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Application of hierarchical goal analysis to the Halifax Class frigate operations room:

A case study

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Abstract

This paper reports on the first application of Hierarchical Goal Analysis (HGA) [1], a relatively new approach to requirements analysis for complex systems, to naval command and control. HGA, applied to 11 positions of the Canadian Forces Halifax Class Frigate operations room, decomposed three top-level goals to a full goal hierarchy of 563 goals. The hierarchy ranged from four to nine levels deep, with an operator assigned to each goal. The HGA process concluded with a stability analysis for identifying potential goal conflicts and an upward flow analysis for identifying requirements for feedback between operators. An examination of the stability analysis revealed that the current design of the operations room includes few sources of instability where multiple operators compete for control of the same variable. The upward flow analysis revealed that the requirement for feedback from operators assigned to lower-level goals to operators assigned to higher-level goals is relatively high, and the operations room could benefit from review and redesign. The goal hierarchy, operator assignments, stability and upward flow analyses, and proposed solutions were reviewed by subject matter experts. While used to model an existing system, the present application of HGA appears to be especially useful in providing a basis for evaluating a system design and developing design recommendations.

Résumé

Le présent document décrit la première application de l'analyse des objectifs hiérarchiques (AOH) [1], une méthode relativement nouvelle d'analyse des besoins pour les systèmes complexes, au commandement et au contrôle navals. L'AOH, appliquée à 11 postes de la salle des opérations de la frégate de classe *Halifax* des Forces canadiennes, a décomposé trois grands objectifs en hiérarchie complète de 563 objectifs qui comportaient quatre à neuf niveaux, un opérateur étant associé à chaque objectif. L'AOH s'est conclue par une analyse de stabilité qui permet de cerner les conflits potentiels d'objectifs et une analyse ascendante qui permet de déterminer les besoins de rétroaction entre les opérateurs. Un examen de l'analyse de stabilité indique que l'aménagement actuel de la salle des opérations compte peu de sources d'instabilité là où de nombreux opérateurs se font concurrence pour le contrôle de la même variable. L'analyse ascendante a démontré que le besoin de rétroaction pour les opérateurs responsables des objectifs des niveaux inférieurs et les opérateurs responsables d'objectifs d'un niveau plus élevé est relativement grand, et que la salle des opérations pourrait bénéficier d'un examen et d'une restructuration. La hiérarchie des objectifs, les tâches des opérateurs, les analyses de stabilité et ascendante et les solutions proposées ont été examinées par des experts en la matière. Même si elle a servi à modéliser un système en place, l'application actuelle de l'AOH semble être un point de départ particulièrement utile pour évaluer la conception de systèmes et formuler des recommandations relatives à la conception.

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Executive summary

Application of Hierarchical Goal Analysis to the Halifax Class Frigate operations room

Renee Chow; Jacquelyn Crebolder; DRDC Toronto TR 2007-161; Defence R&D Canada – Toronto; November 2007.

Introduction or background: This paper reports on the first application of Hierarchical Goal Analysis (HGA) [1] to naval command and control. HGA is a relatively new approach to requirements analysis for complex sociotechnical systems. It uses goals (i.e., desired system states) rather than tasks (i.e., operator activities) or functions (i.e., engineered purposes) as the primary unit of analysis. Goals are identified through a process of hierarchical decomposition. For each goal, HGA identifies a controlled variable whose state is compared to the goal and manipulated as required to meet the goal. Once all goals and their corresponding controlled variables have been identified, each goal is assigned to a human or automated operator.

In the current application, HGA was applied to a Canadian Forces Halifax Class Frigate operations room to inform on the modernization of its workspace design and its command and control systems. HGA was chosen as an appropriate method of analysis for this particular application because of its potential to consider and integrate new and changing aspects of the environment, such as new positions in the operations room and re-allocation of roles between human operators and/or automated systems.

Results: Eleven positions of the current Halifax Class Frigate operations room team were analyzed using HGA. Three top- level goals were decomposed to a full goal hierarchy of 563 goals ranging from four to nine levels deep. The analysis revealed substantial variation in the number of goals assigned to each operator. Of the 11 operators analyzed, the Operations Room Officer (ORO), the Sensor Weapon Controller (SWC), and the Assistant Sensor Weapon Controller (ASWC) accounted for nearly half the goals. In contrast, the Commanding Officer (CO) was only assigned to 34 goals, but these included all seven first-level goals. Due to the HGA process, additional operators, such as the Shipborne Aircraft Controller (SAC) and the Officer of the Watch (OOW), were recognized as positions that should be included in the analysis if an understanding of the overall system is desired.

The HGA included a stability analysis which identified seventeen sources of potential instability in the operations room, where the same variable was associated with multiple goals assigned to multiple operators. Recommendations to resolve each source of instability were proposed, ranging from changes to the workspace layout, to interface design, to the implementation of new supporting technologies or information exchange procedures. The HGA also included an upward flow analysis which identified 776 requirements for feedback from one operator (assigned to a supporting goal) to another operator (assigned to the supported goal). These requirements were rated by domain experts based on importance, frequency, and the modality (i.e., visual or verbal) in which they were being addressed. Considering only the primary operators for each goal, 85% of feedback requirements were found to be addressed verbally, pointing to potential overloading of the auditory channel, and the possibility for new visual aids to provide operators with the necessary feedback. The highest numbers of overall, important, and frequent requirements for feedback were found between the SWC and the ORO, substantiating the need for these two

operators to be co-located, and thereby providing a basis for prioritizing the co-location of other operators.

Significance: Although HGA was conceived and first applied in the aviation world, this study demonstrates the applicability of the approach in a naval context. It also demonstrates that HGA could be used to analyze a system consisting of a large number of operators, thereby establishing it as a suitable methodology for the analysis of other complex military systems, such as the multi-organizational structure of maritime security. Despite the size and complexity of the operations room, HGA was able to identify potential goal conflicts as well as the needs for information flow between operators. HGA provided a systematic method for describing the dependencies between operators in both qualitative terms (e.g., the hierarchical relations between goals, the attributes of each goal, etc.) and quantitative terms (e.g., the number of operators who may compete for control of a specific variable, the number of feedback requirements between two specific operators, etc.). It was then possible to describe the design of the existing operations room in terms of its level of support for these various dependencies. The authors anticipate that the same method can be applied to describe alternate designs of the operations room, so that they can be compared with one another or with the existing design. Different criteria (e.g., support for the provision of important feedback versus frequent feedback) can be applied to compare designs.

Future plans: The knowledge elicitation phase of this HGA was challenging, as subject matter experts (SMEs) were accustomed to thinking in terms of tasks rather than goals. The development of the goal hierarchy and the documentation of goal attributes were conducted using a tool designed for hierarchical task analysis, and the tool did not include support for translating the data collected on goals directly into stability analysis and upward flow analysis outputs. To support future applications of HGA, the development of training modules on HGA and a software tool for performing all phases of HGA would reduce the time and effort required, improve the usability of the outputs, and improve the re-usability of previous related analyses.

The current application, as well as a previous application of HGA to the control of unmanned aerial vehicles, analyzed cognitive work at the tactical level. Future work should explore the applicability of HGA to analyzing cognitive work at the operational or strategic levels.

Sommaire

Application de l'analyse des objectifs hiérarchiques à la salle des opérations de la frégate de classe *Halifax* : Une étude de cas

Renee Chow; Jacquelyn Crebolder; DRDC Toronto TR 2007-161; R & D pour la défense Canada – Toronto; Novembre 2007.

Introduction ou contexte : Le présent document décrit la première application de l'analyse des objectifs hiérarchiques (AOH) [1] au commandement et au contrôle navals. L'AOH est une méthode relativement nouvelle d'analyse des besoins pour les systèmes sociotechniques complexes. Elle utilise des objectifs (c.-à-d. l'état désiré de système) plutôt que des tâches (c.-à-d. les activités des opérateurs) ou des fonctions (c.-à-d. objectifs techniques) comme unités d'analyse de base. Les objectifs sont définis par décomposition hiérarchique. À chaque objectif correspond une variable contrôlée qui lui est comparée et qui est manipulée de façon que l'objectif soit atteint. Après avoir défini tous les objectifs et les variables contrôlées qui y correspondent, on attribue chaque objectif à un opérateur humain ou automatisé.

