

# AUTOMATION FOR TASK ANALYSIS OF NEXT GENERATION AIR TRAFFIC MANAGEMENT SYSTEMS

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**Abstract**—The increasing span of control of Air Traffic Control enterprise automation (e.g. Flight Schedule Monitor, Departure Flow Management), along with lean-processes and pay-for-performance business models, has placed increased emphasis on operator training time and error rates. There are two traditional approaches to the design of Human-Computer Interaction (HCI) to minimize training time and reduce error rates: (1) experimental user testing provides the most accurate assessment of training time and error rates, but occurs too late in the development cycle and is cost prohibitive, (2) manual review methods (e.g. cognitive walkthrough) can be used earlier in the development cycle, but suffer from poor accuracy and poor inter-rater reliability. Recent developments in “affordable” human performance models provide the basis for the automation of task analysis and HCI design to obtain low cost, accurate, estimates of training time and error rates early in the development cycle.

This paper describes a usability/HCI analysis tool that is intended for use by design engineers in the course of their software engineering duties. The tool computes estimates of trials-to-mastery (i.e. time to competence for training) and the probability of failure-to-complete for each task. The HCI required to complete a task on the automation under development is entered into the web-based tool via a form. Assessments of the salience of visual cues to prompt operator actions for the proposed design is used to compute training time and error rates. The web-based tool enables designers in multiple locations to review and contribute to the design. An example analysis is provided along with a discussion of the limitations of the tool and directions for future research.

*Human Computer Interaction, Usability Analysis, Task Analysis, Probability of Failure to Complete a Task, Trials to Mastery.*

## I. INTRODUCTION

The evolution of the air transportation system to a “mature” industrial sector has resulted in cost differentiation as a primary means of competitive advantage for airlines. This cost imperative has flowed through the supply chain to aircraft manufacturers and Air Traffic Control. The result has been new

business models (e.g. low cost carriers, outsourcing) and incentives for the supply chain vendors to reduce installation costs and operational costs (e.g. training, operational efficiency, and safety). Air Navigation Service Providers (ANSPs) have embraced this challenge by privatization of Air Traffic Control, pay-for-performance, and the development of large-scale enterprise management and control automation such as Flight Schedule Monitor (FSM), Departure Flow Management (DFM), Surface Management Systems (SMS).

Human Computer Interaction has emerged as one of the ways to reduce costs by streamlining training as well as increasing the efficiency of operators. For example, Boeing Commercial Aircraft Group funded a large internal R&D project with the specific design goal of reducing training costs and improving flightdeck operational efficiency (Mumaw, Boorman, and Prada, 2006, Castor-Peck, 2006). Several avionics vendors (Faerber, Vogl, and Hartley, 2007; Jacobsen, Chen, and Widemann, 1999), airlines (Fennell, Sherry, and Roberts, 2006), and NASA’s Exploration Mission Directorate, Human Research Program (NASA, 2008) also have similar initiatives in place.

Experimental user testing (Nielsen, 1993) is the most accurate evaluation of the usability of a product. This type of approach is cost prohibitive and can only be conducted at the end of the development cycle when the cost of revisions is highest. Manual review methods (e.g. cognitive walkthrough) can be used earlier in the development cycle, but suffer from poor accuracy and poor inter-rater reliability. Recent developments in “affordable” human performance models provide the basis for the automation of task analysis and HCI design to obtain low cost, accurate, estimates of training time and error rates early in the development cycle (e.g. Cog Tool (John, et al., 2004).

This paper describes a tool based on the Human Computer Interaction Process Analysis model (HCIPA) that is intended for use by software and design engineers in the course of their software engineering duties, to conduct usability analyses.

HCIPA attempts to solve two very hard problems in the design of advanced automated systems. The first is capturing the details of operator-system interactions while performing a large number of mission tasks. The sequence of operator actions and inferred mental operators for each task is then used to solve the second problem, making useful predictions of time to complete a task, repetitions required to master a task, and the likelihood of failure for failure infrequently performed tasks.

