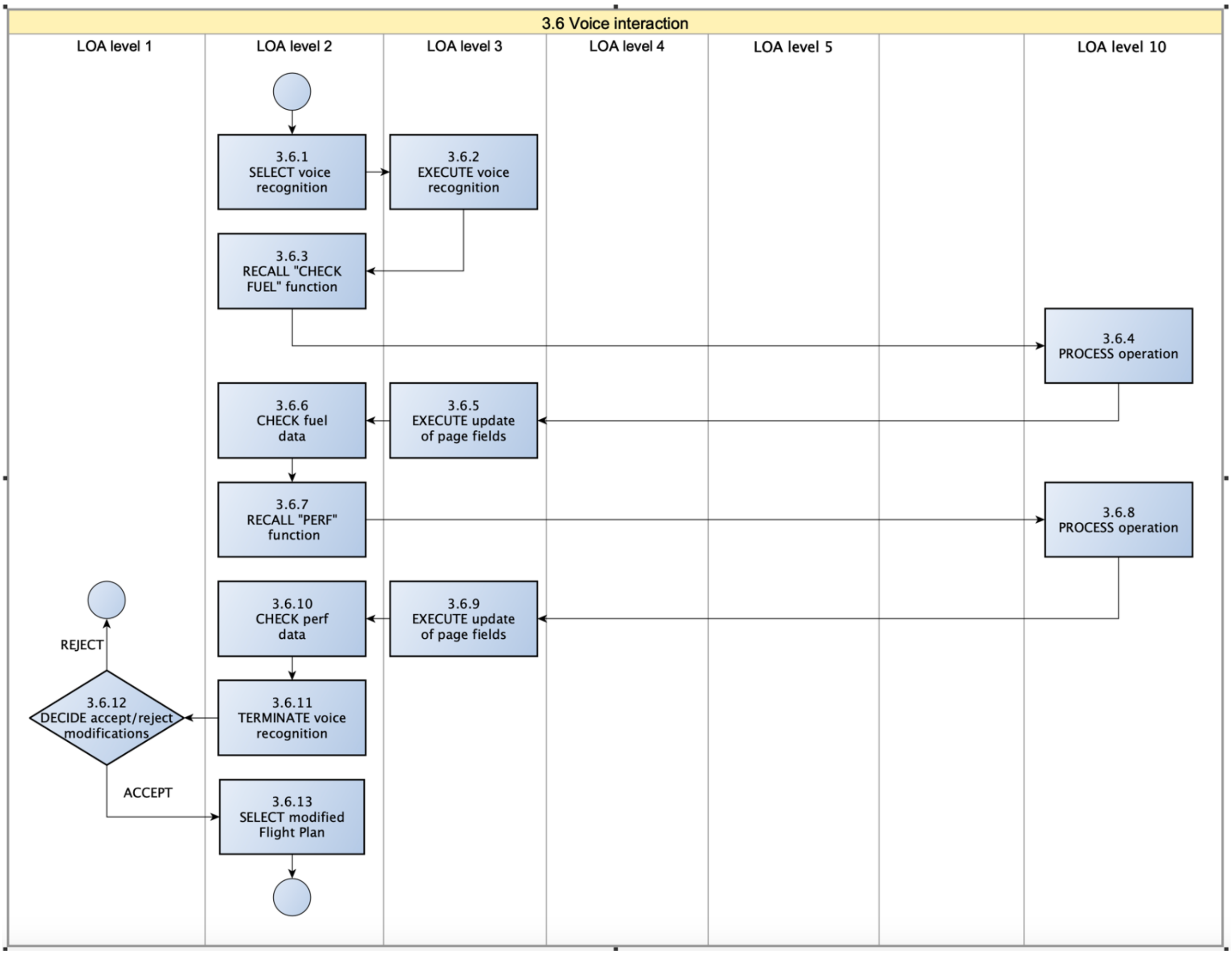


Figure 5.11: Voice interaction assessment procedure, LOA analysis

The characteristics of this procedure are:

- Number of keypresses: 30.
  - Delete waypoints AMGOK, GUDPO, IVMEP: 6 keypresses (approximately 2 per waypoint that are needed to initiate and terminate voice recognition).
  - Add ESODU, ERPOG, ARSOB, NUTRO, LAPVO, MASEG, ANC, BIDMA, SORUG, ASDOR: 21 keypresses (approximately 2 per waypoint, plus key to insert modification).
  - Assess aircraft performance: 3.
- Salience of the visual cues: none because most operations do not present visual cues. Since the pilot issues voice commands, there is no visual aid while performing the interaction.

- Execution times (evaluation based on KLM model):

Table 28: Waypoint deletion execution time, voice interaction

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to cloche	H	0.6	0.6
2	Press push-to-talk to initiate voice recognition	K	1.35	1.95
3	Recall F-PLAN page	K*	2	3.95
4	Recall “delete waypoint name” function	K*	5	8.95
5	Recall “clear discontinuity” function	K*	2	10.95
6	Press push-to-talk to terminate voice recognition	K	1.35	12.3

12.3 seconds represent the time needed to delete a single waypoint and hence, considering the three waypoints that need to be deleted, the total is 36.9 seconds.

Table 29: Waypoint addition execution time, voice interaction

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to cloche	H	0.6	0.6
2	Press push-to-talk to initiate voice recognition	K	1.35	1.95
3	Recall F-PLAN page	K*	2	3.95
4	Recall “add waypoint name” function	K*	5	8.95
5	Press push-to-talk to terminate voice recognition	K	1.35	10.3

10.3 seconds represent the time needed to add a single waypoint and hence, considering the ten waypoints that need to be added, the total is 103 seconds. There is one final step that needs to be added which is not included in the table because it takes place only once: TMPY INSERT key, 1.35 sec. Therefore, the total amount of time that is needed to fulfill this task is 104.35 seconds.

Table 30: Assess aircraft performance execution time, voice interaction

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to cloche	H	0.6	0.6
2	Press push-to-talk to initiate voice recognition	K	1.35	1.95
3	Recall “check fuel” function	K*	2	3.95
4	Search for EFOB data field	M	1.2	5.15
5	Search for FOB data field	M	1.2	6.35
6	Recall “perf” function	K*	2	8.35

7	Search for (T/D) data field	M	1.2	9.55
8	Press push-to-talk to terminate voice recognition	K	1.35	10.9

10.9 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance in order to decide whether to accept/reject the proposed modifications.

Summary: **TOTAL TIME VOICE INTERACTION** = 36.9 + 104.35 + 10.9 = **152.15** seconds.

COMPARISON BETWEEN THE AIRCRAFT-CENTRIC IMPROVEMENT HYPOTHESES

From the analysis of the previous two procedures, the following preliminary conclusions can be drawn:

- Touchscreen interaction appears to be more efficient because, despite requiring slightly more keypresses (33 vs. 30), there is a sensible difference in execution times (85.8 sec vs. 152.15 sec).
- The salience of the visual cues is better for the touchscreen interaction because there are cues that can aid the pilot whilst the voice counterpart does not present any.
- An advantage of the voice interaction is that it reduces the time for the pilot to work “head-down” while interacting with the FMS, whilst the touchscreen counterpart requires more time. Nevertheless, since the touchscreen interaction is much faster, the SA is expected to be better for the latter.

Therefore, based on the previous considerations, the most efficient aircraft-centric improvement hypothesis appears to be the **TOUCHSCREEN INTERACTION**.

DATA LINK

Figure 5.12 outlines the possible procedure to modify the entire route by using a data link communication. The procedure to assess aircraft performance has been outlined previously in Figure 5.4.

