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# A METHODOLOGY AND TOOLS FOR THE PROSPECTIVE IDENTIFICATION OF NEXTGEN HUMAN FACTORS ISSUES

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The Human-Machine Systems Engineering Methodology (HMSEM) is a systematic method to prospectively identify relevant human fallibilities, potential errors, and general human factors issues in a complex, high-risk system, then develop design recommendations for remediations to counteract the fallibilities, avoid or mitigate the errors, and resolve the issues. HMSEM uses IDEF0 functional modeling, task analysis, human fallibilities analysis, and Failure Modes and Effects Analysis, organizing the information for and from the analyses in a workbook. The results of its application to several tasks on the NextGen flight deck suggest that it can be a valuable complement to other means to anticipate and resolve human factors issues in NextGen development.

The problem of human performance in complex, high risk systems was described concisely, accurately, and usefully by Wiener in the phrase, “fallible humans and vulnerable systems” (Wiener, 1987), and the Next Generation air transportation system (NextGen) threatens to be a system highly vulnerable to the errors of its fallible human operators. From the documentation available at this time (e.g., JPDO, 2007), NextGen appears to be a technology-driven system, not a human-centered system, and we know from past experience that technology-driven systems can be particularly vulnerable to human error. Already, some NextGen human factors issues have been identified (e.g., Sheridan et al, 2006; Funk et al, 2009), but much remains to be done. The aviation human factors/psychology community can make a valuable contribution to the development and implementation of NextGen through the thorough and systematic identification of human factors issues. Those issues must be identified, organized, and presented in such a way as to be understandable by and useful to NextGen system architects and engineers.

## Objectives

The objectives of this project were to develop a systematic, analytical methodology to prospectively identify human factors issues and recommend remediations, then apply the methodology to the NextGen flight deck.

## Human-Machine Systems Engineering Methodology, Tools, and Application to NextGen

The result of the development, the Human-Machine Systems Engineering Methodology (HMSEM), is a formal, systematic methodology to identify important human fallibilities relevant to a system, identify specific errors likely to arise from the interactions of those fallibilities with characteristics of the system, identify general human factors issues arising from the potential errors, identify remediations, and organize the findings in a way useful to analysts, Subject Matter Experts (SMEs), system architects, and system engineers. HMSEM analysts, supported by SMEs, work through the following stages: 1) formal functional modeling using IDEF0, 2) task analysis, 3) human fallibilities identification, 4) Failure Modes and Effects Analysis, 5) issue identification, and 6) requirements development. HMSEM was applied, in a test case, to the NextGen flight deck, and HMSEM and the application are described and discussed in the remainder of this paper.

### *IDEF0 Modeling*

Many human factors methodologies begin with some form of hierarchical task analysis (HTA), but HMSEM requires a richer and more detailed representation of system processes (activities, functions, tasks) than HTA typically provides. This requirement is met by modeling the system with IDEF0, a graphical language for modeling system functions. The Oregon NextGen Flight Deck Functional Model (ONFDFM) is an IDEF0 model of a generic NextGen commercial flight deck based on NextGen literature available at this time (e.g., JPDO, 2007) and knowledge of present-day commercial flight deck operations. Figure 1 shows ONFDFM's top-level diagram, its most general representation of flight deck functions.

In IDEF0, a function is a process, performed by mechanisms (humans, devices), that transforms inputs (matter, energy, information, system states) to outputs (matter, energy, information, system states), subject to controls (information, factors) that guide, facilitate, or constrain the process. IDEF0 uses boxes labeled with verb phrases to represent functions and arrows labeled with noun phrases to represent mechanisms, inputs, outputs, and controls. So, omitting some details, Figure 1 represents that the human flight crew [h FC] and flight deck systems (devices) [d FD systems] perform flight deck tasks [Perform flight deck tasks] to transform the aircraft system [s Acft] to a managed and controlled aircraft system [s Acft, managed & controlled]. The performance of flight deck tasks is guided (controlled) by information in flight deck procedures [i FD procedures] and Federal Aviation Regulations [i FARs] and influenced (controlled) by performance shaping factors [f Performance shaping factors], like the aircraft's performance limitations and the flight crew's decision biases. To perform flight deck tasks also transforms the flight crew's mental model [i FC MM] to an updated mental model [i FC MM, updated], utilizes NextGen systems [s NG systems] and the Air Navigation Service Provider [h ANSP], and is controlled by information received from the NextGen system [i NG info] and the ANSP [i Comm from ANSP].

