APPLIED COMPARISON BETWEEN HIERARCHICAL GOAL ANALYSIS AND MISSION, FUNCTION AND TASK ANALYSIS

Renee Chow
DRDC Toronto
Toronto, ON, Canada

Bob Kobierski, Curtis Coates
CMC Electronics, Inc.
Ottawa, ON, Canada

Jacquelyn Crebolder
DRDC Atlantic
Dartmouth, NS, Canada

This paper uses a case study approach to compare applications of Mission, Function and Task Analysis (MFTA) and Hierarchical Goal Analysis (HGA) to identify requirements for systems design in a military context. The two approaches were used to analyze three tactical positions in the Operations Room of a Halifax Class naval frigate. MFTA produced a four-level hierarchy; the bottom level of which specified tasks to be performed by the three naval operators. HGA produced a hierarchy that ranged from four to eight levels; every level specified goals, each assigned to an operator and each associated with a controlled variable. MFTA was found easier to apply, as job positions and time were used as frames of reference to identify tasks. HGA was found harder to apply, as goals were not defined by position, organizational structure, or time. MFTA successfully identified operator tasks, while HGA successfully identified both operator tasks and interactions that could benefit from technological support.

INTRODUCTION

Mission, Function and Task Analysis (MFTA) has long been used to support requirements identification, and interface, training, and systems design in the military. It has been applied in diverse contexts, including helicopter operation (CMC, 1988), and maritime patrol (CMC, 1993). In contrast, Hierarchical Goal Analysis (HGA) is a relatively new approach that, to the best of our knowledge, has only been applied in two contexts: UAV control and frigate operation. The first application used HGA to support the design of intelligent, adaptive interfaces for UAV control by a 3-person, airborne crew (CMC, 2004). The second application used HGA to identify critical activities that could benefit from advanced decision aiding technology in the operations room of a Halifax-class naval frigate (CMC, in review). This second application took place within a larger project that also applied MFTA, where MFTA was first applied to 3 of 11 operations room operators to which HGA was later applied. Although a variety of other cognitive system analysis techniques exist, such as Cognitive Work Analysis (CWA), the Halifax-class naval frigate operations room studies present an interesting and timely opportunity to conduct a specific comparison of the MFTA and HGA methods in terms of their processes and outputs, and their relative strengths and weaknesses. The comparison will assist future systems analysts in identifying an appropriate technique for their purposes.

METHOD

MFTA

MFTA has been used for over 40 years to specify requirements for military systems. It was described in the first (1968) and subsequent (1994, 1996, 1999) editions of the MIL-H-46855 handbook. Often, MFTA begins with the analysis of baseline scenarios to produce a composite scenario (i.e., mission) that exercises all important and relevant functions of the system. This mission is decomposed into mission segments, then functions, then lower level functions. Decomposition may reflect different functional groupings (e.g., aviate, navigate, communicate for an aircrew), or different points in time (e.g., takeoff, cruise, landing). At the lowest level, functions are allocated to a human or a machine. Functions allocated to the human are referred to as tasks.

For each task, completion time and perceptual and cognitive demands are identified. Depending on the purpose of the analysis (e.g., personnel selection, training), additional details like inputs, outputs, skills and knowledge required may also be identified. Critical tasks are identified based on criteria like mission or safety impact, or proximity to human performance limits. Tasks are linked into Operational Sequence Diagrams (OSDs) to provide a graphical representation of the sequential flow. Finally, a workload analysis is conducted based on demands imposed by different tasks and their relations in the OSDs.

HGA

HGA (Hendy et al., 2002) models a cognitive system consisting of one or more operators by identifying goals, at various levels of abstraction, which the system needs to achieve. Goals are desired states to which current states are compared. If the current state does not equal the desired state, otherwise known as an error, then some action must be taken to resolve the error. Unlike the task hierarchy of MFTA, a goal hierarchy does not specify what actions should be taken. Instead, it specifies how the end states of actions should be assessed. Links between goals suggest possible directions where an operator may direct attention (i.e., a series of assessments that he/she may make).

In HGA, every goal at every level must be assignable to a human or machine operator and be perceivable (i.e., an operator must be responsible for asking if the current state of a specified variable equals the desired state, and that operator must know the current state). The controlled variable and the assigned operator are the two key attributes for each goal, and they support two analyses:

1. stability analysis – which identifies variables controlled concurrently by more than one operator; and
2. upward flow analysis – which identifies instances where a lower level goal that is controlled by one operator supports a higher level goal that is controlled by a different operator (hence feedback needs to be provided by one operator to another).

The stability analysis can be used to generate requirements for systems or process (re)design, by identifying situations where one operator (attending to one goal) may try to control a variable that another operator (attending to another goal) may also be trying to control. The upward flow analysis can be used to generate requirements for interface, workspace, or communication design, by identifying situations where one operator (controlling one goal) needs to know the status of a supporting goal (controlled by another operator). These requirements may be addressed by designing an interface to provide direct feedback or by supporting communication between operators.