This paper presents a web based tool that explicitly solves the first problem and presents a preliminary solution for the second. The tool enables designers and testers to describe the sequence of operator actions, assess the salience of visual cues, and then computes estimates of trials to mastery (i.e. time to competence for training) and the probability of failure-to-complete for each task that can be performed by the product under design. The web-based tool also provides designers in multiple locations to view and contribute to the design and the usability evaluation.

This paper is organized as follows: Section 2 provides an overview of Human Computer Interaction (HCI) and introduces the Human Computer Interaction Process Analysis (HCIPA) method. Section 3 describes the tasks that can be performed by the functions of the tool. Section 4 provides case studies of usability analysis conducted with the tool. Section 5 discusses the limitations of the tool and directions for future research.

## II. OVERVIEW OF HUMAN COMPUTER INTERACTION

Human-computer interaction involves the cognitive, motor, and visual activities of an operator using automation to perform a mission task (Card, Moran & Newell, 1983). The interaction between operator and automation follows a human action cycle of goal formulation, execution, and evaluation (e.g. Norman, 1988). The degree to which the content of the user-interface matches the “semantic space” of the operator determines the usability of the automation (Kitajima, Blackmon, and Polson, 2002).

Several techniques have been used to determine the usability of automation (Nielsen, 1992). The most accurate evaluation of the usability of a product is achieved through experimental user testing. Human subjects perform a list of tasks using the automation under test while observers take notes or record the operators behavior. The aim is to identify problems on the product or features that users like and are easy to use. Techniques include “think aloud protocols” and eye tracking. Although quantitative data can be collected by measuring time to learn, speed of performance, and rate of human error; this approach is cost prohibitive and can only be conducted at the end of the development cycle when the cost of revisions is highest (Nielsen, 1994).

Alternative approaches that can be used earlier in the life-cycle, fall into two categories: Manual Inspections and Operator Performance Predictions. Manual inspections, such as participatory design (Muller and Kuhn, 1993), cognitive walkthroughs (Wharton, Rieman, Lewis, and Polson, 1994), heuristic evaluations (Nielsen, 1992), and other forms of expert reviews, have been shown to be effective in certain settings (Dumas, 2003) but are subjective and can be biased by group-

thinking (Turner & Pratkanis, 1998). These methods also exhibit poor inter-rater reliability (Hetzum & Jacobsen, 2003) due to differences in granularities of the task definition and the differences in the subjective ratings.

Automated tools, such as CogTool (John, Prevas, Salvucci, and Koedinger, 2004), seek to eliminate these two sources of poor inter-rater reliability by capturing actual end-user button pushes (to eliminate ambiguity in the task definition), and by estimating performance using human performance models such as Keystroke-Level Model (KLM), (Luo & John, 2005). These tools can also be used early in the development cycle.

CogTool, one of the first tools of this class, provides an easy way model skilled users’ performance behavior through storyboards designs. To create the storyboards, CogTool users include the different screen shots on the tool and specify “hot-spots” or widgets on the screen shots to simulate the user interaction. The screenshots are connected through transitions. Once the screens are connected, the user interacts on the screenshots through the widgets, and CogTool generates an executable script of the actions performed by the user that can be processed by an Operator Performance Model such as KLM (Luo & John, 2005), ACT-R (Anderson et al., 1995) or CORE (Vera, Howes, McCurdy, & Lewis, 2004) to compute a prediction of expert time-on-task.

### A. The HCIPA Method

HCIPA is a manual task/usability analysis inspection method that was designed to address issues with usability in the aviation and space industries (Sherry, et al., 2002, 2006). Specifically, these industries were interested in evaluating usability for trials-to-mastery and probability-to-complete the task.

The HCIPA method has its roots in a model of pilot cognition (Polson, Irving, & Irving, 1994). This method also known as the RAFIV model (Sherry et al., 2002) decomposes tasks into six sequential steps: (1) Identify Task, (2) Select Function, (3) Access Function, (4) Enter data for Function, (5) Confirm and Save Data, and (6) Monitor Function. These steps are illustrated in Figure 1.