In IDEF0, general functions are detailed or decomposed into more specific functions, those functions are further detailed, and the modeling process continues until a representation sufficiently detailed for further analysis is produced. For example, in the ONFDFM, the function [Perform flight deck tasks] is detailed into [Collaboratively manage FP (flight plan)], [Manage 4DT (4-dimensional trajectory)], [Manage acft (aircraft) systems], and [Control acft]. Those are in turn detailed, and so on. Table 1 shows a portion of the function hierarchy of the ONFDFM, elaborating part of the [Manage 4DT] branch.  A-numbers (A#s) define a function's place in the hierarchy ("A" for "Activity" being inherited from IDEF0's precursor, SADT). The hierarchy is, effectively, the task hierarchy resulting from a typical HTA, but the detailed IDEF0 diagrams underlying the hierarchy bear much more information than does the typical HTA. As shown in Table 1, the detailing of [Manage 4DT] ultimately yields [Get traffic info using HSI/CDTI (Horizontal Situation Indicator/Cockpit Display of Traffic Information)], part of whose IDEF0 diagram is shown in Figure 2.

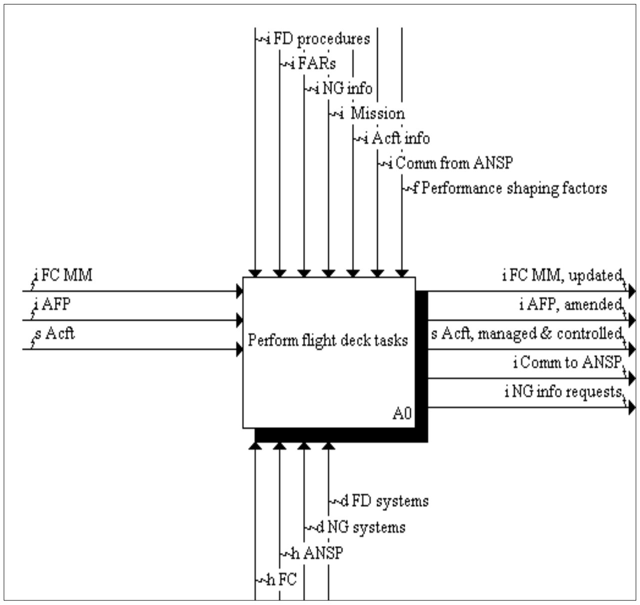

*Figure 1.* Top-level IDEF0 diagram of the Oregon NextGen Flight Deck Functional Model.

*Table 1.*  A portion of the ONFDFM function hierarchy, elaborating the [Manage 4DT] branch.

| A# | Function |
|---|---|
| A0: | Perform flight deck tasks |
| A1: | Collaboratively manage FP |
| A2: | Manage 4DT |
| A21: | Receive ANSP clearances |
| A22: | Assess 4DT WRT AFP & clearances |
| A23: | Assess 4DT WRT terrain |
| A24: | Assess 4DT WRT obstacles |
| A25: | Assess 4DT WRT traffic |
| A251: | Get traffic info from ANSP advisories |
| A252: | Get traffic info from FD alerts |
| **A253:** | **Get traffic info using HSI/CDTI** |
| A2531: | Configure HSI to display traffic |
| A2532: | Locate traffic symbols on CDTI |
| A2533: | Select traffic for detailed info |
| A2534: | Determine traffic IDs, bearings, ..., from CDTI |
| A2535: | Estimate traffic trajectories from CDTI info |
| A254: | Get traffic info visually |
| A255: | Integrate traffic info |
| A256: | Assess integrated traffic picture |
| A26: | Adjust 4DT |
| A3: | Manage acft systems |
| A4: | Control acft |