Case Study: Halifax Class Frigate

The Halifax Class frigate, acquired by the Canadian Navy in the 1990s, is preparing for a mid-life upgrade that will modernize its operations room. It carries a crew of 230 people, and sensors and weapons for Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), and Anti-Submarine Warfare (ASW). The Commanding Officer (CO) leads the entire ship. In the Operations Room, the Operations Room Officer (ORO) is the CO's tactical advisor responsible for countering all threats. The Sensor Weapons Controller (SWC) (who directs AAW and ASuW) and the Assistant Sensor Weapons Controller (ASWC) (who directs ASW) both support the ORO. The Operations Room consists of 20 positions that support the ORO, SWC, or ASWC. The MFTA that was conducted (CMC, 2004) analyzed only the ORO, SWC, and ASWC; the HGA (CMC, in review) analyzed 11 positions in the Operations Room including the ORO, SWC, and ASWC.

FINDINGS

MFTA

An excerpt of the MFTA conducted for the ORO, SWC, and ASWC is shown in Figure 1. The Mission Analysis documented roles of Canada's maritime forces, generic missions of the Halifax Class frigate, and the frigate's weapons and command and control systems. It concluded with the development of a composite scenario depicting the frigate in the performance of its peacetime and wartime missions.

Three top-level functions (i.e., missions) were identified (e.g., conduct transit), and each mission was decomposed into first-level functions (i.e., mission segments) (e.g., conduct continuous surveillance). Mission segments were decomposed into second-level functions (e.g., detect contact) that were measurable and that might involve multiple operators and equipment subsystems. Each second-level function was decomposed into up to three parallel third-level functions (i.e., ORO tasks, SWC tasks, ASWC tasks) representing the actions of the three operators. This study produced 20 first-level, 75 second-level and 198 third-level functions. Finally, third-level functions were decomposed into fourth-level functions that, after function allocation, totalled more than 2600 tasks (e.g., "determine distance" for SWC). While the 2600 tasks were based on only 233 source tasks, the analyst was still required to modify, by name, the tasks to match the third-level function it was supporting.

In total, the hierarchy had five levels, and domain experts assigned a criticality rating to each task based on mission impact, safety impact, and proximity to human performance limits. Of the tasks, 33% were rated as critical and mitigating measures were recommended. Eight OSDs were generated, depicting elements from all three top-level functions. From these OSDs, 15 critical task sequences were identified, examining the information flow between ORO, SWC and ASWC, and others within and outside the operations room.

o 1. Conduct Transit *(mission / top level function)* ...
▪ 1.1 Proceed on Watch
▪ 1.2 Conduct Continuous Surveillance *(mission segment/ first level function)* ...
• 1.2.1 Maintain Picture
• 1.2.2 Detect Contact *(second level function)*
o 1.2.2.1 SWC Task *(third level function - by operator)*
a) Determine distance *(task / fourth level function)*
b) Observe contact / info displayed
o 1.2.2.2 ASWC Task ...
a) Optimize radar for detection
• 1.2.3 Classify Contact ...
• 1.2.4 Localize Contact ...
• 1.2.5 Manage Friendly Track ...
• 1.2.6 Manage Hostile Track ...
• 1.2.7 Manage Unknown Track ...
▪ 1.3 Monitor/Manage Systems ...
▪ 1.4 Maintain Communications ...
o 2. Conduct Peacetime Operations (mission / top level function) ...
o 3. Conduct Warfare Operations (mission / top level function) ...

Figure 1: MFTA for ORO, SWC and ASWC in Halifax Class Operations Room (Excerpt)

The OSDs were very effective at depicting the logical links between tasks and the originators and recipients of verbal communications. Within the operations room the downward flow of directions and information from the ORO, SWC and ASWC was clearly shown; additionally, select feedback and block reports (i.e., formatted verbal reports each containing a preamble followed by specific tactical mission related information) were indicated. When an operator's completed task triggered the initiation of another operator's task, it was clear that a verbal, electronic or visual link existed to provide the cue for the second task. These links were recorded in the task data permitting a classic link analysis to be easily performed. Unlike an HGA, however, the MFTA did not provide any indications of potential confusion caused by more than one operator controlling an operational parameter unannounced to other stakeholders (e.g. ship heading or stateboard information).