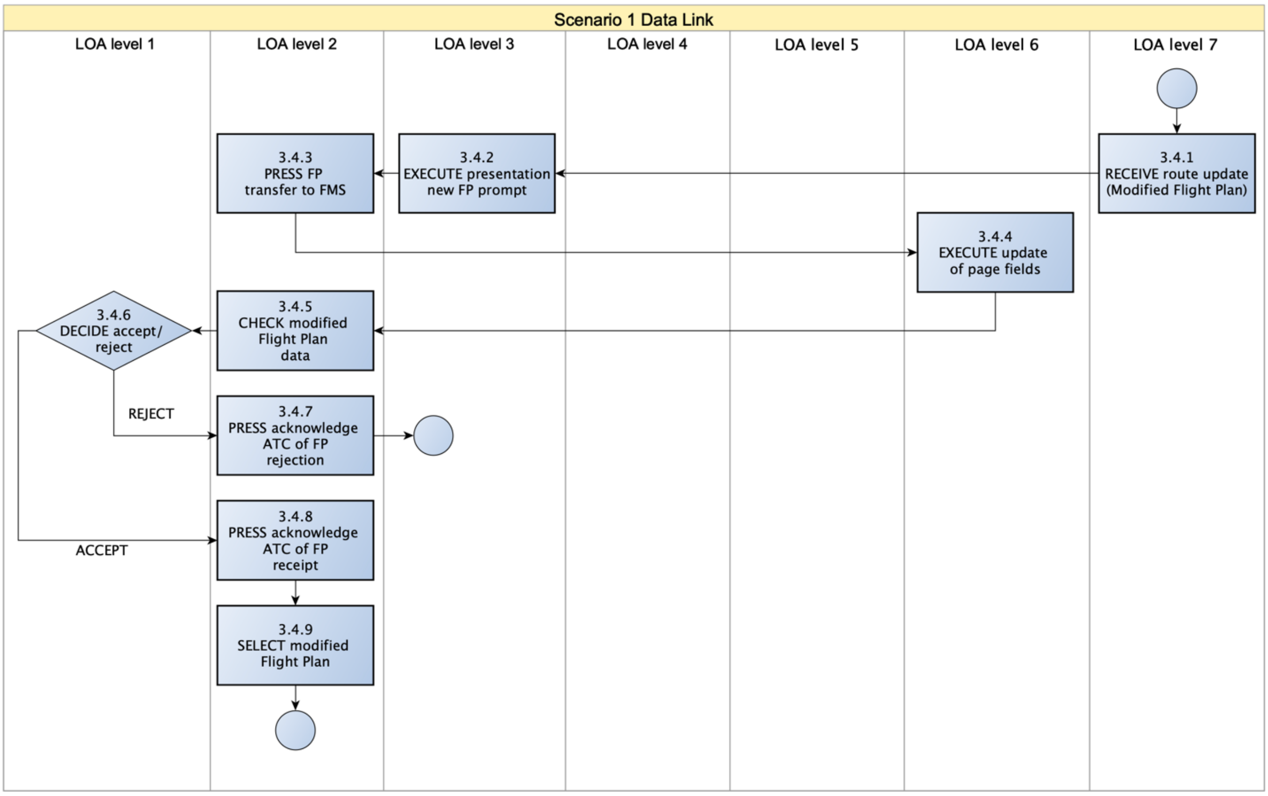


Figure 5.12: Data link complete route modification, LOA analysis

The characteristics of this procedure are:

- Number of keypresses (minimum preliminary estimate that could change in relation to the mechanism of the data link message management rules): 6.
    - Transfer flight plan to FMS, acknowledge ATC of flight plan receipt/rejection and eventually select the modified flight plan: 3 keypresses.
    - Assess aircraft performance: 3.
- Salience of the visual cues: partial because most operations present competing visual cues. A temporary flight plan page is displayed after the modified flight plan has been forwarded to the FMS. If the pilot accepts, the modifications are then loaded into the active flight plan.

COMPARISON BETWEEN THE MOST EFFICIENT SCENARIO 1 OPTIONS

From the analysis of all the procedures related to the first scenario, the following preliminary conclusions can be drawn:

- Data link appears to be the best solution. Nevertheless, this technology needs to be further developed before it can be fully implemented. The deployment of this technology would improve the efficiency of communications between pilots and controllers. Ultimately, ATC safety and capacity could increase as well. As of today, Controller-Pilot Data Link Communications (CPDLC) allows specific non-urgent ATC messages to be communicated via text message, rather than voice.
- Touchscreen interaction presents a few advantages if compared to the current procedure since it requires less keypresses (33 vs. 63) and less time to complete the task (85.8 vs. 126.6). Furthermore, touchscreen technology is already mature and reliable enough to be installed in the flight deck.
- The data link solution provides the best possible SA because the interaction with the FMS would be very short and therefore the pilot would always be in control of the situation.

Therefore, based on the previous considerations, the most efficient improvement hypothesis appears to be the DATA LINK option. Nevertheless, considering the complexity related to infrastructure implementation and operational procedures definition tied to managing flight plan over data link, a touchscreen-based interaction would already provide an improvement if compared to the current MCDU-based counterpart.

5.3.2 FLIGHT FROM GROTTAGLIE TO BOLOGNA WITH DIVERSION TO FORLI’, SCENARIO ANALYSIS

MCDU-BASED PROCEDURE

Figure 5.5 presents the procedure to change destination airport. The procedures to add a waypoint and to assess aircraft performance have been outlined previously in Figures 5.3 and 5.4 respectively.

The characteristics of this procedure are:

- Number of keypresses: 21.

  - Change destination airport: 11 keypresses.
  - Add ASDOR: 7 keypresses (approximately 6 per waypoint plus key to insert data).
  - Assess aircraft performance: 3.

- Salience of the visual cues: partial because most operations present competing visual cues. The FMS proposes various pages that can be accessed by pressing the corresponding line select keys, and therefore the pilot has to search for the desired one.
- Execution times (evaluation based on KLM model):

Table 31: Change destination airport execution time, original procedure

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to FMS	H	0.6	0.6
2	F-PLAN key	K	1.35	1.95
3	Search for diversion waypoint in list	M	1.2	3.15
4	Press key corresponding to diversion waypoint	K	1.35	4.5
5	Enter name new destination airport	T (4)	1.35*4 = 5.4	9.9
6	Verify name correctness on scratchpad	M	1.2	11.1
7	Press “new dest” line select key	K	1.35	12.45
8	Search for destination airport in list	M	1.2	13.65
9	Press destination airport key	K	1.35	15
10	Press “arrival” line select key	K	1.35	16.35
11	Search for runway in list	M	1.2	17.55
12	Press applicable runway line select key	K	1.35	18.9
13	Search for STAR in list	M	1.2	20.1
14	Press applicable STAR line select key	K	1.35	21.45

21.45 seconds represent the time needed to change the destination airport.

Table 32: Waypoint addition execution time, original procedure

Steps	Description	Operator	Operator Time	Elapsed Time
1	Enter waypoint name	T (5)	1.35*5 = 6.75	6.75
2	Verify name correctness on scratchpad	M	1.2	7.95
3	Search for correct waypoint position in list	M	1.2	9.15
4	Press corresponding line select key	K	1.35	10.5

5	Verify correct placement	M	1.2	11.7
6	TMPY INSERT key	K	1.35	13.05

13.05 seconds represent the time needed to add the waypoint ASDOR and insert the modification into the flight plan.

Table 33: Assess aircraft performance execution time, original procedure

Steps	Description	Operator	Operator Time	Elapsed Time
1	FUEL PRED key	K	1.35	1.35
2	Search for EFOB data field	M	1.2	2.55
3	Search for FOB data field	M	1.2	3.75
4	PERF key	K	1.35	5.1
5	Search for (T/D) data field	M	1.2	6.3

6.3 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance.

Summary: **TOTAL TIME MCDU-BASED PROCEDURE** = 21.45 + 13.05 + 6.3 = **40.8** seconds.

TOUCHSCREEN INTERACTION

Figures 5.13 outlines the possible procedure to change destination airport by using a touchscreen interface. The procedures to add a waypoint and to assess aircraft performance have been outlined previously in Figures 5.8 and 5.4 respectively.