ONFDFM was developed using KBSI Inc.'s AI0Win IDEF0 modeling software. An HTML version of the full model, generated by AI0Win, is accessible at http://flightdeck.ie.orst.edu/NextGen/Models/ONFDFM1.0/.

IDEF0 diagrams and the glossary of model elements underlying them provide a very rich representation of the functions performed in and by a complex system. An important benefit over HTA is that IDEF0 explicitly models not only functions (or tasks), but relationships among functions via mechanisms, inputs, outputs, and controls. Those relationships can be identified in the IDEF0 model by examining related diagrams and tracing

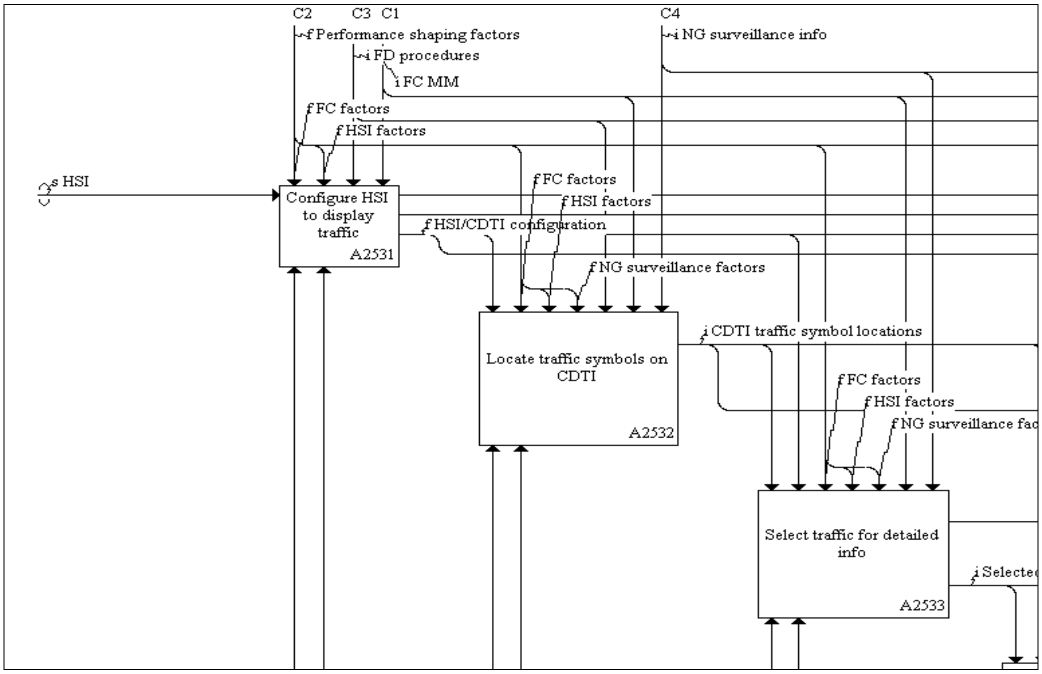

*Figure 2:* Detail from the IDEF0 diagram of the [Get traffic info using HSI/CDTI] function from the ONFDFM.

arrows. However, a complex IDEF0 model may have many diagrams, and navigating them to identify relationships, although in principle straightforward, is in practice difficult and prone to error. As in any reductionist method, it is tempting for the analysts to focus on a small part of the IDEF0 model and ignore its context, thus to “lose the big picture” or “miss the forest for the trees”. HMSEM uses the prototype IDEF0 Navigator (INav) to avoid that. INav operates on an IDEF0 model providing an alternative representation to the IDEF0 diagrams. An arrow entering an IDEF0 diagram can come from another part of the model outside the immediate diagram or from outside the system itself. The INav representation abstracts out some of the details of the IDEF0 diagrams to show from where each arrow (or each group of related arrows) comes or where it goes, allowing the analyst to explore details in the context of the entire model in a single view.