HGA

An excerpt of the HGA conducted for the Halifax Class Operations Room is shown in Figure 2. Three top-level goals were identified. Each was decomposed into the same seven first-level goals, which were further decomposed to form a hierarchy that ranged from four to eight levels deep. Development of the top and intermediate levels of decomposition was difficult and constant reference to the fundamental meaning of a goal and an upper level function, as described in Hendy et al. (2002), was necessary. The analysts considered the operators of the current Halifax Class operations room to be a group with common goals and subgoals. A concentrated effort was made to fully define the goals prior to allocating any to a specific operator. This may seem unusual for a mature system, however the intention was to produce a hierarchy of goals for which a restructured operations room complement could be defined. It was felt that a hierarchy structured around the current crew complement would result in a constrained design effort.

At the end of the development of the hierarchy, goal allocation occurred with all top- and first-level goals assigned to the CO. The ORO, SWC, ASWC were assigned to various second- and lower-level goals down to the bottom level. Although the HGA targeted eleven positions within the Operations Room, some goals were assigned to other positions within or outside the Operations Room. The most important difference from the MFTA was that operator assignments were made at every (not just the bottom) level. Operator assignments reflected actual work practices rather than organizational structure. For example, while the Air Raid Reporting Operator (ARRO) reported to SWC and SWC reported to ORO, ARRO was not assigned to all goals that supported SWC's goals. Sometimes, SWC was assigned to goals that supported his own goals (e.g., 5.1.1, 5.1.1.1); sometimes SWC's superior, the ORO, was assigned to goals that supported SWC's goals (e.g., 5.1.1, 5.1.1.5).

Five hundred and sixty-four goals were decomposed from the top-level goal of "I want to perceive the conduct of sea denial operations", of which 273 were assigned to ORO, SWC, or ASWC. Seventy-two goals were at the bottom level, of which 31 were assigned to ORO, SWC, or ASWC. Most goals (i.e., 88%) assigned to the ORO, SWC, and ASWC were at the higher levels. Even if these numbers were multiplied by 3 to estimate the total number of goals that would be identified if all three top-level goals were decomposed, there would still be much fewer goals assigned to ORO, SWC and ASWC in the HGA than tasks in the MFTA (i.e., "93" bottom level goals vs. 2600 tasks).

The stability analysis identified 17 variables controlled by multiple operators, of which 10 involved all three of the operators also analyzed in the MFTA (CO, ORO, ASWC). The remaining variables involved at least one of the three operators. The HGA reported herein was completed for the fully operational Halifax Class frigate. Over the years operational procedures have been developed and become ingrained into the culture to compensate for potential instabilities caused by multiple individuals attempting to control the same variable at the same time. For example, only the ORO requests a ship heading change to the Officer of the Watch. Even the CO will pass his or her commands through what would initially appear to be a redundant level of communications. However awkward, this procedure avoids instabilities with respect to ship heading. Currently, Canada is undertaking the preliminary design phase of the modernized frigate operations room, and the detailed stability analysis results have influenced the operator interface functionality early in this design effort. This has proved important due to the complex, functionality rich workstations that are currently under development, which can easily and unintentionally produce the same instabilities that the naval culture has sought to avoid. Results from the stability analysis also suggest that a mechanism for feedback or de-confliction should be designed to prevent operators from driving the variable into dangerous states.

The upward flow analysis identified 544 instances, involving at least one of the three targeted operators, where an operator assigned to a higher-level goal required feedback on a lower-level goal. A domain expert rated 331 of these requirements as important, and 127 as frequent. From senior officers down to master seamen, each individual relies on the performance of those assisting with completion of his or her goals. The wealth of specific information regarding upward feedback that is required on the success or progress of lower level goals has provided precise information for preliminary rapid prototyping of operations room interfaces. Rather than requesting updates, waiting unnecessarily while others are furthering lower level goals, or losing shared situational awareness due to a lack of knowledge of other's activities, operators in the modernized frigate operations room will be provided with workstations designed from the onset to provide the upwards flow of information necessary in a modern, rapid pace multi-threat warship.

Goal: I want to perceive	Operator
• … the Conduct of Sea Denial Operations *(top level goal)*	CO
o 1. … current mission is received and acknowledged	CO
o 2. … pre-deployment preparations are complete	CO
o 3. … ship is ready to undertake critical operational taskings – "action stations"	CO
o 4. … combat organization and resources are managed effectively	CO
o 5. … optimal level of Situational Awareness is being maintained *(first-level goal)*	CO
▪ 5.1 … accurate Recognized Maritime Picture is created & maintained *(second-level goal)*	ORO
• 5.1.1 … accurate tactical air picture is compiled *(third-level goal)*	SWC
o 5.1.1.1 … co-ordination of/with other units is effective	SWC
o 5.1.1.2 … effective display configuration	SWC
▪ 5.1.1.2.1 display settings are appropriate	SWC
▪ 5.1.1.2.2 alarms are accurate	SWC
▪ 5.1.1.2.3 display overlays are implemented	ARRO
▪ 5.1.1.2.4 effective radar manipulation occurs	ARRO
o 5.1.1.3 … effective air track management	ARRO
o 5.1.1.5 … effective visual watch is maintained	ORO
• 5.1.2 … accurate tactical surface picture is compiled	SWC
• 5.1.3 … accurate tactical subsurface picture is compiled	ASWC
o 6. … Ongoing operational tasks are being actioned effectively	CO
o 7. … Mission follow-up action is completed	CO
• …the Conduct of Peace Support Operations …	CO
• …the Provision of Assistance to Other Government Departments	CO