Dans le cas présent, l'AOH a été appliquée à la salle des opérations d'une frégate de classe *Halifax* des Forces canadiennes afin de guider la modernisation de l'aménagement de l'espace de travail et des systèmes de commandement et de contrôle. L'AOH a été choisie comme méthode appropriée d'analyse pour cette application particulière en raison de son potentiel de tenir compte et d'intégrer des nouveaux aspects changeants de l'environnement, telles que des nouveaux postes dans la salle des opérations et la réaffectation des rôles entre les opérateurs humains et/ou les systèmes automatisés.

Résultats : Onze postes de l'équipe de la salle des opérations actuelle d'une frégate de la classe *Halifax* ont été soumis à l'AOH. Trois grands objectifs ont été décomposés en hiérarchie complète de 563 objectifs qui comportaient quatre à neuf niveaux. L'analyse a révélé que le nombre d'objectifs attribués à chacun des opérateurs variait considérablement. Parmi les onze opérateurs analysés, l'officier de la salle des opérations (OSO), le contrôleur d'armes par capteurs (CAC) et l'assistant du contrôleur d'armes par capteurs (ACAC) ont compté pour presque la moitié des objectifs. Par comparaison, le commandant ne s'est vu attribuer que 34 objectifs, qui comprenaient toutefois les sept objectifs du premier niveau. Vu le processus de l'AOH, il a été établi que, pour comprendre le système dans l'ensemble, il faudrait ajouter à l'analyse d'autres opérateurs comme le contrôleur d'aéronefs embarqués et l'officier de quart.

L'AOH a compris une analyse de stabilité qui a permis de reconnaître dix-sept sources d'instabilité potentielle dans la salle des opérations, où la même variable est associée à de multiples objectifs attribués à des opérateurs différents. On a fait des recommandations pour corriger chaque source d'instabilité, allant de changements à l'aménagement de l'espace de travail et de la conception des interfaces à la mise en place de technologies de soutien ou de procédures d'échange de renseignements. L'AOH a également compris une analyse ascendante qui a permis de cerner 776 besoins de rétroaction de la part d'un opérateur (affecté à un objectif de soutien) à un autre opérateur (affecté à un objectif de soutien). Ces besoins ont été évalués par des experts du domaine selon l'importance, la fréquence et le moyen (c.-à-d. visuel ou verbal) par lequel on les satisfait. En limitant l'analyse aux opérateurs principaux de chaque objectif,

85 p. 100 des rétroactions se font verbalement, ce qui pourrait faire craindre une saturation dans le conduit auditif et laisser entrevoir l'utilisation possible de nouvelles aides visuelles pour fournir aux opérateurs la rétroaction nécessaire. C'est entre le CAC et l'OSO qu'ont été observées les rétroactions les plus importantes et les plus fréquentes; ce qui confirme la nécessité pour ces deux opérateurs de travailler au même endroit et justifie le fait d'accorder la priorité au regroupement d'autres opérateurs.

Importance : Même si l'AOH a été conçue et appliquée d'abord en aviation, la présente étude démontre que la méthode peut être appliquée dans un contexte naval. Elle démontre également que l'AOH peut servir à analyser un système qui se compose d'un grand nombre d'opérateurs, faisant ainsi de cette analyse une méthode appropriée pour analyser d'autres systèmes militaires complexes, tels que la structure multi-organisationnelle de la sécurité maritime. Malgré la taille et la complexité de la salle des opérations, l'AOH a permis de cerner les conflits potentiels d'objectifs ainsi que les besoins en matière de cheminement de l'information entre les opérateurs. L'AOH a fourni une méthode systématique pour décrire la dépendance entre les opérateurs en termes qualitatifs (p. ex. les liens hiérarchiques entre les objectifs, les caractéristiques de chaque objectif, etc.) et en termes quantitatifs (p. ex. le nombre d'opérateurs qui peuvent se faire concurrence pour le contrôle d'une variable précise, le nombre de besoins de rétroaction entre deux opérateurs précis, etc.). Il a ensuite été possible de décrire l'aménagement de la salle des opérations actuelle en fonction de son niveau de soutien pour ces diverses dépendances. Les auteurs prévoient que la même méthode peut être utilisée pour décrire d'autres aménagements de la salle des opérations, pour que l'on puisse les comparer entre eux ou avec l'aménagement actuel. On peut appliquer différents critères (p. ex. soutien pour la rétraction importante par opposition à la rétroaction fréquente) pour comparer les aménagements.

Plans futurs : La phase d'élicitation de la connaissance de l'AOH s'est avérée difficile, puisque les experts en la matière étaient habitués à penser en termes de tâches plutôt que d'objectifs. L'élaboration de la hiérarchie des objectifs et la description des caractéristiques des objectifs ont été effectuées à l'aide d'un outil conçu pour l'analyse des tâches hiérarchiques, et l'outil ne comprenait pas de soutien pour convertir directement les données recueillies sur les objectifs en résultats d'analyse de stabilité et d'analyse ascendante. Afin d'appuyer l'application future de l'AOH, le développement de modules de formation sur l'AOH et un outil logiciel pour effectuer toutes les phases de l'AOH réduirait le temps et l'effort requis, améliorerait la convivialité des résultats ainsi que la réutilisation des analyses connexes précédentes.

L'application actuelle, ainsi que l'application précédente de l'AOH au contrôle de véhicules aériens sans pilotes, a analysé le travail cognitif au niveau tactique. Les travaux futurs doivent porter sur l'applicabilité de l'AOH à l'analyse du travail cognitif aux niveaux opérationnel ou stratégique.

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1 Introduction

1.1 Background

In the human factors literature, different approaches have emerged for the analysis of complex cognitive systems to identify requirements for the design of workspaces, displays and controls, decision support systems, and/or computer supported cooperative work. Many of these approaches have used either tasks, defined as activities performed by human operators (cf., [2], [3], [4]) or functions, defined as capabilities afforded by a system and its components (cf., [5], [6], [7]) as the primary units of analysis. Recently, Hendy, Beevis, Lichacz, and Edwards proposed a contrasting approach called Hierarchical Goal Analysis (HGA) [1]. Rather than tasks and functions, HGA uses goals, defined as desired states for variables that are monitored and controlled by human operators or automation in a system, as the primary units of analysis. This paper reports on the first application of HGA to naval command and control, specifically the analysis of 11 operator positions in the operations room of the Halifax Class Frigate. There had been a previous, less complex application of HGA to analyze the control of Uninhabited Aerial Vehicles (UAVs) [8, 9].

The current analysis served two purposes. On one hand, it served as a case study for investigating the applicability of a relatively new analytical approach to a problem domain where it had never been applied. The lessons learned provide some information for other human factors analysts to consider, as they choose between HGA and other approaches for analyzing their systems of interest. On another hand, this analysis identified needs and opportunities for changes to the current operations room of the Halifax Class Frigate, providing some information for the Canadian Navy to consider as they look towards developing their capabilities in support of future operations.

1.2 Contrasting approaches

While HGA is not the first approach to analyze goals, there are some key contrasts between HGA and previous, more well-known approaches such as Hierarchical Task Analysis (HTA) [2] and Goal-Directed Task Analysis (GDTA) [10]. In general, HTAs or GDTAs are performed for a specific operator, class of operators, or team of operators, so the identification and decomposition of goals are based on the roles and responsibilities that have been assigned to the operator(s). If an operator’s role is modified, goals may need to be added and/or removed from the hierarchy. In contrast, an HGA is performed for a system with an unspecified number of operators belonging to different classes and/or teams. It identifies and decomposes all goals before any goal is assigned to any operator. Even if there are changes to the role(s) assigned to the operator(s), the goal hierarchy itself does not need to be revised. So while HTA and GDTA readily support design in the context of mature, existing systems and organizations (i.e., ones where goals are assigned to roles), the process followed in an HGA seems to offer the flexibility required to support the design of “envisioned worlds” (cf., [11], [12]), where the number, types, and roles of operators may be undecided or subject to change.