### *Task Analysis*

In HMSEM, task analysis is used to further analyze the most detailed IDEF0 functions – referred to as tasks – to compile, from the model and elsewhere, information needed for human fallibilities identification. The analysts enter, for example, task location and timing information into the HMSEM workbook. Table 2 shows the results of task analysis of [A2534: Determine traffic IDs, bearings, ranges, & relative altitudes from CDTI].

*Table 2.* Results of the task analysis of [A2534: Determine traffic IDs, bearings, ranges, & relative altitudes from CDTI].

| Task Analysis Attribute | Value |
|---|---|
| Purpose / Value Added | Necessary to detect conflicts and determine if separation and spacing is appropriate. |
| Location | Flight deck |
| Frequency & Timing | Continuous, intermittent |
| Environmental Conditions | Darkness (red illum) to direct sunlight, glare, etc.; Noise; Vibration (low, high freq.) |
| Information Requirements | i Selected traffic; i CDTI traffic symbol locations; f HSI/CDTI configuration; i FD procedures; i FC MM; i NG surveillance info |
| Sensory/Cognitive/Motor Actions | View CDTI; Identify traffic; Estimate bearings, ranges, relative altitudes, and probable trajectories |

### *Human Fallibilities Identification*

Human factors analysis sometimes employs a Human Error Identification (HEI) technique like SHERPA (Embrey, 1986) to identify errors that could occur in a system. HEI techniques typically start with a functional representation of the system (often from HTA) and analysts and SMEs, referring to that representation, use their knowledge and experience to hypothesize potential errors that could occur in specific tasks. HEI techniques rely heavily on analyst and SME memory and judgment (and, one could say, serendipity) to compile a comprehensive list of likely errors and are, therefore, subject to the same kinds of limitations that affect human performance in systems like the one they are studying. Rather than to attempt to identify errors directly, HMSEM first identifies the human fallibilities likely to be significant in each task and, from system and task information from the IDEF0 model and task analysis, proceeds to project errors that could occur as a result of those fallibilities interacting with system and task characteristics.

HMSEM uses the Human Fallibilities Identification and Remediation Database (HFIRDB) for fallibilities identification. The HFIRDB is a database consisting of human fallibilities and remediations for them compiled from Wickens' and Hollands' *Engineering Psychology and Human Performance* (Wickens & Hollands, 2000). The user interface leads the analysts through a series of questions about each task to be analyzed for fallibilities and errors and the analysts refer to the IDEF0 model and the task analysis to answer them. The HFIRDB first asks the analysts to select from among seven information processing stages (i.e., sensory registration, perception, attention allocation, working memory, long-term memory, decision-making, and response control) those employed in the task under consideration. Next the analysts are asked to choose general human fallibility categories (e.g., visual display processing or working memory limitations) that apply to the selected information processing stages. Then HFIRDB asks the analysts to choose from a list of possibilities just those conditions that exist in the task under consideration. For example, that operators must appropriately allocate attention to concurrently process or selectively attend to visual stimuli presented in displays is a condition necessary for visual display processing fallibilities to be relevant. The HFIRDB uses a series of queries to produce a list of human fallibilities that may manifest themselves in performance of the task, such as the sensitivity-related vigilance decrement, the tendency for operator performance to degrade during vigilance tasks as a result of a decrease in sensitivity level. The HFIRDB then asks the analysts to confirm task conditions that enable manifestation of the fallibilities and a complete list of relevant fallibilities is generated, which may be copied into the HMSEM workbook for the next analysis stage.