The first step is to identify a task based on various external stimuli such as visual cues (menu item, error message), hearing cues (warning sounds), a request (e.g. checklist) or by remembering (e.g. recall from long-term memory). Operator proficiency is reduced when the user interface does not provide any guidance by salient visual cues (Sherry, Fennell, Feary, Polson, 2006).

Once the user knows what to do, the next step is to decide the right function to accomplish the task, which is to select a function. The function may be the name of a screen, the label on a button, a prompt or any other characteristic that tells the user to initiate the task. The more accessible the function is to the user, the higher the probability is to accomplish the task.

A set of operator actions are performed by a user in order to accomplish the task through the selected function. These operator actions are grouped under Access, Enter, Confirm and Save, and Monitor step.

The Access Step encloses the operator actions needed to access the function on the device. The goal for a designer is to reduce the number of operator actions needed to access the function.

The Enter Step encloses the operator actions needed to successfully execute the function. The operator actions may include data entry, visual data evaluation, and communication with external devices or personnel.

The Confirm and Save Step are all the operator actions needed to trigger the function.

Finally, the Monitor Step encloses the operator actions needed to monitor any change on the system state after the function is triggered.

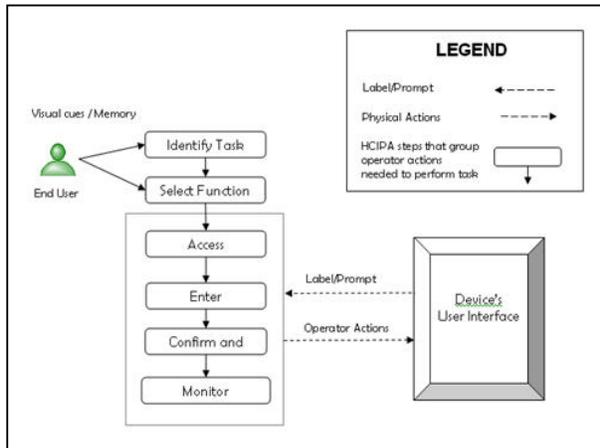


Figure 1. HCIPA Method

There are two basic classes of operator actions: (i) physical actions such as press a button or click on a link, and (ii) decision actions that cannot be viewed externally. A Task is executed by performing operator actions for each of the steps.

HCIPA estimates operator performance based on the minimization of memorized action sequences. When a user interface lacks clear labels, prompts, and/or organizational structure, additional training is required and operators must recall memorized action sequences (Sherry, Polson & Feary, 1998; Fennel, Sherry & Roberts, 2004).

The HCIPA approach has been successfully applied in several applications (Sherry, Polson & Feary, 2002; Sherry, Fennel, Feary, & Polson, 2006). The unguided manual process suffered from several issues: (1) ambiguity of granularity in descriptions of steps, (2) ambiguity in identification of salient visual cues, (3) problems in assessing salience of visual cues, (4) no method to determine trials-to-mastery or probability of failure to complete a task. The tool described in this paper is designed to overcome these shortfalls and includes an affordable Operator Performance Model to compute trials-to-mastery and probability-to-complete the task.

### III. THE E-HCIPA TOOL

e-HCIPA is a web based application developed to provide an automated way to apply the HCIPA method. The e-HCIPA is a free accessible web application; therefore, no username or password is required to use the tool. The current version of e-HCIPA runs only on Mozilla Firefox web browser and provides the following functionalities: Create a Task Analysis, Predict Operator Performance, Edit a Task Analysis, Delete a Task Analysis, and Generate PDF report (Task Analysis Report and User Guideline).

#### A. e-HCIPA Features

1) *Create Task Analysis*: Allows the user to create a new task analysis by inserting the device name, task name and function name. Once the device, name and function are saved, the labels for all steps are generated and the user can insert the operator actions for each step. Figure 2 shows the screen where user creates a new task analysis.