This flexibility offered by HGA may also come at an analytical cost. HGA’s emphasis on goals and variables may complicate the knowledge elicitation phase of the analysis. Subject matter experts (SMEs) may have little difficulty in answering questions about what tasks they perform or what decisions they make (as in an HTA or a GDTA, respectively) to meet goals, but they may find questions about what variables need to be monitored and what states these variables need to achieve (which must be asked in an HGA) quite abstract and difficult to relate to their day-to-day work [13]. The goal and error states of variables may seem especially difficult to elicit from operators when the variables themselves are qualitative and governed by intentional (rather than physical) constraints. Ultimately, the strengths and weaknesses of HGA relative to previous techniques may depend on the objectives of, and the constraints imposed on, a specific analysis.

Although HGA is goal-based, it does bear similarities as well as differences to task-based and function-based approaches. Like task-based approaches, HGA tends to view the system from the operators' perspective. HGA asks what operators need to monitor, control, and achieve; and task-based approaches ask what activities operators need to perform. In contrast, function-based approaches tend to view the system from the designer/engineer's perspective, by asking what the system is designed to achieve. In other words, HGA and task-based approaches take a psychological perspective to analyzing work, while function-based approaches take a systems perspective [14].

Nevertheless, HGA and function-based approaches are similar in that they identify all of the goals or functions for the entire system before any goal or function is assigned to any operator. In fact, in the case of function-based approaches, there is no (immediate or delayed) requirement to perform any operator assignments. For both HGA and function -based approaches, operators can be human or automated systems. In contrast, task-based approaches tend to identify and analyze tasks that have been pre-assigned specifically to human operators [4], often because they are conducted to inform the design of training procedures or other forms of support for specific operators.

For the current analysis of the Halifax Class Frigate operations room, HGA was chosen as an appropriate method of analysis for two reasons: first because it focused on the operators rather than the system; and second, because it was intended to accommodate a constantly moving target (cf., [15]). In terms of focus, a frigate's engineered functions (e.g., "to float, to move, to fight") and the physical constraints associated with these functions might be relatively straightforward to identify using a function-based approach. However, the operations room was specifically responsible for executing the crew's missions (e.g., sea denial, peace support, humanitarian assistance) [16], and as such, its analysis would be more appropriately focused on identifying what goals the crew needed to achieve and the intentional constraints associated with these goals. In terms of accommodating changes, new operator positions were being created and new automated processes were being introduced in the operations room to support future operations. The flexibility to consider re-allocation of roles between human operators and/or automation by re-using and adapting significant portions of the original analysis was therefore both necessary and valued.

1.3 Previous application

A literature survey completed as part of this project showed that HGA had only had one previous application, where an HGA was conducted to support the design of intelligent agents to aid a three-person airborne crew in the control of UAVs [8, 9]. In that application, only the initial phases of HGA, as proposed in [1], were completed. These phases included:

- the development of a goal hierarchy,
- the assignment of a "controlled variable" to each goal, and
- the assignment of each goal to an operator, that may be human or machine.

Since the objective of the UAV analysis was to predict the impact of two different interfaces (i.e., one without and one with intelligent agents), two sets of goal assignments were made: one where each goal was assigned to one of the three human operators, and another where each goal was assigned to one of the three human operators or to an intelligent agent.

There were several key differences between the previous UAV analysis and the current frigate operations room analysis.

- First, the current analysis took HGA out of the aviation domain, where it was conceived and first applied, into the maritime domain;
- Second, the current analysis extended beyond the initial phases of HGA, and included a stability analysis and an upward flow analysis (to be described in detail in the next section);
- Third, the current analysis was significantly greater in scale and in complexity, considering the possibilities for interactions between 11 operators, compared to 3 operators in the UAV analysis.

Therefore, the current analysis was an important step forward in exploring the utility of the HGA approach for analyzing a complex military system. It provided an opportunity to reflect on the success factors, limitations, and challenges for conducting a large-scale HGA. It also produced much-needed examples of each step in an HGA that can be referenced by other analysts who are interested in applying HGA. While the original conceptual paper on HGA [1] did include examples, they were hypothetical, and were not based on the complete analysis of an actual system. In contrast, this paper provides a real-world case study to demonstrate each step in an HGA, including a stability analysis and an upward flow analysis, both of which had not been included in the UAV analysis.

The focus of this paper is on the practice rather than the theory of HGA. Therefore, the next section contains only a brief summary of the analytical approach. For a detailed theoretical and methodological account of HGA, the reader is directed to [1].

1.4 Hierarchical goal analysis

HGA is based on Perceptual Control Theory [17], which posits that humans operate as perceptually driven, goal referenced, feedback systems, in that all human behaviours are responses to errors, or differences, that are perceived between current states of the world and goal states. To analyze a cognitive system, HGA identifies goals that serve as reference points for perception (i.e., the detection of error) and control (i.e., the correction of error). Goals are identified through a process of hierarchical decomposition, starting with top-level goals that characterize the overall system, to lower-level goals that support the attainment of the higher-level goals. Since all goals in an HGA are reference points for perception and control, each goal can be considered to be prefaced by the phrase: "I want to perceive that". Throughout this paper the expression "I want to perceive that" is represented by an ellipsis (…). For each goal, HGA also identifies the controlled variable whose state is compared to the goal and manipulated as required to meet that goal.

Once all goals and their corresponding controlled variables have been identified, each goal is assigned to an operator in the system. This operator can be human or automated. Depending on the purpose of the analysis, operator assignment may be based on an existing system (e.g., to identify needs or opportunities for improvement) or on an envisioned system (e.g., to consider different alternatives for system design). Regardless, every goal at every level is assigned to an individual operator, not a collection of operators. The same operator can be assigned to multiple goals, at high and/or low levels of the hierarchy, along one or multiple branches of the hierarchy. A key characteristic of HGA is that every goal at every level of the hierarchy is analyzed in the same way, to the same degree of detail. Controlled variables are identified for all high and middle-level goals (not just bottom-level goals), and operator assignments are made for all middle-level goals (not just top-level goals or bottom-level goals).

Once goal assignment is complete, two types of follow-on analyses can be conducted: a stability analysis; and an upward flow analysis. A stability analysis identifies all instances where the same controlled variable is associated with multiple goals that are assigned to different operators, causing potential instability in the system as operators attempt to drive the variable in different directions. In essence, a stability analysis produces control requirements that specifically point to where control may need to be limited to specific operators, times and/or contexts. The second analysis, an upward flow analysis, looks at each lower-level goal and determines if the supported higher-level goal is assigned to a different operator. This would require the state of the variable for the lower-level goal to be fed back to the operator assigned to the higher-level goal. In essence, an upward flow analysis produces feedback requirements, specifically the need for information to be transferred between operators so that the individual responsible for the upper-level goal can maintain awareness of the state or progress of the lower-level goal. The form (e.g., verbal or visual) in which information is transferred may also be relevant to the analysis.

2 Method

2.1 Halifax class frigate operations room

The Canadian Navy's Halifax Class Frigates were launched between 1992 and 1996. They are helicopter-carrying warships with anti-submarine, surface-to-surface, and surface-to-air capabilities. It is important for the design of the frigate's operations room to be adapted to the needs of future missions – from the physical layout of the operations room, to the individual workstations, including displays and controls, to the decision aiding technologies that are available on these workstations, to new positions that may be added to the operations room team. This HGA included, but was not be limited to, 11 positions in the operations room, including the Commanding Officer (CO) of the frigate, the Operations Room Officer (ORO), the Directors of Above Water Warfare (Sensor Weapon Controller (SWC)) and Under Water Warfare (Assistant Sensor Weapon Controller (ASWC)) who supported the ORO, and their key support staff including the Track Supervisor (TS), the Electronic Warfare Supervisor (EWS), the Operations Room Supervisor (ORS), the Air Raid Report Officer (ARRO), the Anti-Submarine Plotting Operator (ASPO), the Information Management Director (IMD) and Warfare Duty Officer. However, since the HGA approach initially required identifying goals for the entire system (i.e., the operations room) some goals in the resulting analysis were assigned to positions other than the 11 targeted. Instances of these additions are identified throughout the paper, and not all of these additional operators worked within the operations room. Although the Navy engages in a wide range of operations, a "composite" military scenario (i.e., one that included aspects of above water and under water warfare) was used as the basis for this analysis of the operations room (see Section 3.1).