Figure 2: HGA for Halifax Class Operations Room (Excerpt)

DISCUSSION

In terms of process, MFTA was relatively easy to apply by analysts and subject matter experts (SMEs), who had little difficulty identifying actions (i.e., tasks) that need to be performed to support a given function or that need to be performed in parallel or in sequence. Most SMEs have undergone training based on task analyses that involved extensive use of mission scenarios, so they readily drew on past experience to visualize the flow of information or activities in the presented scenario. Task sequences were constructed bottom-up from task lists; they supported evaluation of the operators' abilities to multi-task. Task analyses tended to be highly reusable from one mission or system to the next.

In contrast, the use of HGA required substantial training, to convert users from thinking about what actions a given operator needs to perform, to thinking about who needs to assess effects and how effects need to be assessed. Instead of working bottom-up, an HGA needed to be worked both top-down and bottom-up (reflecting how an operator may direct attention), and the endpoint for analysis was not as obvious. SMEs found it harder to review goal hierarchies than task sequences, because goals in the same part of a hierarchy were not necessarily aligned or related in time.

However, the volume of effort required for MFTA was quite extensive (e.g., 2600 tasks to analyze) and could increase rapidly if more operators were added. By adding an operator, every low-level function would need to be revisited and a task list generated for that operator. In the study being examined the 75 second-level functions generated 198 third-level functions for only three operators – a fourth operator, depending on their overall involvement in the operations room, would increase the number of third-level functions to approximately 260. The modification of source tasks to support the additional third-level functions generated by one additional operator would be extensive. In contrast, in HGA, operators were assigned after all goals were identified, so consideration of all operators who might interact with the targeted operators was already "built into" the analysis. Since HGA produced goals that could be assigned to humans or machines, the hierarchy itself does not need to be changed when goals get re-assigned to intelligent agents. But a MFTA task hierarchy would need to be modified and expanded to consider intelligent agents.

In terms of outputs, MFTA readily produced information and action requirements for specific operators performing specific tasks, which could inform training, interface design, or task re-allocation to support these operators. MFTA also identified potential task conflicts and periods of high workload, which could highlight where support is most needed. It is important to note, however, that in the context of large-scale military procurement and/or development projects (like the Halifax Class Frigate modernization project supported by the studies reported here), the group of analysts (likely working for the military) who conduct the MFTA to support the specification of system requirements may not be the same group (likely working for manufacturers) who will perform the detailed design of the system. Therefore, large volumes of very detailed and very specific data produced by an MFTA may be quite difficult to transfer to the design team who may also find the data quite difficult to use. Unlike the MFTA, the HGA database is more abstract in nature, but smaller and more focused in that it does not attempt to track a mission timeline. Information to be displayed and controls necessary to complete specific goals are clearly indicated. Also included are other control requirements (e.g., limit access to a variable) that may be addressed by system or process design, and shared information requirements (e.g., feedback on a goal that affects another goal) that may be addressed by interface design or by facilitating communication between operators. The eventual allocation of all goals, regardless of level, to operators or multi-agent systems permits a wider range of system design solutions, which may step outside the bounds of traditional job classifications or human/machine allocations. The inherent value of the MFTA: short time required, ease of contribution by domain experts, straightforward methodology, clear (although limited) output, and links to training, system safety and personnel make the MFTA well suited for the support of Commercial-Off-The-Shelf and Military-Off-The-Shelf procurement programs. In full development programs such as the procurement of a new class of warship or the development of new Uninhabited Aerial Vehicle Workstations, the additional time available and the inherent interest in the development of new technologies (such as multi-agent systems) makes HGA a suitable choice for conceptual phase human factors analyses.

CONCLUSION

MFTA was found to be easy to learn and use. If the number of operators was small, and there was little need to consider new human or machine operators, it should effectively identify tasks that could benefit from technological support and the form of support required. It seemed especially suited for the design of training or interfaces for specific operators. HGA required a heavy initial investment in terms of time and effort to learn, and required continual support from a knowledgeable support team to ensure that the domain experts' efforts were meaningfully applied. This might be justified if the number of operators was large, or if interest was not limited to specific operators but rather to a combination of new trades and multi-agent systems. It seemed especially suited for system-level design, such as design of a new operations room involving new roles, physical layouts, and technological support.

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