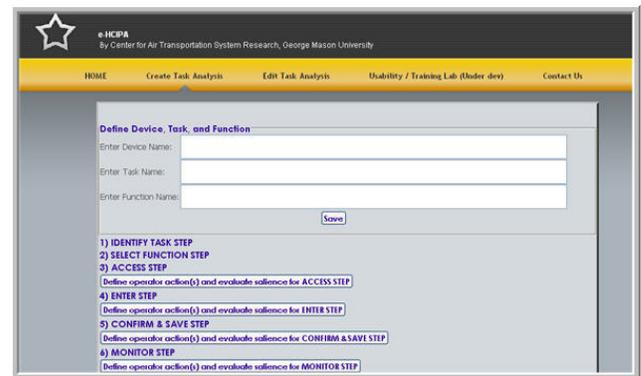


Figure 2. e-HCIPA Create Task Analysis screen

The operator actions may involve physical actions (press button, link), visual actions (read data from display field), audio actions (hear warning buzzer) or decision-making actions. Operator actions are automatically generated for the Identify Task and Select Function step based on the information entered on the task name and function name. The operator action for the Identify Task step is always generated as “Recognize need to:” concatenated with the task name entered by the analyst. The operator action generated for the Select function step is generated as “Decide to use function:” concatenated with the function name entered by the analyst. These two operator actions cannot be deleted by the user. The labels for the steps are created as follow:

- Identify Task Step: <task name>
- Select Function: <function name>
- Access Step: Access + <function name> + function
- Enter Step: Enter data for + <function name> + Function
- Confirm & Save Step: Confirm & Save data using + <function name> + Function

- Monitor Step: Monitor results of + *<function name>* + Function

The analyst can continue inserting operator actions for the Access, Enter, Confirm and Save and Monitor steps. Figure 3 shows the screen where the operator actions are inserted and the salience assessment takes place.

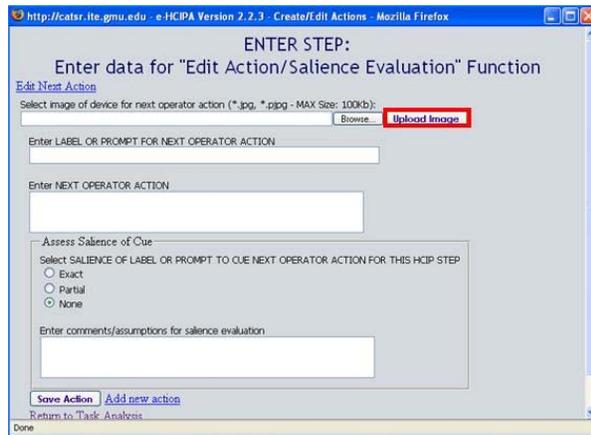


Figure 3. e-HCIPA Enter operator action

2) *Predict Operator Performance*: e-HCIPA calculates the two metrics based on the salience assessment conducted while inserting or editing an operator action: probability to fail a task, and trials to mastery the task. The probability of failure is calculated using (1), while the trials to mastery the task is obtained from (2). In (1), the maximum value used is 1. The values for the operator actions are calculated from the salience assessment using the following values: 0 for Exact, ¼ for Partial and 0 for None. Existing data support the prediction of trials to mastery a task (Bovair, Kieras, Polson, 1990).

$$\text{Probability to Failure} = 0.1753 * \sum \text{Operator actions} \quad (1)$$

$$\text{Trials Mastery Task} = 0.5916 * \sum \text{Operator actions} + 1.9632 \quad (2)$$

3) *Edit a Task Analysis*: e-HCIPA allows to modify any task analysis previously created. The device, task and function name can be changed at any time. If this is done, all the labels for the different steps will change also. The operator actions, including image, operator action description, label and salience assessment can be edited at any time. In order to edit a task analysis, the user must select the desired one from the list of task currently existing in the database.

4) *Delete a Task Analysis*: A task analysis can only be deleted using an administrator username and password.

5) *Generate a PDF report*: e-HCIPA allows to generate two .pdf reports. The reports are accessible only when a task analysis exists and it is being edited. The Task Analysis Report contains all the operator actions grouped by step, it

shows the two metrics for the given task (trials to mastery and probability to complete the task), a thumbnail image, the label, the salience evaluation, and the salience comments. The User Guideline report contains all the operator actions inserted for the task and ordered sequentially. The User Guideline report can be used for training purposes.