2.2 Goal analysis

The HGA began with identification of the top-level goals of the operations room. The core analysis team included two human factors experts (one an experienced ORO), who were supported by two additional domain experts[1] (an ex-CO and an Above Water Director). Naval doctrine, training manuals, standard operating procedures, and other relevant documentation were reviewed by the team and used to identify the top-level goals, which were subsequently decomposed into first- and second-level goals. The decomposition was reviewed for completeness and accuracy at this point by two representatives of the Navy (i.e., the clients) to ensure that the analysis, especially its scope and focus, reflected the objective of supporting redesign of the operations room, and by two Defence Scientists to ensure that the analysis adhered to the principles of HGA.

[1] It is important to distinguish between domain experts and SMEs in this study. Domain experts refers specifically to the two experienced operators who formed part of the analysis team. They worked hand-in-hand with the human factors experts over an extended period to identify and analyze the goals of the operations room. These two domain experts were different from the 36 SMEs who reviewed the outputs of the analyses that were performed by the domain experts together with the human factors experts. Aside from two review sessions scheduled specifically for key points in the analysis process, there was no ongoing interaction between the SMEs and the analysis team consisting of domain experts and human factors experts.

The analysis team then decomposed the goal hierarchy and assigned operators to the goals at all levels. A validation session was conducted with 14 SMEs who were serving together on an operational frigate and represented all but one of the targeted positions. The review of the goal hierarchy proceeded both top-down and bottom-up. The top-down approach was relatively structured; the SMEs started at the top of the hierarchy and examined each level for completeness, and for accurate connections to the next level. The bottom-up approach was less structured; the SMEs described activities they performed and challenged the analysts to identify the goal that captured that activity. This process helped to confirm that the goal hierarchy was complete and the relationships between goals were accurate. The SMEs also reviewed the operator assignments for all goals as recorded by the analysts. As a result of the SME session, appropriate revisions were made to the goal hierarchy and to the operator assignments. The most important revision was the creation of a new first-level goal, "… predeployment preparations are complete", that inherited some sub-goals from an existing first-level goal.

2.3 Stability analysis and upward flow analysis

The analysis team used the revised goal hierarchy and operator assignments as the basis for a stability analysis, and with these produced a list of controlled variables with the potential for instability (i.e., goal conflict). Each of these variables was associated with two or more goals that could cause the variable to be driven in different directions. The operators associated with these goals were identified, as was a list of all possible combinations of these operators. For each variable with the potential for instability, at least one method for amelioration was recommended by the analysis team. For example, the variable "ship's heading" was determined to be a source of possible conflict because it related to both above water as well as under water warfare. Consequently, tactics could dictate requirements for more than one course. A corrective recommendation proposed was that all orders for the ship's course must go through the ORO when there are simultaneous threats from above water and under water. The resolution of goal conflicts can be considered as an application of the stability analysis results, rather than a step within the analysis itself.

The analysis team also used the revised goal hierarchy and operator assignments to conduct an upward flow analysis. The process began with a list of all goals excluding the highest level goals. For each goal, the assigned operator was identified, along with the assigned operators for its parent goal. For every case where a goal and its sub-goal were assigned to different operators (i.e., there was a requirement for feedback), the current method for providing feedback was identified. The analysis team then went beyond a basic upward flow analysis by rating, based on their operational experience, each feedback requirement as important or not important, and as frequent or not frequent. For each feedback requirement, they also categorized the current method for providing feedback as visual (e.g., reading text or graphics, observing activities) or verbal (e.g., listening to reports or alarms). Finally, for each pair of operators (i.e., the 11 targeted operators could be arranged into 110 possible pairs), the total number of feedback requirements was computed, as well as the number of important requirements, the number of frequent requirements, and the numbers of requirements addressed verbally versus visually.

The results of the stability analysis and the upward flow analysis were validated in a second SME session, involving 22 SMEs who were part of the ship's company on an operational high-readiness frigate. In this session, SMEs represented all but two of the targeted positions. For the stability analysis, the SMEs reviewed the sources of instability and augmented the list of proposed amelioration techniques for stable control. For the upward flow analysis, the SMEs also reviewed the feedback requirements and their categorizations (i.e., importance, frequency, type).

3 Results

3.1 Goal analysis

The HGA identified three top-level goals for the Halifax Class Frigate operations room:

1. … use of the sea is denied to enemy forces;

2. … assistance is provided to other government departments; and

3. … peace support operations are conducted.

These goals corresponded respectively to the military, constabulary, and diplomatic roles that are held by the Navy across time and across ships [16]. Each of these top-level goals was decomposed into seven first-level goals. Reviews by stakeholders and by SMEs confirmed that the decomposition of goals from the top-level to the first and second levels were identical across the three top-level goals. Therefore, the decision was made to only decompose the military goal in full. The top and first levels of the military goal are shown in Figure 1.

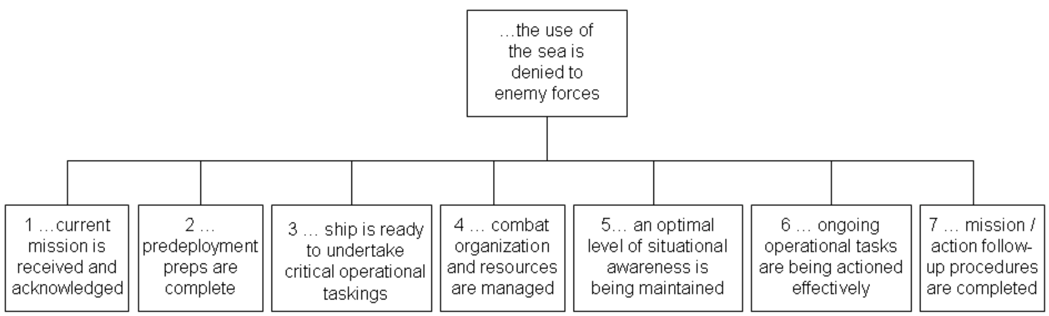

Figure 1: Top and first levels of the military goal.

Figure 2 shows decomposition of the goal "… an optimal level of situation awareness is being maintained" to the second level. Table 1 displays in tabular form the successive decomposition of one of these second-level goals "… an accurate Recognized Maritime Picture (RMP) is created and maintained" to the lowest level by showing the decomposition of one sub-goal at every level. Table 1 also shows the controlled variable and the assigned operator for each goal. The full goal hierarchy included 563 goals and ranged from four to nine levels deep. It is shown in a tabular format in [18], along with 563 one-page templates that are populated with the attributes for each goal. In this paper, only the most significant results related to the goal hierarchy and the assigned operators are summarized below.

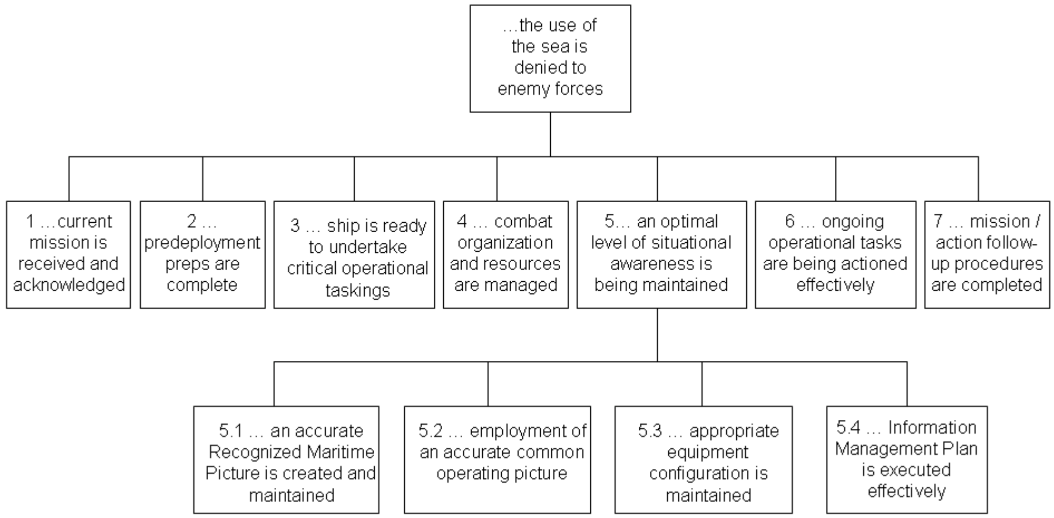

Figure 2: Partial decomposition of the situation awareness goal

All of the 11 targeted operators were assigned to goals at multiple levels of the hierarchy. Ten percent of the goals (i.e., 56) were assigned to operators other than the 11 who were targeted. Of these other operators, the SAC and the OOW were both assigned to the largest number of goals (i.e., 16). Since the SAC was a member of the operations room, the subsequent analyses that were focusing on stability and upward information flow were extended to include the SAC. The OOW did not work within the operations room so was excluded from subsequent analyses.