### *Failure Modes and Effects Analysis*

Failure Modes and Effects Analysis (FMEA) is an analytic technique used to prospectively identify the ways in which a system can fail. FMEA begins with a process or functional description of the system to be analyzed. For each function, the analysts use knowledge of the function to identify failure modes, that is, ways in which it could fail to achieve its intended outcome. For each failure mode, the analysts identify the causes of or contributing factors to the failure mode, and try to predict its consequences. To prioritize the failure modes for further study or remediation, the analysts assign numeric ratings as to the severity of the consequences of the failure mode, the probability or expected frequency of its occurrence, and the likelihood that it would not be detected in time to avoid the consequences. These three ratings are multiplied to give a Risk Priority Number (RPN) for each failure mode and the RPNs are used to prioritize the failure modes for further analysis or remediation.

In HMSEM, FMEA is used to identify potential operator errors as failure modes. The analysts use the IDEF0 model, operator fallibilities identified with the help of the HFIRDB, and general domain and human factors knowledge to identify specific failure modes – i.e., operator errors – that could occur in performing the task as a result of the interaction of system and task characteristics with those fallibilities. These are entered into the HMSEM workbook. Table 3 presents some results from FMEA applied to the task [A2534: Determine traffic IDs, bearings, ranges, & relative altitudes from CDTI].

### *Issue Identification*

To identify issues, the HMSEM analysts collect similar failure modes and those related by common fallibilities and task characteristics. For each such collection, the analysts compose a statement which, if it is or should become true in the implementation and operation of the system, describes a condition or situation related to system operations where natural human characteristics, capabilities, limitations, and tendencies are very likely to lead to significant problems with system effectiveness, efficiency, or safety. These issues are added to the HMSEM workbook. Table 4 presents some NextGen flight deck failure modes and general issues arising from them.

### *Requirements Development*

Perhaps hundreds of human factors issues related to the NextGen flight deck may be identified in this and

*Table 3.* Excerpts from the Failure Modes and Effects Analysis of the task, [A2534: Determine traffic IDs, bearings, ranges, & relative altitudes from CDTI].

| **Human_Fallibility** | **Other Contributing Factor(s)** | **Potential Failure Mode** | **Potential Effects of Failure Mode** | **Severity** | **Probability** | **Nondetect.** | **RPN** |
|---|---|---|---|---|---|---|---|
| Perceptual competition | High symbol density on HSI/CDTI | MM error: FC confuses two CDTI traffic symbols, mis-estimates bearing/range/altitude/trajectory of one or both. | Inaccurate perception and projection of traffic bearing/range/altitude/trajectory, loss of separation/spacing. | 5 | 4 | 5 | 100 |
| Negative skill transfer | CDTI display format, symbology differ from those of similar equipment. | MM error: FC misinterprets CDTI traffic info, mis-estimates bearing/range/altitude/trajectory. | Inaccurate perception and projection of traffic bearing/range/altitude/trajectory, loss of separation/spacing. | 5 | 4 | 4 | 80 |
| Strategic task-management bias | Other high-priority, concurrent tasks/stimuli. | TM error: FC fixates on CDTI, fails to perform other high-priority tasks. | Other tasks ignored or performed poorly. | 4 | 5 | 4 | 80 |

*Table 4.* Some general issues identified by analysis of the NextGen flight deck.