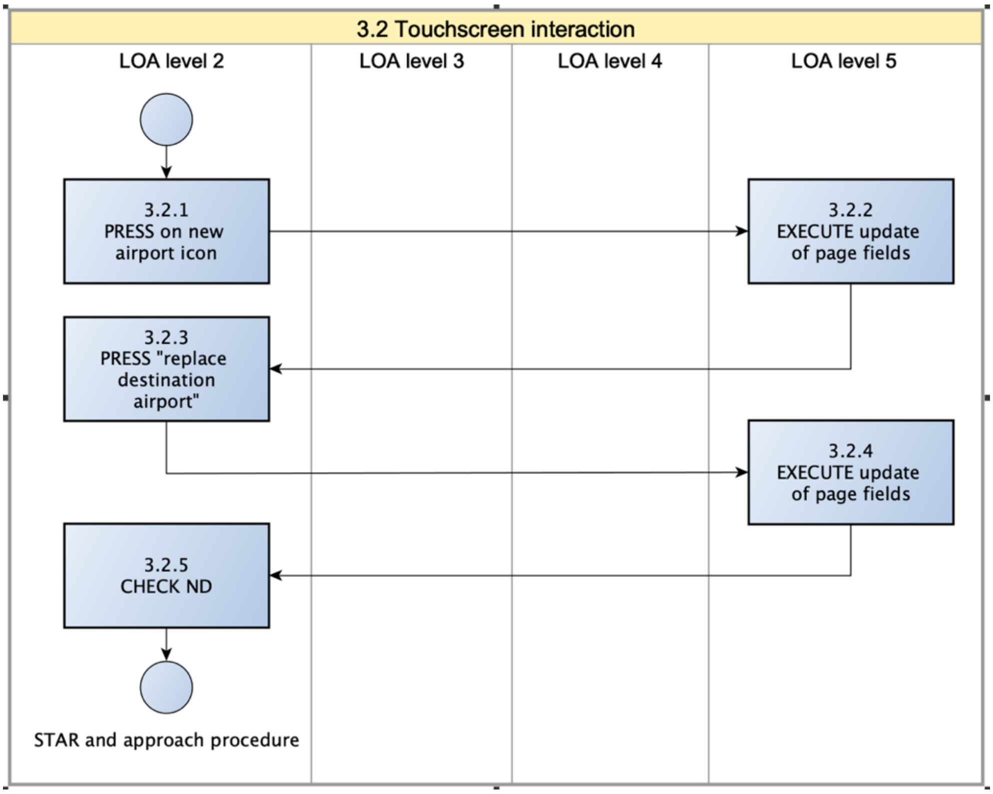


Figure 5.13: Touchscreen change destination airport procedure, LOA analysis

The characteristics of this procedure are:

- Number of keypresses: 16.
  - Change destination airport: 9 keypresses.
  - Add ASDOR: 4 keypresses (approximately 3 per waypoint, plus key to insert modification).
  - Assess aircraft performance: 3.
- Salience of the visual cues: partial because most operations present competing visual cues. The touchscreen shows on the map various waypoints that could be added by clicking on them, and therefore the pilot has to search for the desired ones. It is assumed that the scale of the map is optimized for the area of interest.
- Execution times (evaluation based on KLM model):

Table 34: Change destination airport execution time, touchscreen

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to touch screen	H	0.6	0.6
2	Search for new destination airport on map	M	1.2	1.8
3	Press on new destination airport	K	1.35	3.15
4	Press on “replace destination airport”	K	1.35	4.5
5	Verify implementation of the modification	M	1.2	5.7
6	Press on new destination airport	K	1.35	7.05
7	Press on “arrival”	K	1.35	8.4
8	Search for runway in list	M	1.2	9.6
9	Press on applicable runway	K	1.35	10.95
10	Search for STAR in list	M	1.2	12.15
11	Press on applicable STAR	K	1.35	13.5
12	Verify implementation of the modification	M	1.2	14.7

14.7 seconds represent the time needed to change the destination airport.

Table 35: Waypoint addition execution time, touchscreen

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to touch screen	H	0.6	0.6
2	Search for waypoint on map	M	1.2	1.8
3	Press on waypoint to add	K	1.35	3.15
4	Press on “add waypoint”	K	1.35	4.5
5	Verify correct addition	M	1.2	5.7
6	TMPY INSERT key	K	1.35	7.05

7.05 seconds represent the time needed to add the waypoint ASDOR and insert the modification into the flight plan.

Table 36: Assess aircraft performance execution time, touchscreen

Steps	Description	Operator	Operator Time	Elapsed Time
1	FUEL PRED key	K	1.35	1.35
2	Search for EFOB data field	M	1.2	2.55
3	Search for FOB data field	M	1.2	3.75
4	PERF key	K	1.35	5.1
5	Search for (T/D) data field	M	1.2	6.3

The performance of the aircraft is assessed in the standard way and 6.3 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance.

Summary: **TOTAL TIME TOUCHSCREEN INTERACTION** = 14.7 + 7.05 + 6.3 = **28.05** seconds.

VOICE INTERACTION

Figure 5.14 outlines the possible procedure to change destination airport by using a vocal interaction. The procedures to add a waypoint and to assess aircraft performance have been outlined previously in Figures 5.10 and 5.11 respectively.

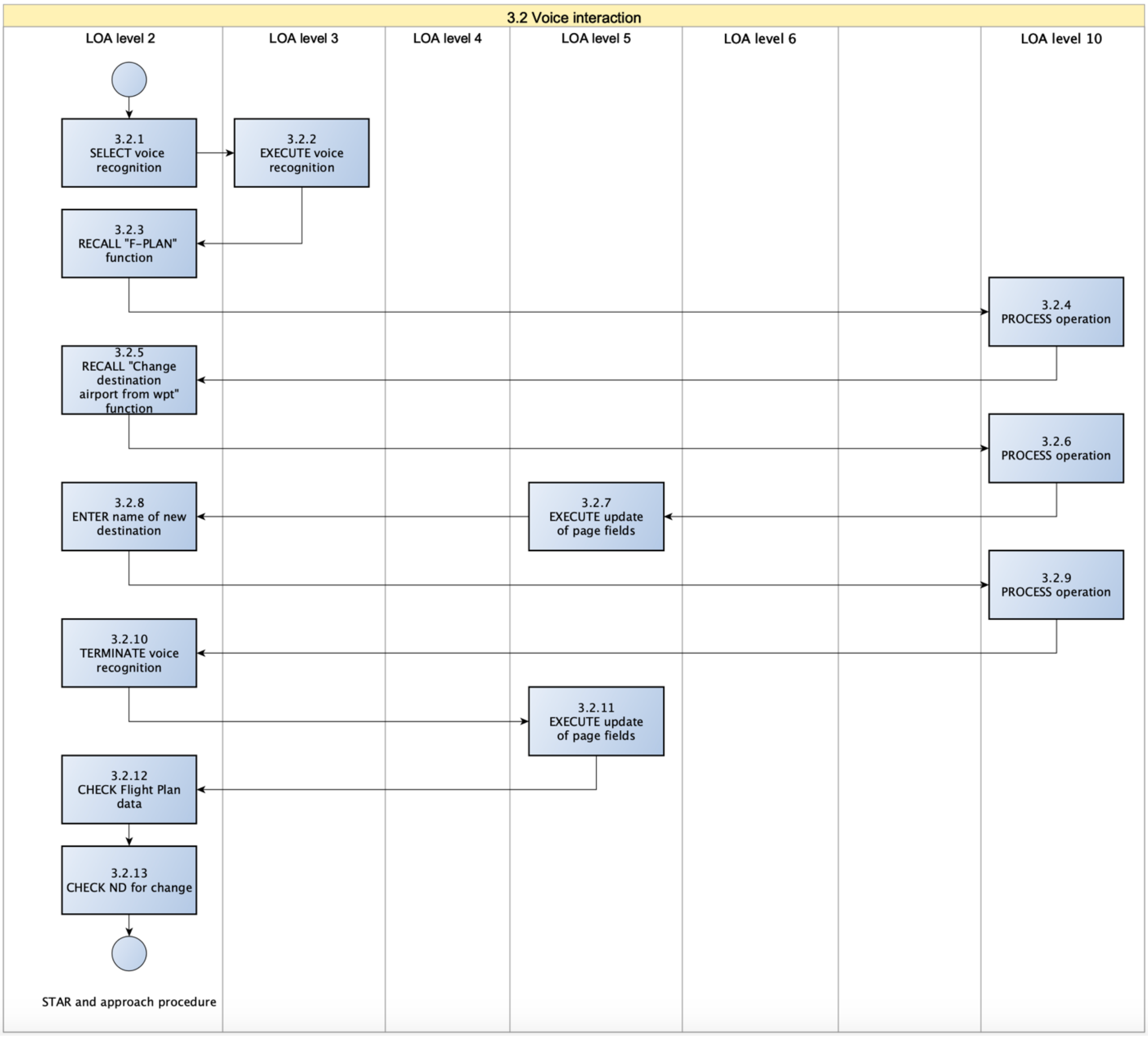


Figure 5.14: Voice interaction change destination airport procedure, LOA analysis