Of the 11 targeted operators, the ORO (assigned to 86 goals), the SWC (assigned to 111 goals) and the ASWC (assigned to 76 goals) accounted for nearly half the goals (i.e., 273/563 or 48%). They were assigned to goals ranging from as high as the first level to as low as the fifth level for the ORO, or the eighth level for the two directors (SWC and ASWC). Goals assigned to the ORO were decomposed from six of the seven first-level goals, and goals assigned to the two directors were decomposed from five of the seven first-level goals. In contrast, the CO was only assigned to 34 goals, but these included all seven first-level goals. Note that the total number of goals assigned to an operator is not a direct indication of workload. For example, the SAC was allocated only 16 goals, but when controlling aircraft, this operator could experience a high attentional demand. However, the number of goals is related to the breadth of responsibility assigned to an operator and the knowledge and experience that would be required to achieve these goals.

During the analysis the domain experts determined that in the frigate operations room every goal should actually be assigned to a primary operator, and to a secondary operator who was expected to take over responsibility for a goal if the primary operator was otherwise engaged. Results discussed so far have pertained only to the assignment of the primary operator. The following discussion of the stability analysis and the upward information flow analysis considers both primary and secondary operators.

Table 1: Subset of the decomposition of the Recognized Maritime Picture (RMP) goal.

Level	Goal Number	Goal	Controlled Variable	Assigned Operator	Sub-Goals	
2	5.1	...an accurate RMP is created and maintained	Currency of the RMP	ORO	5.1.1	...an accurate tactical air picture is compiled
					5.1.2	...an accurate tactical surface picture is compiled
					5.1.3	...an accurate subsurface picture is compiled
3	5.1.2	...an accurate tactical surface picture is compiled	Status of the tactical surface picture	SWC	5.1.2.1	...coordination with/of other units is effective
					5.1.2.2	... tactical displays are optimized
					5.1.2.3	...effective surface track management
					5.1.2.4	...effective visual watch is maintained to support tactical surface picture
					5.1.2.5	...effective use of sensors to compile a surface picture
					5.1.2.6	...information is gathered through the use of ship-ship warnings
4	5.1.2.3	...effective surface track management	Status of surface track management	TS	5.1.2.3.1	...proper application of criteria to new surface contacts
					5.1.2.3.2	...existing tracks are updated
					5.1.2.3.3	...reports are made to support the tactical surface picture
5	5.1.2.3.2	...existing tracks are updated	Status of surface track	TS	5.1.2.3.2.1	...manual updates are successfully executed
					5.1.2.3.2.2	...automatic updates are occurring
6	5.1.2.3.2.1	...manual updates are successfully executed	Status of surface track	TS		

3.2 Stability analysis

As mentioned previously, the goal hierarchy included 563 goals. Each goal controlled a variable, and each goal was assigned to an operator. The stability analysis identified 17 variables as potential sources of instability (i.e., goal conflict) because they were controlled by multiple operators to achieve multiple goals. Table 2 shows the detailed analysis of one of these variables. These variables were controlled by 2 to 11 different operators. The same operator often controlled the same variable for multiple goals. In one case, a variable was controlled by 9 operators, and one of the operators controlled that variable for 17 different goals. While there were also cases where each operator controlled the potentially unstable variable for only a single goal, most of the potentially unstable variables were associated with multiple goals per operator.

Table 2: Sample stability analysis.

Influenced Variable (External)	Operator or system Assign-ment	Goal #	Goal / Objective / Reference	Potential for Simul-taneous Control	For Stable Control
Ship's heading and speed					
	ASWC	5.1.3.6.3	...sensor depth is monitored/adjusted	ASWC and SWC	~all demands for ship's course or speed must go through the CO or ORO
	WO	6.1.2.2.1.1.1	...assigned sectors/station maintained	ASWC and EWS	
	WO	6.1.2.2.1.1.2	...due regard for sensor limitations	SWC and ORO	
	WO	6.1.2.2.1.1.3	...due regard for navigational safety	ASWC and ORO	~CO and ORO must remain co-located to prevent simultaneous control demands
	WO	6.1.2.2.1.1.4	...due regard for engineering status	CO and ORO	
	WO	6.1.2.2.1.1.5	...territorial boundaries are observed	OOW and ORO	
	ORO	6.2.1.1	...assigned sectors/station maintained	WO and ORO	
	ASWC	6.2.1.2	...due regard for sensor limitations	WO and CO	~only one of the CO or ORO should have control of ship's course and speed, this is typically the ORO
	ORO	6.2.1.3	...due regard for navigational safety		
	CO	6.2.1.4	...due regard for engineering status		
	ORO	6.2.1.5	...territorial boundaries are observed		
	ORO	6.2.2.1.1	...helicopter is at appropriate status		
	EWS	6.5.1.1.2.3.4	...the ship is effectively manoeuvred		~OOW retains safety responsibility
	SWC	6.5.1.3.2	...appropriate positioning to support consorts		
	SWC	6.5.2.2.3	...ship is optimally positioned for offence		~relationship between the Warfare Officer and ship's officers will have to be worked out in advance of entering area of conflict
	SWC	6.5.2.2.4.6.1	...an effective application of tactics		
	ASWC	6.5.3.1.3	...defensive tactics are appropriately conducted		
	ASWC	6.5.3.1.3.1	...appropriate course/helm and speed are chosen		
	ASWC	6.5.3.2.1.1	...effective manoeuvring for offence		
	ASWC	6.5.3.2.2.1.1	...assigned sectors/station maintained		
	ASWC	6.5.3.2.2.2	...search effectively executed		
	ASWC	6.5.3.2.2.2.1	...assigned sectors/station maintained		
	ASWC	6.5.3.3.4	...assets are effectively stationed/employed		
	ORO	6.7.4	...ship is effectively conducting the search		
	ORO	6.8	...emergencies are responded to efficiently		

For the 17 potential sources of instability, the number of recommendations for stable control ranged from two to five. Some recommendations pertained to workspace design (e.g., co-location of specific operators). Others pertained to technologies including computer support for cooperative work (e.g., text-messaging between operators), interface design for monitoring (e.g., shared displays) and for control (e.g., lock-out of specific operators). Still others pertained to processes (e.g., all requests of a specific type to go through a specific operator).

A table similar to Table 2 was developed for each of the 17 sources of potential stability. These tables can be found in [18].

3.3 Upward flow analysis

The upward flow analysis identified 878 instances where an operator assigned to a higher-level goal required feedback on a lower-level goal. The domain experts rated 518 of these feedback requirements as important, and 182 as frequent. The analysis also found that currently 38 requirements were primarily being satisfied visually, and 248 were primarily being satisfied verbally. Considering all possible pairs of the 12 operators (including the SAC), the highest overall requirement for feedback was found between the SWC and the ORO (i.e., 112 instances), followed by the ORO and the CO (i.e., 81 instances), and the ASWC and the ORO (i.e., 78 instances). Fifty-one percent of the requirements between these three pairs of operators were addressed verbally rather than visually. The highest number of important feedback requirements were found between the SWC and the ORO (i.e., 66 requirements), and 58% of these were addressed verbally. The highest number of frequent feedback requirements were found between the SWC and the ORO (i.e., 25 requirements), and 60% of these were addressed verbally. Figure 3 provides a three-dimensional view of the overall numbers of feedback requirements between the targeted operators. Figure 4 shows only those requirements that are currently addressed verbally.