*B. e-HCIPA Technical Implementation*

e-HCIPA has been developed using PHP 4.4.4 and MySQL database. Figure 4 shows the Entity-Relationship Diagram of e-HCIPA.

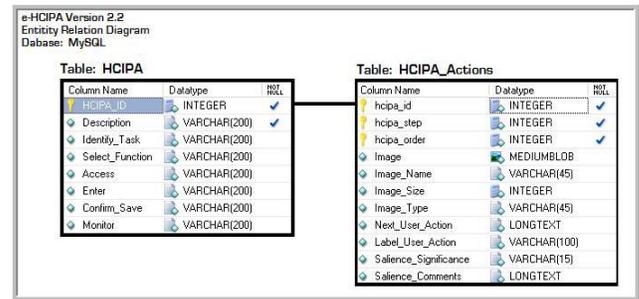


Figure 4. e-HCIPA Entity Relationship Diagram

The database table HCIPA stores the information for the device name, task description and function on fields Description, Identify\_Task and Select\_Function respectively. Once the user saves a new Task Analysis, e-HCIPA populates the rest of the fields on table HCIPA based on the information stored on the fields Identify\_Task and Select\_Function. Furthermore, two default operator actions are created. One for the Identify\_Task step and the other one for Select\_Function.

Table HCIPA\_Actions stores all operator actions for the given task. The field hcipa\_step is a enumerated field that keeps track of current step for the operator action. The values are: 1 for Identify\_Task, 2 for Select\_Function, 3 for Access, 4 for Enter, 5 for Confirm and Save and 6 for Monitor. The field hcipa\_order is a number used to reference the current order of the operator action for the step.

IV. CASE STUDY

An example HCIP analysis is illustrated below for a Multi-function Control and Display Unit (MCDU) of Boeing 737. The HCIPA analysis is summarized in table 2. The fields shown in italics are automatically generated by the tool. The report generated by the tool for this task is included in Appendix A.

TABLE I. INPUT DATA FOR A HCIP ANALYSIS ON FMS737

Define Device, Task, and Function	
Device Name	FMS737
Task Name	Modify Departure Runway
Function Name	Departures

Identify applicable sponsor/s here. (*sponsors*)

TABLE II. HCIP ANALYSIS FOR TASK “MODIFY DEPARTURE RUNWAY”

Step	Operator Action	Label to Prompt next Operator Action	Saliency of Label to Cue Next Operator Action
Id Task: ATC” Cleared for Taxi. Expect Departure on Runway XX, maintain runway heading until xxxx, then fly Departure Procedure zzz.	<i>Recognize need to Modify Departure Runway</i>	ATC instruction	Exact
Select Function DEPARTURES	<i>Decide to use the DEPARTURE Function</i>	None	None
Access DEPARTURES Function	Press Mode key labeled DEP/ARR	DEP/ARR	Partial
	Press LS 1L	DEP KSLC	Exact
Enter data for DEPARTURES Function	Line Select XL desired SID (Press NEXT PAGE or PREV PAGE Mode Key to see other options)	SIDS	Exact
	Line Select XR desired Runway (Press NEXT PAGE or PREV Page Mode Key top see other options)	RUNWAYS	Exact
	Line Select XL desired SID Transition (Press NEXT PAGE or PREV PAGE Mode Key to see other options)	TRANS	Exact
Confirm & Save data using “DEPARTURES” Function	Check SID is <SEL>	SID... <SEL>	Exact
	Check RUNWAY is <SEL>	RUNWAY ...<SEL>	Exact
	Check TRANS is <SEL>	TRANS ... <SEL>	Exact
	Confirm changes with other pilot	None	Partial
	Press EXECute Key	EXEC	Exact
Monitor results of “DEPARTURES” Function	Check LEGS includes desired Runway, SID waypoints, and SID Transition waypoints	LEGS	Exact
	Check LEGS does not include a –ROUTE DISCONTINUITY – between SID or SID Transition waypoints	None	Partial
	Check ND shows desired course and sequence of waypoints	None	Exact

The first column includes the HCIPA steps. The second column lists the operator actions. Note, that the operator actions of the Id Task and Select Functions steps are automatically generated by the tool. The third column lists the visual cue (if any) that prompts the next user action. The fourth column is an assessment of the saliency of the cue.