The characteristics of this procedure are:

- Number of keypresses: 14.
  - Change destination airport: 8.
  - Add ASDOR: 3 keypresses (approximately 2 per waypoint, plus key to insert modification).
  - Assess aircraft performance: 3.
- Salience of the visual cues: overall partial. For what regards the issuing of voice commands, most operations do not present visual cues. Nevertheless, since the selection of runway and approach procedure is performed like in the MCDU-based interaction, many operations present competing visual cues. The FMS proposes various pages that can be accessed by pressing the corresponding line select keys, and therefore the pilot has to search for the desired one.
- Execution times (evaluation based on KLM model):

Table 37: Change destination airport execution time, voice interaction

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to cloche	H	0.6	0.6
2	Press push-to-talk to initiate voice recognition	K	1.35	1.95
3	Recall F-PLAN page	K*	2	3.95
4	Remember name of waypoint to divert from	M	1.2	5.15
5	Recall “change destination airport from wpt” function	K*	6	11.15
6	Enter name of new destination airport	K*	2	13.15
7	Press push-to-talk to terminate voice recognition	K	1.35	14.5

14.5 seconds represent the time needed to change the destination airport. The selection of runway and approach procedure is performed like in the MCDU-based interaction:

- Hand to FMS, 0.6 sec
- F-PLAN key, 1.35 sec
- AIRPORT key, 1.35 sec
- Press destination airport line select key, 1.35 sec

- Press “arrival” line select key, 1.35 sec
- Search for runway in list, 1.2 sec
- Press applicable runway line select key, 1.35 sec
- Search for STAR in list, 1.2 sec
- Press applicable STAR line select key, 1.35 sec

11.1 seconds represent the time needed to select runway and approach procedure. Therefore, the total amount of time that is needed to fulfill this task is 25.6 seconds.

Table 38: Waypoint addition execution time, voice interaction

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to cloche	H	0.6	0.6
2	Press push-to-talk to initiate voice recognition	K	1.35	1.95
3	Recall F-PLAN page	K*	2	3.95
4	Recall “add waypoint name” function	K*	5	8.95
5	Press push-to-talk to terminate voice recognition	K	1.35	10.3
6	TMPY INSERT key	K	1.35	11.65

11.65 seconds represent the time needed to add the waypoint ASDOR and insert the modification into the flight plan.

Table 39: Assess aircraft performance execution time, voice interaction

Steps	Description	Operator	Operator Time	Elapsed Time
1	Hand to cloche	H	0.6	0.6
2	Press push-to-talk to initiate voice recognition	K	1.35	1.95
3	Recall “check fuel” function	K*	2	3.95
4	Search for EFOB data field	M	1.2	5.15
5	Search for FOB data field	M	1.2	6.35
6	Recall “perf” function	K*	2	8.35
7	Search for (T/D) data field	M	1.2	9.55
8	Press push-to-talk to terminate voice recognition	K	1.35	10.9

10.9 seconds represent the time needed for the pilot to access the pages to obtain data needed to assess the aircraft performance.

Summary: **TOTAL TIME VOICE INTERACTION** = 25.6 + 11.65 + 10.9 = **48.15** seconds.

COMPARISON BETWEEN THE AIRCRAFT-CENTRIC IMPROVEMENT HYPOTHESES

From the analysis of the previous two procedures, the following preliminary conclusions can be drawn:

- Touchscreen interaction appears to be more efficient because, despite requiring slightly more keypresses (16 vs. 14), there is a considerable difference in execution times (28.05 sec vs. 48.15 sec).
- The salience of the visual cues is better for the touchscreen interaction because there are always cues that can aid the pilot whilst the blended MCDU-based/voice counterpart does not always present visual cues, especially when the pilot is issuing voice commands.
- An advantage of the voice interaction is that it reduces the time for the pilot to work “head-down” while interacting with the FMS, whilst the touchscreen counterpart requires more time. Nevertheless, since the touchscreen interaction is much faster, the SA is expected to be better for the latter.

Therefore, based on the previous considerations, the most efficient aircraft-centric improvement hypothesis appears to be **TOUCHSCREEN INTERACTION.**

DATA LINK

Figure 5.15 outlines the possible procedure to modify the entire route by using a data link communication. The procedure to assess aircraft performance has been outlined previously in Figure 5.4. As opposed to the previous scenario, the pilot has to mandatorily accept the modified flight plan.

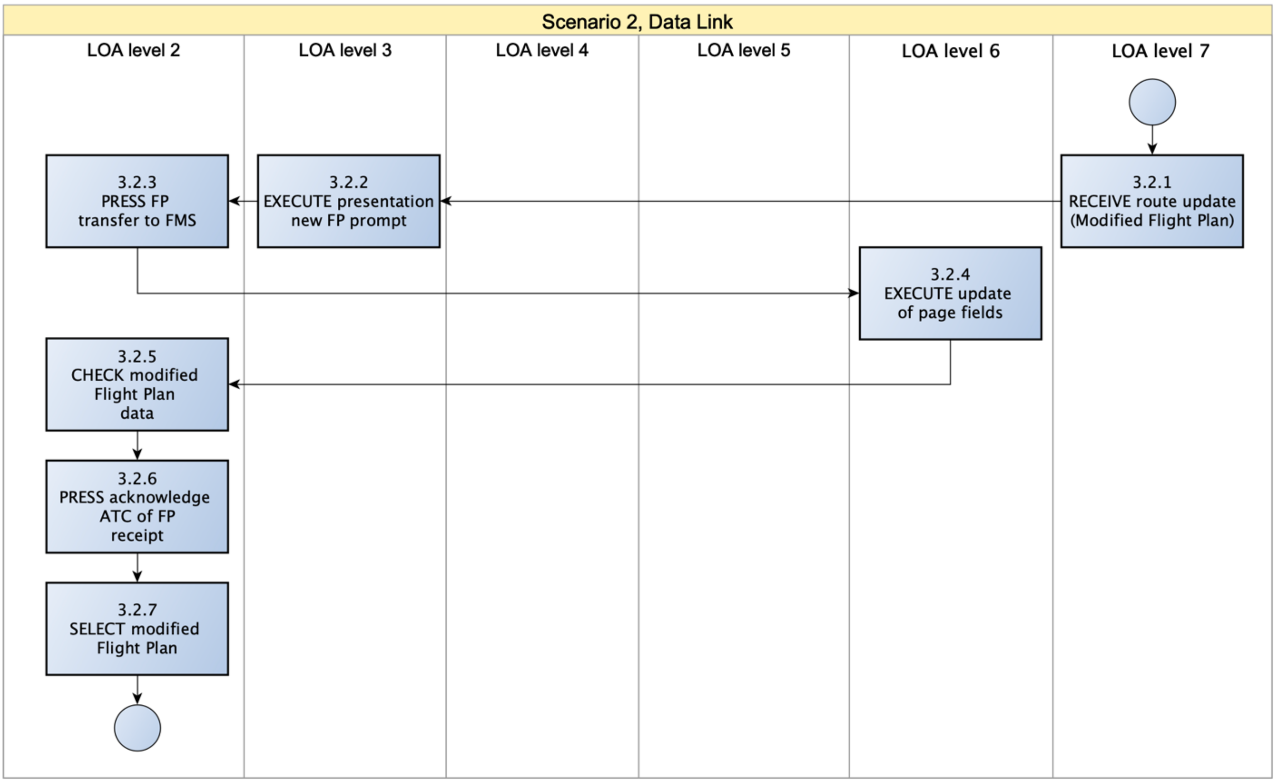


Figure 5.15: Data link complete route modification, LOA analysis

The characteristics of this procedure are:

- Number of keypresses (minimum preliminary estimate that could change in relation to the mechanism of the data link message management rules): 6.
    - Transfer flight plan to FMS, acknowledge ATC of flight plan receipt and select the modified flight plan: 3 keypresses.
    - Assess aircraft performance: 3.
- Salience of the visual cues: partial because most operations present competing visual cues. A temporary flight plan page is displayed after the modified flight plan has been transferred to the FMS. When the pilot acknowledges the receipt, the modifications are loaded into the active flight plan.