| Related Failure Modes | In Task(s) | Resulting General Issue |
|---|---|---|
| Miss: FC misses traffic on CDTI. | A2532 | The flight crew's CDTI traffic detection performance decreases over long periods of self-separation authority. |
| Delay: CDTI scan is prolonged. Miss: FC fixates on one region of CDTI, misses other traffic. | A2532 | The effectiveness and efficiency of the flight crew's CDTI traffic scan is very susceptible to stress and other performance-shaping factors and performance can suffer as a result. |
| mistake: FC chooses and sets HSI/CDTI to inappropriate config. | A2531 | Complex device configuration procedures induce pilots to select suboptimal configurations, leading to diminished performance when the devices are used. |
| slip: FC sets HSI/CDTI to unintended config. lapse: FC omits step to properly configure HSI/CDTI. MM error: FC misinterprets CDTI traffic info, mis-estimates bearing/range/altitude/trajectory. | A2531,<br>A2534 | Attempting to perform two or more tasks that require the same mental resources concurrently causes the performance of at least one of them to be diminished, |

other ways, but unless guidance is given to avert the potential effectiveness, efficiency, and safety problems they raise, merely citing them is of little value. Here is an opportunity for aviation human factors scientists and practitioners to go the next step toward solution. In addition to human fallibilities information, the HFIRDB contains general guidance information for remediations to reduce the likelihood that human fallibilities will interact with system and task characteristics to manifest themselves as errors. With fallibility, failure mode, error, and issue information from the HMSEM workbook, the analysts may turn again to the HFIRDB to retrieve countermeasures it suggests to counteract the fallibilities. Table 5 presents some suggested requirements for the NextGen flight deck. Following requirements engineering convention, terms and phrases enclosed in asterisks (* ... *) are, for the time being, ambiguous and unverifiable. Further analysis, and possibly research, will be required to refine them.

### *Discussion*

HMSEM is prospective, systematic, and is based on validated human factors knowledge. Moreover, its use of a rich functional modeling formalism provides a framework to organize human fallibilities, potential errors, human factors issues, and recommendations or requirements in a way compatible with the functional models used by system architects and engineers. It thus offers a natural way for human factors scientists and engineers to collaborate with system designers in the critical early stages of system development. But HMSEM has important limitations. In its present form, it is a time-consuming process. Most HMSEM tools are presently in the prototype stage. Despite its

*Table 5.* Some preliminary NextGen flight deck requirements to address issues identified in HMSEM analysis. Asterisks (* ... *) denote as-yet unverifiable terms.

| **A#** | **Requirement** | **Type** |
|---|---|---|
| A0 | NextGen flight crews shall receive concurrent task management training, including *topics TBD*. | Training |
| A253 | CDTI traffic symbol visual coding, for whatever purpose, shall *manifest* exactly three levels of salience corresponding to the three levels of traffic priority: low for the symbols of normal priority traffic, medium for symbols of intermediate priority traffic, and high for symbols of high priority traffic. | Equipment |
| A2532 | CDTI procedures shall *recommend or specify* a *systematic* display scan pattern that covers the entire display each cycle and which cycle is completed in no more than *C* seconds. | Procedures |

attempt to be systematic, its application is still subject to analyst biases and analyst knowledge and cognitive limitations. Its application to NextGen, described in this paper, is limited in scope to a few tasks related to CDTI-based traffic awareness. The functional model itself is limited in scope and based on as-yet very limited documentation on the envisioned NextGen flight deck.

### *Recommendations*

Therefore, the knowledge base of the HFIRDB should be expanded to address more dimensions of human performance and the HMSEM workbook should be converted to a more robust software tool that integrates the other tools, provides a repository for findings, and generates publishable reports. A team of human factors analysts, SMEs, and engineers should be assembled to continue applying HMSEM to NextGen. They should refine and expand the ONFDFM to incorporate the most recent plans for NextGen implementation, modeling, in detail, the full scope of flight deck functions. They should use the model and refined tools to identify human fallibilities, potential errors, and human factors issues, and make recommendations for engineering requirements to guide NextGen system design. Throughout this process, the team should work with NextGen system architects and engineers to make the ONFDFM consistent with functional models used for NextGen development, to utilize the latest NextGen plans in their analyses, and to organize and present their findings in a way compatible with NextGen design documents. In this way, human factors analysis and recommendations will be more likely to have greater impact on NextGen.

### *Acknowledgments*

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