Figures 3 and 4 are screen shots from a three-dimensional viewer that had been developed specifically at the request of the Navy to enable the visualization and comparison of feedback requirements between different pairs of operators. The viewer provides controls along the left and the bottom of the screen that enable the user to view:

– the feedback requirements associated with one or more of the seven top-level goals;
– the feedback requirements considering only the primary, only the secondary, or both operator(s) assigned to each goal;
– the feedback requirements that have been rated by domain experts (and verified by SMEs) as frequent, as important, or all requirements regardless of ratings;
– the feedback requirements that were addressed verbally or visually or both; and
– the feedback requirements in absolute numbers, or as percentages of the overall number of requirements.

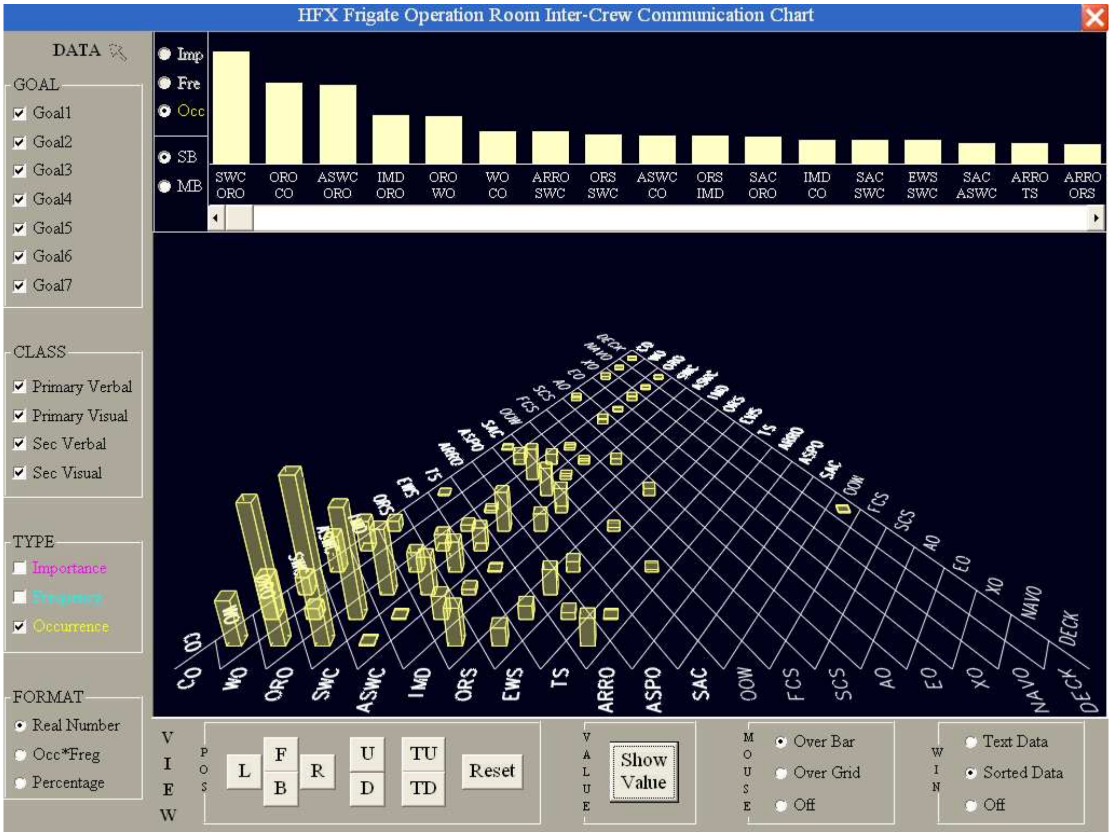

Figure 3: Overall number of feedback requirements.

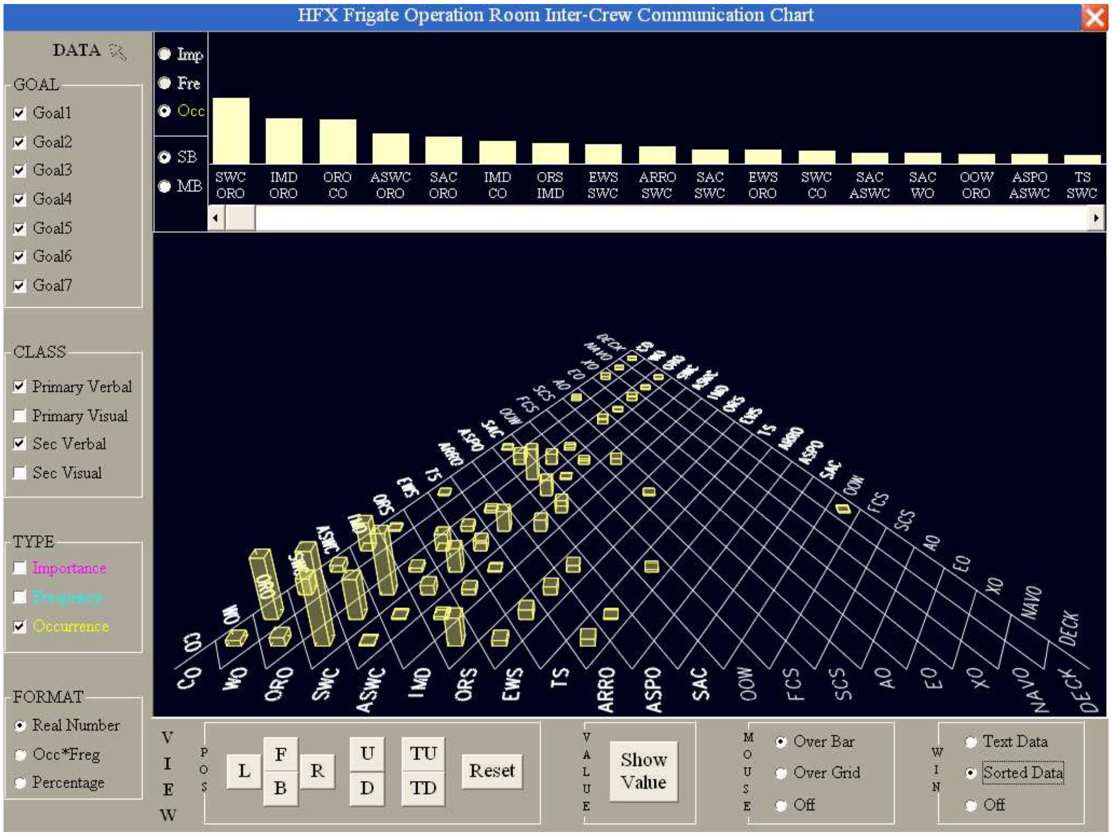

Figure 4: Numbers of feedback requirements addressed verbally.

4 Discussion

Development of the goal hierarchy revealed that there was substantial variation in the number of goals assigned to each operator (e.g., 111 goals for the SWC compared to 16 goals for the SAC, and compared to an estimated average of approximately 51 goals per operator based on the total number of goals and targeted operators). Operators in the most senior positions were not necessarily assigned to more goals than their subordinates (e.g., the ORO had 86 goals compared to the CO's 34; the SWC had 111 goals compared to the ORO's 86). Nor were senior positions assigned only to high-level goals (e.g., the SWC and the ASWC were assigned to some eighth-level goals). Although the analysts targeted select operators within a system, the HGA naturally revealed additional operators who should be included in the analysis if an understanding of the overall system is desired (e.g., the SAC and the OOW were both assigned to goals that provided direct or indirect support to the high-level goals of the operations room).