COMPARISON BETWEEN THE MOST EFFICIENT SCENARIO 2 OPTIONS

From the analysis of all the procedures related to the second scenario, the following preliminary conclusions can be drawn:

- Data link appears to be the best solution. Nevertheless, this technology needs to be further developed before it can be fully implemented.
- Touchscreen interaction presents a few advantages if compared to the current procedure since it requires less keypresses (16 vs. 21) and less time to complete the task (28.05 vs. 40.8). Furthermore, touchscreen technology is already mature and reliable enough to be installed in the flight deck.
- The data link solution provides the best possible SA because the interaction with the FMS would be very short and therefore the pilot would always be in control of the situation.

Therefore, based on the previous considerations, the most efficient improvement hypothesis appears to be the DATA LINK option. Nevertheless, considering the complexity related to infrastructure implementation and operational procedures definition tied to managing flight plan over data link, a touchscreen-based interaction would already provide an improvement if compared to the current MCDU-based counterpart.

5.4 CRITICAL REVIEW

Table 40 summarizes the results of the analysis that has been performed in the previous paragraph.

Table 40: Summary of the analysis

Best options / Scenario	Most efficient MCDU-based option	Most efficient aircraft centric option	Most efficient scenario option
Route modification	Modification strategy 2	Touchscreen interaction	Data link
Change destination airport		Touchscreen interaction	Data link

Considering the outcomes of the analysis that has been performed, it can be concluded that the best improvement hypothesis would be the data link option and, therefore, an ATC-system centric solution. Nevertheless, considering the complexity related to infrastructure implementation and operational procedures definition tied to managing flight plan over data link, the touchscreen interaction would already provide an improvement if compared to the current MCDU-based interaction.

The voice interaction improves the task execution by using a different channel; however, due to the disadvantages tied to voice recognition technology, it cannot become the primary means to interact with the FMS. Nevertheless, it may be considered an interesting solution allowing pilots to issue FMS commands while maintaining focus also on other tasks. The improvement hypotheses that have been presented will impact the LOA of the system. In order to simplify the interaction between pilots and FMS, the LOA is expected to increase, thus requiring more complex avionic equipment to be installed on board the aircraft:

- Touchscreen: the LOA would slightly increase but operating the FMS would become more efficient by reducing the interaction time and the need to swap attention across MCDU and navigation display. Furthermore, it is important to notice that future generations of pilots would already be experienced with this specific interface because it is widely adopted in consumer electronics.
- Voice interaction: the LOA would increase because this technology requires advanced systems to recognize and process the voice commands that are issued. Communicating by means of our voice is a natural process for humans and, therefore, this kind of interaction could be simpler than the current MCDU-based counterpart.
- Data link: the LOA would slightly increase but this option would significantly reduce the number of operations/tasks that the pilot has to perform, hence allowing to reduce his/her workload.

6 CONCLUSIONS

Starting from the definition of two operational scenarios, the aim of this work has been to study the interaction between pilots and the MCDU-based FMS for what concerns entry and modification of route data, in order to present ideas on how to improve the latter. First, the interaction has been described in detail with the aid of task analysis methodologies. Then, a level of automation assessment has been performed to allocate a LOA to each operation by means of Endsley's taxonomy. Successively, possible improvement hypotheses based on a specific automation philosophy have been presented. Finally, a comparison between the MCDU-based FMS and the proposed hypotheses has been performed using specific metrics. It has been decided to structure this document in the following way:

- In the first part (chapters 2 and 3), the reader was provided with the theoretical notions that were needed to understand the topics of the subsequent section.
- In the second part (chapters 4, 5 and 6), two operational scenarios have been defined (route modification and diversion to different destination airport) and the results of the task analysis have been presented. Then, the improvement hypotheses have been described in detail, and finally a comparison between MCDU-based procedures and possible implementations of the improvement hypotheses has been performed.

The interaction between pilots and FMS, within the boundaries of the selected scenarios, has been described in detail by means of Hierarchical Task Analysis. HTA was the method of choice because it allowed to break-down the task under analysis by defining the single operations that pilots need to perform while interacting with the system. Moreover, the aim of this work was to perform a preliminary analysis of a navigation system, in which the TA was a means to structure and compare the tasks, rather than being used to perform a detailed design. Therefore, the method had to be simple and effective enough for the abovementioned objective.
Among the proposed scales, it has been decided to perform the LOA allocation by means of Endsley's taxonomy. This scale provided an adequate description of the different levels of automation that can be used to characterize the LOA of a given system. The proposed improvement hypotheses have been defined as being:

- “aircraft centric”, i.e. the modifications would mainly impact the equipment installed on-board.
- “ATC-system centric”, in the sense that these modifications would impact both the aircraft and the related ATC infrastructures/procedures that manage air traffic.

Aircraft centric hypotheses included:

- **Touch screen interaction:** the idea was to adopt a novel means of interaction with the flight deck, in order to optimize data entry activities. Advantages associated with this technology could be the ability to manage avionic systems in a more intuitive manner, and to control systems and view their status from the same display. Considering that touchscreen technology is consolidated and can be ruggedized for flight deck applications, this option could be implemented by working on a software that manages interaction aspects.
- **Voice interaction:** also known as Direct Voice Input, the solution could have many potential benefits. For instance, pilots could issue commands “hands-free”, thus allowing them to use their hands for other tasks. Furthermore, pilots would reduce their look down times and could therefore increase their focus on concurrent tasks.

As for the ATC-system centric improvement hypotheses, an option based on the evolution of nowadays data link communications has been proposed. This technology could be used to improve the way pilots interact with the ATC and with the FMS when they have to modify a route. Nevertheless, this option cannot supersede an on-board means of control of the FMS due e.g. connectivity (availability and stability of the link) issues. Instead of modifying waypoints manually, the idea was to employ a data link message that included every modification of the route and could be directly loaded into the FMS.

Starting from the task analysis and the previously defined scenarios, both the original procedures and the improvement hypotheses have been analyzed in terms of number of keypresses, salience of the visual cues and execution times (by means of the Keystroke Level Model).

From the results of the analysis that has been performed, the following preliminary conclusions have been drawn:

1. The best improvement hypothesis would be the data link option and, therefore, an ATC-system centric solution. Nevertheless, considering the complexity related to infrastructure implementation and operational procedures definition tied to managing flight plan over data link, the touchscreen interaction would already provide an improvement if compared to the current MCDU-based interaction.
2. The voice interaction could provide certain advantages, but it is believed that it cannot become the primary means to interact with the FMS. Nevertheless, it could be used by pilots in busy situations in order to improve their SA, allowing them to focus their sight on important tasks while still being able to issue voice commands.
3. The improvement hypotheses that have been presented will impact the LOA of the system. In order to simplify the interaction between pilots and FMS, the LOA is expected to increase, thus requiring more complex avionic equipment to be installed on board the aircraft:

    a. Touchscreen: the LOA would slightly increase but operating the FMS would become more efficient by reducing the interaction time and the need to swap attention across MCDU and navigation display.
    b. Voice interaction: the LOA would increase because this technology requires advanced systems to recognize and process the voice commands that are issued.
    c. Data link: the LOA would slightly increase but this option would significantly reduce the number of operations/tasks that the pilot has to perform, hence allowing to reduce his/her workload.

Based on these preliminary results, the introduction of touchscreen technology to manage the interaction between pilots and the FMS appears to be beneficial. Therefore, this work could be used as a starting point to:

- Study and design a touchscreen interface, implement a prototype and integrate it into a representative simulation environment for validation assessments.