The tool calculates the estimated trials to mastery the task as 2.55 and the probability to fail the task as 0.18 according to the saliency evaluation of all operator actions. Figure 5 shows the distribution of operator actions by HCIPA step and saliency evaluation.

Based on the HCIPA analysis done in this task, we can conclude that operators using the MCDU on B737 do not have issues identifying the task. However, they must remember how to access the function that allows modifying the departure runway. Furthermore, special attention should be given on the actions where the saliency evaluation is partial. According to the existing model, operators will need to practice the task approximately three times to memorize the operator actions which lack exact saliency.

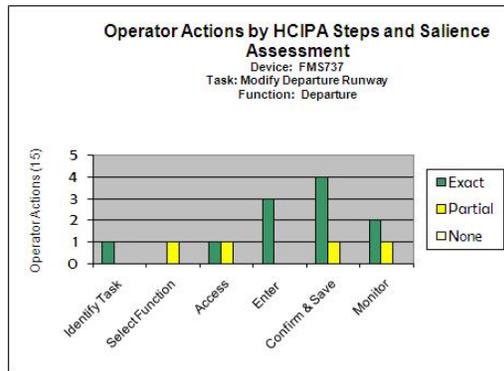


Figure 5. Operator Actions per HCIPA step

## V. FUTURE WORK

This paper describes a tool that this intended for use by software and design engineers in the course of their software engineering duties, to conduct usability analyses. Specifically, the tool enables designers and testers to rapidly assess the trials to mastery (i.e. time to competence for training) and the probability of failure-to-complete for each task that can be performed by the product under design. The computation of these human performance measures is based on the specification of operator actions and an assessment of the saliency of visual cues in the proposed automation user-interface to prompt the next operator action. The web-based tool also provides designers in multiple locations to view and contribute to the design and the usability evaluation.

Beta testing of the tool is underway. Future work includes tool implementation, development of new functionalities, improvement of human performance model, and inter-rater reliability of the Assessment of the Saliency of the Visual Cues.

- **Tool implementation:** The current version of tool only runs in Mozilla Firefox and has been limited to the use of PHP 4.4. The short term goal is to make it compatible with other web browsers, and to migrate the application to another server with newer versions of PHP. Furthermore, a security model should be implemented to protect sensitive data in a task analysis description. In terms of outputs, the current version only provides two reports on a .pdf format. These two reports will be also available in other format and, as needed; more reports will be developed, including the development of graphs reports. These will also solve the current limitation of the tool to accept graphics only on .jpg or .png format.
- **New functionality:** (i) hierarchical organization of task that allows to relate other tasks analysis as sub-task, (ii) provide API to enable import/export of models (e.g. with CogTool), (iii) development of a training laboratory by reusing task analysis description and images
- **Operator Performance Model:** The current model is based on empirical data from 4 experiments. Further

work is planned to increase empirical data set and leverage existing models such as CORE, ACT-R, etc.

- **Inter-rater Reliability of the Assessment of the Saliency of the Visual Cues:** The assessment of the saliency of visual cues for prompting the operator's next action is critical for the accuracy of the tool. The current version of the tool relies on the assessment of the saliency of the cue by the designer (i.e. None, Partial, Exact). This manual form of assessment suffers several issues. First, the assessment is reliant on the overlap of the designers "semantic state-space" with the end-users "semantic state-space." Recent studies have shown wide variance in semantic state-spaces and large differences between the semantic state-spaces of the designers and end-users. Second, even within a group of end-users and domain experts, the semantic state-space can exhibit a wide distribution. This issue will be investigated in two ways. First it is proposed to add a feature of the tool, loosely named, "Usability Lab." This feature will enable the collation of domain experts assessment of the saliency of the visual cues. Second, several automated techniques exist to automate the saliency assessment. Latent Semantic Analysis, LSA (Landauer & Dumais, 1997; Kitajima, Blackmon, and Polson, 2000) and Scent-based Navigation and Information Foraging in the ACT architecture, SNIF-ACT (Pirolli & Fu, 2003) are two of these automated technique that will be researched to evaluate their feasibility to be included in e-HCIPA.