In other words, HGA did not take an organization-based or position-based approach to analyzing a sociotechnical system. In reality, the number of operators in a system, how they are organized into teams, and to whom they report should be the end points (i.e., solutions) rather than the start points to a systems design problem. When an organization-based or position-based approach is used to analyze a cognitive system, these specifics are pre-defined, and all that remains to be analyzed is how the performance of specific operators in their pre-specified roles can be supported and/or measured. But truly innovative system-wide solutions such as changes to the command or reporting structure, addition or removal of operators, or re-distribution of authority and responsibility between operators become difficult if not impossible to consider through organization- or position-based approaches. Through these approaches it would not be clear how the requirements of one position would change if changes were made to any or all of the other positions. By first identifying all of the goals that need to be achieved (rather than all of the operators in the system) and defining the relationships between these goals (rather than between the operators), HGA provided a solid foundation upon which different system design options (i.e., different goal assignments) might be considered, without the need to re-analyze the entire system as soon as any assumption about an operator's role was violated.

Assumptions about an operator's role (i.e., goal assignments) had to be made before proceeding to the stability analysis and the upward flow analysis. But it would certainly be possible and likely useful to apply different goal assignments (e.g., representing an existing system vs. a new system; representing two different designs of a new system) and to compare the stability and upward flow results based on these different assignments to help choose the optimal design option. In this application, only one set of goal assignments was made based on the existing system, but it provided benchmarks to which design options being developed for the operations room could be compared.

4.1 Stability analysis

One benchmark resulting from the stability analysis related to how a new operations room could be considered an improvement over the existing operations room. Since the existing operations room had 17 variables that could contribute to instability because they were under the control of multiple operators, the new operations room should have fewer than 17 variables with the potential for instability. For example, one target for the new operations room design might be to achieve a 50% reduction in the number of potentially unstable variables (i.e., to 8 or fewer variables) by re-assigning goals between operators. Moreover, without changing the goal assignments, results of the stability analysis could still support options analysis: first, each recommendation for improving stability could be rated in terms of the number of variables it would help to stabilize or the number of operators it would help to de-conflict, which could be easily tabulated from results in the form shown in Table 2. Then, each design option, embodying some specific combination (but not all) of the recommendations, could be given an aggregated rating and a ranking relative to the other options. It would also be possible to attach costs to the recommendations and to aggregate these costs to produce the total costs for complete design options. A cost-benefit analysis could then be conducted, once again using the number of variables and/or operators affected to measure the benefit associated with each option.

Results of a stability analysis could also support risk analysis. For example, each recommendation for ameliorating instability could be categorized based on the expected effect of neutralizing the instability and weighted for comparison. Categories might be: eliminating instability (lowest risk), reducing instability (medium risk), or discouraging instability (highest risk). A recommendation that makes it absolutely impossible for multiple operators to access the same variable at the same time would be considered to eliminate instability. Generally, technological or system design interventions would be used to eliminate instability. One such recommendation from the current application was for the system to lock out non-critical users of a radar during weapon engagement. A recommendation would be considered to reduce instability if it makes it difficult for multiple operators to access the same variable at the same time. For example, in the current application one recommendation was for all changes to the engineering state to go through the ORO to the OOW and then the CO. While it is physically possible for someone to request or to initiate a change without seeking the required approval, it is highly unlikely for the change to be accepted or implemented in full. Consequently, training or process interventions would generally be necessary to reduce instability. Finally, a recommendation that makes it unlikely for multiple operators to try to access the same variable at the same time would be considered to discourage instability. One such recommendation from the current application was the co-location of the two directors to make it easier for them to detect and immediately resolve any conflict, before either one tries to control a variable in a way that is inconsistent with what the other wishes or has agreed to do. Generally, design of the workspace or of collaborative or communication aids would be used to discourage instability. To conduct a risk analysis, a weighting factor could be assigned to each category of recommendations to represent its level of risk. An overall level of risk could then be computed for an overall operations room design (defined as specific combinations of the high, medium, and low risk recommendations). An overall design (including technological, process and other aspects) could then be compared against alternate overall designs.

4.2 Upward flow analysis

One important finding from the upward flow analysis was that the design of the existing operations room imposed much greater demands on the operators' verbal channel than on their visual channel (e.g., 58% of the communication requirements between the ORO and the SWC were addressed verbally). Therefore, the new operations room design might consider increasing the operators' capability to give and receive feedback visually through the design of individual and/or shared displays, or through the co-location of operators such that they can better observe one another's activities. It might also be useful to explore other non-verbal modes of feedback such as tactile feedback, since all feedback requirements were addressed visually or verbally in the existing operations room.

The upward flow analysis identified additional opportunities for improving the design of the existing operations room, if the design goal was to optimize the room layout based on the requirement for feedback between operators. First, in the existing design, some operators were positioned adjacent to each other although they had a very low requirement to provide feedback to each other (e.g., the SWC and the ASWC sat side by side, but they shared only one feedback requirement). On the other hand, some operators were separated when they had a high requirement to provide feedback to each other (e.g., the SWC sat between the ORO and the ASWC, separating them, but the ASWC actually shared 78 feedback requirements with the ORO). There were other examples where the physical proximity between two operators did not correspond to the requirement for feedback between these operators. For instance, the ASPO sat in the front row of the operations room between the SAC and the TS, even though they shared zero and one feedback requirement, respectively. The ASPO actually shared the highest number of feedback requirements (i.e., 18) with the ASWC, but they sat in separate rows, and the ASPO actually faced away from the ASWC. In fact, the ASPO's position was closer to the SWC (with whom the ASPO shared no feedback requirement) than to the ASWC. Of course, it was quite possible that the existing operations room had been designed with a different objective in mind (e.g., perhaps to locate operators based on the command structure rather than on communication need, when voice nets provided an alternative to face-to-face communication). Ultimately, the relative merits of different design options would depend on the criteria applied.

In any case, if supporting communication between operators was the design objective, then one reasonable application of the upward flow analysis results would be to develop design options that would place operators who shared the highest number of feedback requirements closest together and operators who shared the lowest number of feedback requirements furthest apart. Admittedly, it could be very challenging to place some operators who shared a large number of feedback requirements with many others, but the importance and the frequency of these requirements could provide additional help in prioritizing the needs for proximity. When generating a new layout for the operations room, instead of placing the operators one-by-one, it might be useful to perform a cluster analysis based on the feedback requirements, to identify logical groupings of the operators (e.g., into rows, cells). It might even be possible to optimize the physical distance between these groupings.

In addition to using the upward flow analysis results to generate new layouts for the operations room, the results could be used to evaluate alternate layouts, such as giving credit to layouts where positions with high communication needs were oriented so that they faced each other. To conduct the evaluation it would be important to pre-determine the primary (versus secondary or even tertiary) basis for the assessments. For example, the evaluator(s) might emphasize total feedback requirements over important feedback requirements and important feedback requirements over frequent feedback requirements. However, a different set of criteria might be just as reasonable.

4.3 Optional analyses

Stability analysis and upward flow analysis were just two of many different types of analyses that could be performed using HGA as the basis. In particular, these two types of analyses required as inputs: 1) the goal hierarchy, 2) the controlled variable for each goal, and 3) the assigned operator for each goal. Hendy et al [1] had proposed a template to capture other attributes for each goal, including: required knowledge states (declarative and situational), perceptual/cognitive processes, initiating conditions, ending conditions, input sensation, output behaviour, input interface and output interface. Once elicited from domain experts and validated by SMEs, these additional attributes could serve as inputs to other follow-on analyses, including but not limited to:

- Training needs analysis, primarily based on the required knowledge states but possibly also the initiating and ending conditions, and the input and/or output interfaces;
- Manpower analysis, primarily based on the required knowledge states but possibly also on the output behaviours;
- Workflow analysis possibly by developing a task network simulation, likely based on the initiating conditions, ending conditions and the perceptual/cognitive processes; and
- Workload analysis possibly by using a task network simulation, likely based on the input sensations and the perceptual/cognitive processes.

In the current case study, the template proposed by Hendy et al [1] was used to capture additional attributes for each goal, and the gathered information was used to develop a task network simulation to analyze workflow and workload. These additional analyses were beyond the scope of this paper given its focus on HGA as a requirements analysis approach. However, details on the task network simulation can be found in [18].

4.4 Lessons learned and future work

The current application of HGA benefited tremendously from the participation of two domain experts on the analysis team and of two large teams of SMEs as reviewers at key stages of the HGA process (i.e., upon completion of the goal hierarchy and operator assignments; and upon completion of the stability analysis and upward flow analysis). However, both the analysis team and the SMEs found the HGA methodology to be difficult to learn, primarily because they were much more accustomed to thinking in terms of:

1. tasks rather than goals;
2. specific operator positions rather than the overall system; and
3. a timeline of activities to conduct a mission rather than a set of criteria to evaluate mission effectiveness.