- Study and analyze in detail the data link option with respect to the current developments related to this technology.

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ANNEXES: COMPLETE TASK ANALYSIS

Super-Ordinate Goal: MANAGE FLIGHT PLAN
PLAN: 1, 2, 3

Ref	Sub Goals	Ref	Sub-Goal Tasks	Ref	Operations	Task Type OODA LOOP	Description	LOA (Endsley's scale)
1	INITIALIZE FLIGHT PLAN						Flight data are entered or confermed via MCDU pages	
		1.1	Check aircraft status				Flight data related to the status of the aircraft are evaluated	
				1.1.1	PRESS "DATA" key	A	Page key that needs to be pressed in order to access DATA INDEX page. Number of keypress: 1. Visual cues: EXACT	1
				1.1.2	PRESS "A/C STATUS" key	A	Line select key that needs to be pressed in order to access aircraft status page. Number of keypress: 1. Visual cues: EXACT	2
				1.1.3	EXECUTE retrieval of A/C Status	OODA	The FMS provides the pilot with relevant information related to the aircraft; the pilot CANNOT modify these info	3
				1.1.4	CHECK navigation database	OO	Check period of validity and if the correct database is installed. Visual cues: PARTIAL	2
				1.1.5	DECIDE validity of the database	D	If the database is valid then proceed to the next task, otherwise 1.1.6	1
				1.1.6	TERMINATE initialization	A	If the database is not valid then the flight plan cannot be completed until the db is updated	1
		PLAN: 1.1. Do the operations in the provided order until 1.1.5 then 1.1.6 or 1.2						
		1.2	Initialization				Important flight data are entered	
				1.2.1	PRESS "INIT" key	A	Page key that needs to be pressed in order to access INIT page. Number of keypress: 1. Visual cues: EXACT	1
				1.2.2	ENTER data relevant to field "FROM/TO" using keyboard	OODA	Departure and arrival airports are inserted in the system. Number of keypress: 9 (example: LIBG/LIPE). Visual cues: PARTIAL	2
				1.2.3	PRESS corresponding key to insert data	A	Line select key that needs to be pressed in order to insert the data. Number of keypress: 1. Visual cues: PARTIAL	2
				1.2.4	EXECUTE update of page fields	OODA	After the pilot enters departure and arrival info, the FMS checks for data entry error and then automatically fills in certain data fields (like present position)	7

				1.2.5	ENTER data relevant to field "ALTERNATIVE" (if available) using keyboard	OODA	An alternative destination airport can be added to the flight plan. Number of keypress: 4. Visual cues: PARTIAL	2
				1.2.6	PRESS corresponding key to insert data	A	Line select key that needs to be pressed in order to insert the data. Number of keypress: 1. Visual cues: PARTIAL	2
				1.2.7	EXECUTE update of page fields	OODA	When the pilot enters the alternative airport, the FMS checks for data entry error	7
				1.2.8	ENTER data relevant to field "FLIGHT NUMBER" using keyboard	OODA	Flight number is inserted in the system (exactly as written in ATC flight plan). Number of keypress: up to 8. Visual cues: PARTIAL	2
				1.2.9	PRESS corresponding key to insert data	A	Line select key that needs to be pressed in order to insert the data. Number of keypress: 1. Visual cues: PARTIAL	2
				1.2.10	CHECK present position (LAT and LONG)	OO	Check if LAT and LONG data fields provide the correct info. Visual cues: PARTIAL	2
				1.2.11	DECIDE if present position is correct (LAT and LONG)	D	Decide if the present position is correct or needs to be modified.	1
				1.2.12	CORRECT present position (if need be) using slew keys	OODA	If the coordinates are not correct they can be adjusted. Number of keypress: depends on error on present position.	2
		PLAN: 1.2. Do the operations in the provided order until 1.2.11 then 1.2.12 or 2.1						
PLAN: 1.1, 1.2								
2	EDIT FLIGHT PLAN						In this phase the flight plan is built	
		2.1	Enter departure info				The information related to the departure airport are defined	
				2.1.1	PRESS "F-PLAN" key	A	Page key that needs to be pressed in order to access flight plan page. Number of keypress: 1. Visual cues: EXACT	1
				2.1.2	PRESS origin airport key	A	Line select key that needs to be pressed in order to access details of the departure airport that has been previously entered. Number of keypress: 1. Visual cues: PARTIAL	2
				2.1.3	PRESS "DEPARTURE" key	A	Line select key that needs to be pressed so that the MCDU displays the available runways found in the navigation database. Number of keypress: 1. Visual cues: PARTIAL	2
				2.1.4	EXECUTE update of page fields	OODA	The FMS automatically shows the pilot the available runways that are found in the db; the pilot can only choose among the proposed options	7
				2.1.5	PRESS applicable runway key	OODA	The correct runway, from all the available ones, is selected by pressing the corresponding line select key. Number of keypress: 1. Visual cues: PARTIAL	2

				2.1.6	EXECUTE update of page fields	OODA	The FMS now shows the pilot the available SIDs that are found in the db; the pilot can only choose among the proposed options	7
				2.1.7	PRESS applicable SID key	OODA	The correct SID, from all the available ones, is selected by pressing the corresponding line select key. Number of keypress: 1. Visual cues: PARTIAL	2
				2.1.8	PRESS "TMPY F-PLAN" key	A	Line select key that needs to be pressed so that the MCDU switches to TMPY F-PLAN page (the flight plan is considered to be temporary until it is finalized and inserted). Number of keypress: 1. Visual cues: PARTIAL	2
		PLAN: 2.1. Do the operations in the provided order						
		2.2	Enter route information				After the initialization phase has been completed, the pilot needs to enter the various waypoints along the route	
				2.2.1	CHECK route to be entered	OO	The pilot reviews the route to be entered in the flight plan	1
				2.2.2	DECIDE strategy for entering route data	D	The pilot decides which procedures should be employed to enter the route in the FMS	1
		PLAN: 2.2. Do the operations in the provided order						
		2.3	Enter subsequent waypoints with airways				The waypoints along the route and the airways that need to be used are defined	
				2.3.1	PRESS origin waypoint key	A	Line select key that needs to be pressed so that the subsequent waypoint, and the airway to be used, can be defined. It can be the choosen SID or any waypoint along the route. Number of keypress: 1. Visual cues: PARTIAL	2
				2.3.2	PRESS "AIRWAYS" key	A	Line select key that needs to be pressed so that waypoint and airway data fields can be filled. Number of keypress: 1. Visual cues: PARTIAL	2
				2.3.3	ENTER airway in data field "VIA" using keyboard	OODA	Enter the name of the airway that needs to be used. Number of keypress: up to 4. Visual cues: PARTIAL	2
				2.3.4	PRESS corresponding key to insert data	A	Line select key that needs to be pressed to insert the airway. Number of keypress: 1. Visual cues: PARTIAL	2
				2.3.5	EXECUTE update of page fields	OODA	After the pilot enters the airway, the FMS does a data entry error check and prompts the pilot if there is an error in the name, allowing for correction of the latter	5
				2.3.6	ENTER next waypoint in data field "TO" using keyboard	OODA	Enter the name of the waypoint that is linked by the airway defined in the previous point. Number of keypress: 5. Visual cues: PARTIAL	2
				2.3.7	PRESS corresponding key to insert data	A	Line select key that needs to be pressed in order to insert the next waypoint. Number of keypress: 1. Visual cues: PARTIAL	2