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APPENDIX A

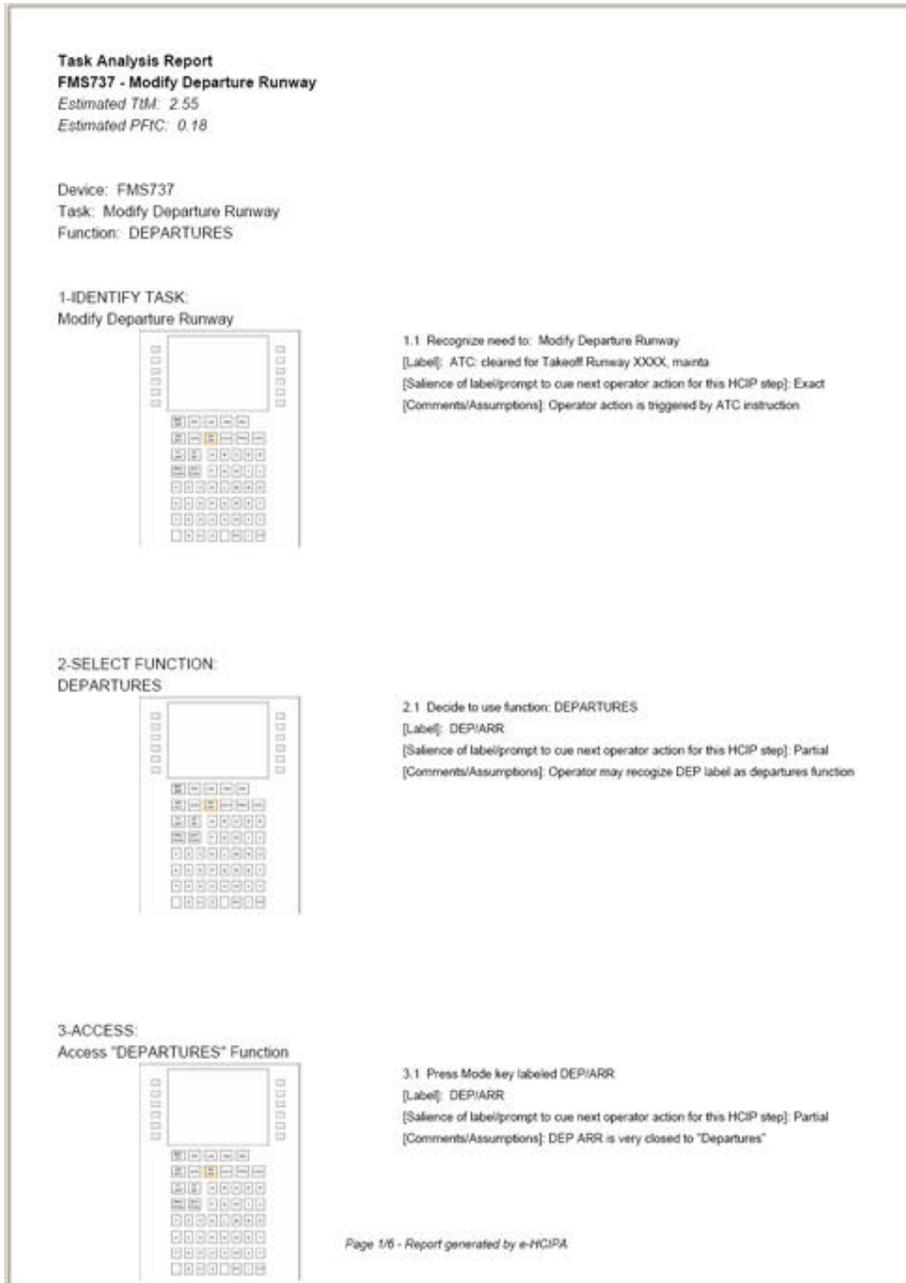


Figure 6. Report generated on e-HCIPA for Task "Modify Departure Runway", FMS737