For operators, most of the training, exercises, and operations they have been exposed to have been structured in terms of tasks, positions, and timelines. While the learning presented some challenges, the SME sessions were completed as scheduled (i.e., three work days for the first session, and three work days for the second session), and the overall HGA was completed withinbudget and on-time (i.e., 750 person-hours over two months). However, given the iterative nature of the analysis, the goal hierarchy was revised during the entire duration of the project.

Future applications could benefit from a carefully designed, tested, and standardized training program on the HGA methodology, both for analysts and for SMEs. The training program could be paper-based or computer-based, and could take the form of tutorials, with exercises and tests. Specifically, the training should focus on:

1. the definition of a goal as distinguished from a task or a function;

2. the decomposition of a goal, as distinguished from the step-by-step description of a process;

3. the identification of the controlled variable for a given goal, as distinguished from the identification of all variables relevant to a goal or all variables controlled by all sub-goals; and

4. the assignment of an operator to a goal, as distinguished from a mapping of the goals to the organizational structure, or a listing of all operators who contribute directly and indirectly to a goal.

Future applications could also benefit from the development of a re-usable HGA tool for documenting and manipulating the HGA results, and to support the development and evaluation of alternate design options. Specifically, the tool should provide templates for the analysts to store the goals as entities and the relationships between goals, and automatically generate the goal hierarchy based on these entities and relationships. For each goal, the tool should capture, as a minimum, the controlled variable and a “baseline” operator assignment. The tool should also enable the saving of alternate operator assignments. Based on the stored information, the tool should automatically produce results of the stability analysis and the upward flow analysis, based on whichever set of operator assignments was chosen by the analyst/designer. An even more ambitious tool would include capability to capture the rating and/or weighting of different control requirements (from the stability analysis) and feedback requirements (from the upward flow analysis), and to document, tabulate, and compare the costs and/or benefits of different design options that address these requirements.

Considering the complexity of the Halifax Class Frigate operations room (i.e., more than 11 operators controlling 93 different external variables for 563 goals), the potential for instability was relatively low (i.e., only 17 or 18% of the variables were under the control of multiple operators). While the clients were appreciative of the stability analysis outputs and recommendations, they observed that the existing operations room had been designed to minimize instability. On the other hand, the requirement for feedback was relatively high (i.e., 878 instances where feedback on one goal needs to be given to an operator of another goal), and the application of these results was of keen interest to the clients. Therefore, another key success factor for this application of HGA was the development of a three-dimensional viewer (as shown in Figures 3 to 4) for reviewing and interpreting the outputs from the upward flow analysis. Specifically, the viewer enhanced the value of the feedback requirements by allowing:

1. the selection of a specific pair of operators for closer examination;

2. the selection of primary or secondary (or both) operators assigned to the goals;
3. the selection of all, or important, or frequent feedback requirements; and
4. the selection of feedback requirements being satisfied visually or verbally.

The ability to view the outputs from (combinations of) these meaningful perspectives helped the analysts, the SMEs, and the clients gain a deeper understanding of the system and of the solutions that could be considered. Future applications of HGA would benefit from improved tools to support all phases of the HGA process, including goal identification and assignment, and the stability analysis.

5 Conclusion

HGA was found to be applicable to naval command and control, since analysts and domain experts were able to identify a hierarchy of goals for the overall system and to assign goals to operators within the system. These results were validated by two teams of SMEs. Since the Halifax Class Frigate operations room included more than 11 human operators and is utilized in actual operations, this application also demonstrated that HGA could be used to analyze a multi-operator system of industrial scale and maturity.

HGA was found to be especially useful because of its flexibility. While it was used to model an existing system, it provided a basis for developing and for evaluating alternate system designs by producing control requirements and feedback requirements that could be prioritized using some reasonable and intuitive metrics. HGA did not rely on pre-defined roles for the operators as the starting point for analysis. The resulting goal hierarchy could be re-used by analysts/designers who might wish to assign completely different operators to the goals, in order to consider system-wide redesigns involving the addition, removal and/or re-organization of operators. Requirements produced by the HGA were relevant to the design of physical workspaces, of command and control systems including individual and shared displays, and of visual and verbal modes of communication.

The results and recommendations from the current application of HGA are being used to develop and evaluate prototypes of new designs for the operations room (including three-dimensional virtual reality prototypes). The purpose of these prototypes is to support the definition of specifications for the design of the operations room. Therefore, this application of HGA is having significant input into shaping the design of an upgraded operations room to support future operations.

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List of symbols/abbreviations/acronyms/initialisms

ARRO	Air Raid Report Operator
ASPO	Anti-Submarine Plotting Operator
ASWC	Assistant Sensor Weapon Controller
CO	Commanding Officer
EWS	Electronic Warfare Supervisor
GDTA	Goal-Directed Task Analysis
HGA	Hierarchical Goal Analysis
HTA	Hierarchical Task Analysis
IMD	Information Management Director
OOW	Officer Of the Watch
ORO	Operations Room Officer
ORS	Operations Room Supervisor
RMP	Recognized Maritime Picture
SAC	Shipborne Aircraft Controller
SME	Subject Matter Expert
SWC	Sensor Weapon Controller
TS	Track Supervisor
UAV	Uninhabited Aerial Vehicle

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Application of Hierarchical Goal Analysis to the Halifax Class Frigate operations room

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This paper reports on the first application of Hierarchical Goal Analysis (HGA) [1], a relatively new approach to requirements analysis for complex systems, to naval command and control. HGA, applied to 11 positions of the Canadian Forces Halifax Class Frigate Operations Room, decomposed three top-level goals to a full goal hierarchy of 563 goals. The hierarchy ranged from four to nine levels deep, with an operator assigned to each goal. The HGA process concluded with a stability analysis for identifying potential goal conflicts and an upward flow analysis for identifying requirements for feedback between operators. The stability analysis analyses revealed that the current design of the operations room limits instability stemming from multiple operators competing for control of the same variable. The upward flow analysis revealed that the requirement for feedback from operators assigned to lower-level goals to operators assigned to higher-level goals is relatively high, and the operations room could benefit from review and redesign. The goal hierarchy, operator assignments, stability and upward flow analyses, and proposed solutions were reviewed by subject matter experts. While used to model an existing system, the present application of HGA was found to be especially useful in providing a basis for evaluating a system design and developing design recommendations.

Le présent document décrit la première application de l’analyse des objectifs hiérarchiques (AOH) [1], une méthode relativement nouvelle d’analyse des besoins pour les systèmes complexes, au commandement et au contrôle navals. L’AOH, appliquée à 11 postes de la salle des opérations de la frégate de classe *Halifax* des Forces canadiennes, a décomposé trois grands objectifs en hiérarchie complète de 563 objectifs qui comportaient quatre à neuf niveaux, un opérateur étant associé à chaque objectif. L’AOH s’est conclue par une analyse de stabilité qui permet de cerner les conflits potentiels d’objectifs et une analyse ascendante qui permet de déterminer les besoins de rétroaction entre les opérateurs. Un examen de l’analyse de stabilité indique que l’aménagement actuel de la salle des opérations compte peu de sources d’instabilité là où de nombreux opérateurs se font concurrence pour le contrôle de la même variable. L’analyse ascendante a démontré que le besoin de rétroaction pour les opérateurs responsables des objectifs des niveaux inférieurs et les opérateurs responsables d’objectifs d’un niveau plus élevé est relativement grand, et que la salle des opérations pourrait bénéficier d’un examen et d’une restructuration. La hiérarchie des objectifs, les tâches des opérateurs, les analyses de stabilité et ascendante et les solutions proposées ont été examinées par des experts en la matière. Même si elle a servi à modéliser un système en place, l’application actuelle de l’AOH semble être un point de départ particulièrement utile pour évaluer la conception de systèmes et formuler des recommandations relatives à la conception.

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Hierarchical Goal Analysis; Command and Control; Halifax Class Frigate; Requirements Analysis; Options Analysis

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