		2.3.8	EXECUTE update of page fields	OODA	After the pilot enters the waypoint linked by the airway, the FMS does a data entry error check and prompts the pilot if there is an error in the name, allowing for correction of the latter	5
		2.3.9	PRESS "TMPY F-PLAN" key	A	The waypoint and the airway are added to the temporary flight plan. Number of keypress: 1. Visual cues: PARTIAL	2
		2.3.10	CHECK Flight Plan data	OO	Review the waypoints that are currently in the Flight Plan. Visual cues: PARTIAL	2
		2.3.11	DECIDE data entry completion	D	Determine if other waypoints of this kind need to be added.	1
PLAN: 2.3. Do the operations in the provided order until 2.3.11 then 2.3.1 or 2.4						
2.4	Enter subsequent waypoints WITHOUT airways				The waypoints along the route are defined. No airways are specified in this case	
		2.4.1	PRESS waypoint of interest key	A	Line select key that needs to be pressed so that the subsequent waypoint can be defined. The waypoint of interest can be the origin waypoint or any subsequent one. Number of keypress: 1. Visual cues: PARTIAL	2
		2.4.2	ENTER name of next waypoint using keyboard	OODA	Enter the name of the waypoint. Number of keypress: 5. Visual cues: PARTIAL	2
		2.4.3	PRESS "NEXT WPT" key	A	Line select key that needs to be pressed so that the waypoint can be added to the flight plan. Number of keypress: 1. Visual cues: PARTIAL	2
		2.4.4	EXECUTE update of page fields	OODA	After the pilot enters the name of the waypoint, the FMS does a data entry error check and prompts the pilot if there is an error in the name, allowing for correction of the latter	5
		2.4.5	CHECK Flight Plan data	OO	Review the waypoints that are currently in the Flight Plan. Visual cues: PARTIAL	2
		2.4.6	DECIDE data entry completion	D	Determine if other waypoints of this kind need to be added. If not, proceed to the next task, otherwise start again with operation 2.4.1	1
PLAN: 2.4. Do the operations in the provided order until 2.4.6 then 2.4.1 or 2.5						
2.5	Enter arrival information				The information related to the destination airport are defined	
		2.5.1	PRESS "AIRPORT" key	A	Page key that needs to be pressed in order to shift to the end of the entered flight plan. Number of keypress: 1. Visual cues: EXACT	1
		2.5.2	PRESS destination airport key	A	Line select key that needs to be pressed in order to access details of the destination airport. Number of keypress: 1. Visual cues: PARTIAL	2
		2.5.3	EXECUTE update of page fields	OODA	The FMS updates the page and aids the pilot by showing "ARRIVAL" line select key	3

				2.5.4	PRESS "ARRIVAL" key	A	Line select key that needs to be pressed so that the MCDU displays the available runways found in the navigation database. Number of keypress: 1. Visual cues: PARTIAL	2
				2.5.5	EXECUTE update of page fields	OODA	The FMS automatically shows the pilot the available runways that are found in the db; the pilot can only choose among the proposed options	7
				2.5.6	PRESS applicable runway key	OODA	The correct runway, from all the available ones, is selected. The MCDU display shifts to the ARRIVAL page with the arrivals available in the navigation database. Number of keypress: 1. Visual cues: PARTIAL	2
				2.5.7	EXECUTE update of page fields	OODA	The FMS automatically shows the pilot the available STARs that are found in the db; the pilot can only choose among the proposed options	7
				2.5.8	PRESS applicable STAR key	OODA	The correct STAR, from all the available ones, is selected by pressing the corresponding line select key. Number of keypress: 1. Visual cues: PARTIAL	2
				2.5.9	PRESS "TMPY F-PLAN" key	A	Line select key that needs to be pressed so that the MCDU switches to TMPY F-PLAN page (the flight plan is considered to be temporary until it is finalized and inserted). Number of keypress: 1. Visual cues: PARTIAL	2
				2.5.10	CHECK Flight Plan data	OO	The complete flight plan is reviewed by the pilot to check whether it has been filled completely. Visual cues: PARTIAL	2
				2.5.11	DECIDE data entry completion	D	Determine if the flight plan is complete or needs to be further modified	1
				2.5.12	PRESS "TMPY INSERT" key	A	Line select key that needs to be pressed in order to enter the complete flight plan in the system. The flight plan is no longer temporary. Number of keypress: 1. Visual cues: PARTIAL	2
		PLAN: 2.5. Do the operations in the provided order until 2.5.11 then 2.5.12 or 2.3/2.4						
		2.6	Compute aircraft performance				After the flight plan has been entered, the pilot checks the fuel predictions calculated by the FMS and the position of the Top of Descent point	
				2.6.1	PRESS "FUEL PRED" key	A	Page key that needs to be pressed in order to access FUEL PRED page. Number of keypress: 1. Visual cues: EXACT	1
				2.6.2	EXECUTE update of page fields	OODA	The FMS provides the pilot with computed data related to the readings of the sensors	3
				2.6.3	CHECK EFOB data field	OO	Data field that displays the estimated fuel on board at destination and alternate airport (if previoulsy defined). Visual cues: PARTIAL	2

				2.6.4	CHECK FOB data field	OO	Data field that displays the actual fuel on board based on the readings of the sensors. Visual cues: PARTIAL	2
				2.6.5	DECIDE if FOB is adequate to operate	D	The pilot needs to decide if the fuel on board is enough.	1
				2.6.6	TERMINATE editing	A	The on board fuel is not enough, standby for refuelling	1
				2.6.7	PRESS "F-PLAN" key	A	Page key that needs to be pressed in order to access flight plan page. Number of keypress: 1. Visual cues: EXACT	1
				2.6.8	EXECUTE update of page fields	OODA	The FMS shows the pilot the complete flight plan that has been previously entered	3
				2.6.9	CHECK pseudo waypoints (T/C) and (T/D)	OO	The Top of Climb point is shown in the flight plan as a pseudo-waypoint called (T/C) whilst the Top of Descent point is shown as (T/D). Visual cues: PARTIAL	2
				2.6.10	CHECK ND	OO	The Top of Descent point is shown on the ND by a white arrow. Visual cues: EXACT	2
		PLAN: 2.6. Do the operations in the provided order until 2.6.5 then 2.6.7, 2.6.8, 2.6.9, 2.6.10 or 2.6.6						
PLAN: 2.1, 2.2, 2.3/2.4, 2.5, 2.6								
3	MODIFY FLIGHT PLAN							
		3.1	Acknowledge modification request				The pilot is asked to implement some modifications	
				3.1.1	CHECK need to modify route	OO	Depending on the request, the pilot checks if there is a need to modify the route	1
				3.1.2	DECIDE modification strategy	D	Depending on the required modifications, the pilot will decide for the correct procedure among the ones described by 3.2, 3.3, 3.4, 3.5	1
		PLAN: 3.1. Do the operations in the provided order						
		3.2	Change destination airport				Used to modify destination airport	
				3.2.1	PRESS "F-PLAN" key	A	Page key that needs to be pressed in order to access flight plan page. Number of keypress: 1. Visual cues: EXACT	1
				3.2.2	PRESS key corresponding to diversion waypoint	A	Line select key that needs to be pressed in order to change the destination airport if a diversion is intended. The key selects the waypoint from which it is intended to divert to the new destination. Number of keypress: 1. Visual cues: PARTIAL	2
				3.2.3	EXECUTE update of page fields	OODA	The FMS updates the page and aids the pilot by showing "NEW DEST" data field	3
				3.2.4	ENTER name of new destination using keyboard	OODA	Enter the name of the new destination airport. Number of keypress: 4. Visual cues: PARTIAL	2
				3.2.5	PRESS "NEW DEST" key	A	Line select key that needs to be pressed in order to insert the new destination airport. Number of keypress: 1. Visual cues: PARTIAL	2

				3.2.6	EXECUTE update of page fields	OODA	The FMS deletes the waypoints that are after the diversion point and then controls the flight plan and, if it is incomplete, shows the label "F-PLAN DISCONTINUITY"	5
				3.2.7	CHECK Flight Plan data	OO	Check that in the flight plan all the WPTs after the revision point are deleted. Visual cues: PARTIAL	2
				3.2.8	PRESS destination airport key	A	Line select key that needs to be pressed in order to access details of the destination airport. Number of keypress: 1. Visual cues: PARTIAL	2
				3.2.9	EXECUTE update of page fields	OODA	The FMS updates the page and aids the pilot by showing "ARRIVAL" line select key	3
				3.2.10	PRESS "ARRIVAL" key	A	Line select key that needs to be pressed so that the MCDU displays the available runways found in the navigation database. Number of keypress: 1. Visual cues: PARTIAL	2
				3.2.11	EXECUTE update of page fields	OODA	The FMS automatically shows the pilot the available runways that are found in the db; the pilot can only choose among the proposed options	7
				3.2.12	PRESS applicable runway key	OODA	The correct runway, from all the available ones, is selected. The MCDU display shifts to the ARRIVAL page with the arrivals available in the navigation database. Number of keypress: 1. Visual cues: PARTIAL	2
				3.2.13	EXECUTE update of page fields	OODA	The FMS automatically shows the pilot the available STARs that are found in the db; the pilot can only choose among the proposed options	7
				3.2.14	PRESS applicable STAR key	OODA	The correct STAR, from all the available ones, is selected by pressing the corresponding line select key. Number of keypress: 1. Visual cues: PARTIAL	2
		PLAN: 3.2. Do the operations in the provided order						
		3.3	Route revision, method 1				Used to modify existing list of waypoints by adding new ones	
				3.3.1	PRESS "F-PLAN" key	A	Page key that needs to be pressed in order to access flight plan page. Number of keypress: 1. Visual cues: EXACT	1
				3.3.2	ENTER name of new waypoint to be inserted using keyboard	OODA	Enter the name of the new waypoint that will modify the route. Number of keypress: 5. Visual cues: PARTIAL	2
				3.3.3	PRESS key corresponding to waypoint to be modified	A	The old waypoint will appear one line further down separated from the new waypoint by a "F-PLAN DISCONTINUITY" . A temporary flight plan page is displayed. Number of keypress: 1. Visual cues: PARTIAL	2

				3.3.4	EXECUTE update of page fields	OODA	The FMS controls the flight plan and, if it is incomplete, shows the label "F-PLAN DISCONTINUITY"	5
				3.3.5	CHECK ND for change	OO	After each revision it is important to check ND to see if the change has been applied. Visual cues: PARTIAL	2
				3.3.6	CHECK Flight Plan data	OO	The modified flight plan is reviewed by the pilot to check whether further modifications need to be implemented. Visual cues: PARTIAL	2
				3.3.7	DECIDE data entry completion	D	Determine if the flight plan is complete or needs to be further modified	1
				3.3.8	PRESS "TMPY INSERT" key	A	Line select key that needs to be pressed so that the applied changes are inserted in the flight plan. The actual flight plan page is displayed. Number of keypress: 1. Visual cues: PARTIAL	2
		PLAN: 3.3. Do the operations in the provided order until 3.3.7 then 3.3.8 or 3.3.2						
		3.4	Route revision, method 2				Used to manually delete specific waypoints	
				3.4.1	PRESS "F-PLAN" key	A	Page key that needs to be pressed in order to access flight plan page. Number of keypress: 1. Visual cues: EXACT	1
				3.4.2	PRESS "CLR" key	A	Key that needs to be pressed so that an existing waypoint (or a flight plan discontinuity) can be deleted from the flight plan. Number of keypress: 1. Visual cues: EXACT	1
				3.4.3	PRESS key corresponding to waypoint to be deleted	A	Line select key corresponding to the waypoint to be deleted. A temporary flight plan page is displayed. Number of keypress: 1. Visual cues: PARTIAL	2
				3.4.4	EXECUTE update of page fields	OODA	The FMS updates the flight plan and creates a "F-PLAN DISCONTINUITY" between the cleared and the next waypoint	5
				3.4.5	PRESS "CLR" key	A	Key that needs to be pressed so that the flight plan discontinuity can be cleared. Number of keypress: 1. Visual cues: EXACT	1
				3.4.6	PRESS key corresponding to "F-PLAN DISCONTINUITY"	A	Line select key corresponding to the flight plan discontinuity to be deleted. Number of keypress: 1. Visual cues: PARTIAL	2
				3.4.7	EXECUTE update of page fields	OODA	The FMS updates the flight plan. Clearing the discontinuity sequences the flight plan	5
				3.4.8	CHECK ND for change	OO	After each revision is important to check ND to see if the change has been applied. Visual cues: PARTIAL	2
				3.4.9	CHECK Flight Plan data	OO	The modified flight plan is reviewed by the pilot to check whether other waypoints need to be deleted. Visual cues: PARTIAL	2

		3.4.10	DECIDE deletion completion	D	Decide if other waypoints should be deleted from the flight plan	1
		3.4.11	PRESS "TMPY INSERT" key	A	Line select key that needs to be pressed so that the applied changes are inserted in the flight plan. The actual flight plan page is displayed. Number of keypress: 1. Visual cues: PARTIAL	2
PLAN: 3.4. Do the operations in the provided order until 3.4.10 then 3.4.11 or 3.4.2						
3.5	Route revision, method 3				Used when several waypoints or long segments have to be deleted	
		3.5.1	PRESS "F-PLAN" key	A	Page key that needs to be pressed in order to access flight plan page. Number of keypress: 1. Visual cues: EXACT	1
		3.5.2	ENTER name of new waypoint to be inserted using keyboard	OODA	Enter the name of the new waypoint that will delete several previous ones. Number of keypress: 5. Visual cues: PARTIAL	2
		3.5.3	PRESS key corresponding to the initial waypoint of the segment to be deleted	A	All WPTS between the new one and the initial waypoint of the segment are collapsed. A temporary flight plan page is displayed. Number of keypress: 1. Visual cues: PARTIAL	2
		3.5.4	EXECUTE update of page fields	OODA	The FMS updates the flight plan and automatically sequences it	5
		3.5.5	CHECK ND for change	OO	After each revision it is important to check ND to see if the change has been applied. Visual cues: PARTIAL	2
		3.5.6	CHECK Flight Plan data	OO	The modified flight plan is reviewed by the pilot to check whether further modifications need to be implemented. Visual cues: PARTIAL	2
		3.5.7	DECIDE data entry completion	D	Determine if the flight plan is complete or needs to be further modified	1
		3.5.8	PRESS "TMPY INSERT" key	A	Line select key that needs to be pressed so that the applied changes are inserted in the flight plan. The actual flight plan page is displayed. Number of keypress: 1. Visual cues: PARTIAL	2
PLAN: 3.5. Do the operations in the provided order until 3.5.7 then 3.5.8 or 3.3						
3.6	Assess aircraft performance				After the flight plan has been modified, the pilot needs to check how these modifications will impact the performances in order to be able to accetp/refuse	
		3.6.1	PRESS "FUEL PRED" key	A	Page key that needs to be pressed in order to access FUEL PRED page. Number of keypress: 1. Visual cues: EXACT	1
		3.6.2	EXECUTE update of page fields	OODA	The FMS provides the pilot with computed data related to the readings of the sensors	3
		3.6.3	CHECK EFOB data field	OO	Data field that displays the estimated fuel on board at destination. Visual cues: PARTIAL	2

				3.6.4	CHECK FOB data field	OO	Data field that displays the actual fuel on board based on the readings of the sensors. Visual cues: PARTIAL	2
				3.6.5	PRESS "PERF" key	A	Page key that needs to be pressed in order to access PERF page. At this phase of the flight, the FMS will display the cruise-related page. Number of keypress: 1. Visual cues: EXACT	1
				3.6.6	EXECUTE update of page fields	OODA	The FMS provides the pilot with important information related to the current flight phase	3
				3.6.7	CHECK "to (T/D)" data field	OO	This data field displays the ETA and distance to the Top of Descent point. If the "to (T/D)" field indicates 0, it means that the point has been passed. Visual cues: PARTIAL	2
				3.6.8	CHECK ND	OO	The Top of Descent point is shown on the ND by a white arrow. Visual cues: EXACT	2
				3.6.9	DECIDE acceptance/rejection of modifications	D	Based on the parameters that the pilot has checked, he/she can accept or refuse the modifications suggested by the ATC. If the pilot accepts, proceed to the next operation, otherwise the modified Flight Plan is not entered into the FMS	1
				3.6.10	SELECT modified Flight Plan	A	If the pilot accepts the proposed modifications, he/she switches to the modified Flight Plan	2
		PLAN: 3.6. Do the operations in the provided order until 3.6.9 then 3.6.10 or no selection						
PLAN: 3.1, 3.2/3.3/3.4/3.5, 3.6								