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IPME model of dynamic decision-making in C3Fire platform

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Defence R&D Canada
Technical Memorandum
DRDC Toronto TM 2011-169
March 2012

Canada

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In conducting the research described in this report, the investigators adhered to the policies and procedures set out in the Tri-Council Policy Statement: Ethical conduct for research involving humans, National Council on Ethics in Human Research, Ottawa, 1998 as issued jointly by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada.

Abstract

Recent developments in microworld-based experiments provide researchers with an opportunity to conduct complex and dynamic experiments in laboratory-controlled environments, thus narrowing the gap between laboratory-based and field experiments. The performance assessment in a dynamic decision making environment, however, requires new modelling techniques for evaluation and analysis of data. This memorandum discusses the application of Hierarchical Goal Analysis and IPME modelling to evaluate cognitive systems in a distributed team environment.

The HGA-derived goals and controlled variables provided a basis for modelling and were embedded into a dynamic IPME model. The use the HGA outputs as the basis for the development of a computational model for predicting subject performance under specific task conditions. The model replicated some basic findings of empirical study conducted with C3Fire platform. An implementation of HGA into IPME model shows promising results.

Résumé

De récents développements dans le domaine des expériences basées sur les micromondes offrent aux chercheurs la possibilité de mener des expériences complexes et dynamiques dans des environnements contrôlés en laboratoire, ce qui permet de réduire l'écart entre ce type d'expériences et celles menées sur le terrain. Toutefois, l'évaluation du rendement dans un environnement dynamique de prise de décisions requiert de nouvelles techniques de modélisation pour l'évaluation et l'analyse des données. Le présent document se penche sur l'utilisation de l'analyse des buts hiérarchiques (ABH) et la modélisation de l'environnement intégré de modélisation des performances (EIMP) pour évaluer les systèmes cognitifs dans un environnement où les membres d'une équipe sont dispersés à plusieurs endroits.

Les variables contrôlées et les buts dérivés de l'ABH offrent une base de modélisation et ont été intégrés à un modèle d'EIMP dynamique. On propose d'utiliser les résultats de l'ABH comme base pour la mise au point d'un modèle computationnel permettant de prévoir le rendement du sujet sous certaines conditions de réalisation de tâche. Le modèle est la copie de certaines conclusions d'une étude empirique réalisée à l'aide de la plateforme C3Fire. La mise en œuvre de l'ABH à l'intérieur d'un modèle d'EIMP montre des résultats prometteurs.

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Executive summary

IPME model of dynamic decision-making in C3Fire platform:

Zotov, Vlad; DRDC Toronto TM 2011-169; Defence R&D Canada – Toronto; February 2011

Background: The Canadian Forces (CF) are engaged in domestic and international operations that require co-ordination among its own elements as well as with allies and other groups. To work effectively in complex settings, decisions have to be constantly adjusted in response to rapidly changing environment. One way to evaluate the decision-making (DM) in such settings is to observe human decisions in a controlled environment—such as synthetic environments and microworlds—that would possess important characteristics of the real-world situations.

The complex, dynamic and opaque characteristics of microworlds make them similar to the cognitive tasks that people experience in the real world and it is expected that the microworlds provide a greater degree of experimental control. Moreover, it becomes possible to observe a team of subjects working with the same system, thus allowing observations of personal interactions and communications under controlled conditions.

The goal of this work was to develop a model that can simulate and predict decision-making behaviour of subjects acting in a dynamic environment of microworld experiment. The platform used to replicate and simulate the operator's behaviour was Integrated Performance Modelling Environment (IPME). The IPME model was based on the goal network developed with Hierarchical Goal Analysis (HGA). The HGA goal structure was translated into dynamic network of IPME tasks. The variables obtained from HGA were used as free parameters to fit the operators' performance in the model. These measures of team performance were closely related to the specific decisions subjects made while engaged in pursuing that goal.

Results: The IPME model successfully captured general trends in team performance predicting time to complete the task as well as efficiency of performance in terms of number of fires extinguished. The model was able to predict how specific errors in team performance (e.g., delays in communications, not providing timely feedback, underestimating spread of fires, etc.) would affect overall performance.

Significance: The IPME model provided a new framework for testing optimality of subjects' decisions in the microworld-based experiments. It provides opportunity to test new experimental conditions prior to running experiments and predicted human errors resulting from specific deficiencies in the decision-making process.

Future plans: The IPME model will be extended by adding new cognitive modules (similar to Adaptive Control of Thought—Rational and Simulated Operator for Networks models) for conducting pluggable, human in-the-loop simulations.

Sommaire

Contexte : Les Forces armées canadiennes (FAC) participent à des opérations nationales et internationales qui exigent une coordination entre leurs propres éléments de même qu'avec leurs alliés et d'autres groupes. Afin de travailler efficacement dans des structures complexes, les décisions doivent être constamment adaptées à un environnement qui évolue rapidement. Une façon d'évaluer la prise de décisions dans de telles structures consiste à observer les décisions humaines prises dans un environnement contrôlé, comme dans des environnements synthétiques et des micromondes, qui posséderaient d'importantes caractéristiques de situations du monde réel.

Les caractéristiques complexes, dynamiques et opaques des micromondes les rendent semblables aux tâches cognitives que vivent les gens dans le monde réel et on s'attend à ce que les micromondes offrent un niveau plus élevé de contrôle expérimental. De plus, il devient possible d'observer une équipe de sujets travailler avec le même système, ce qui permet l'observation d'interactions et de communications personnelles dans des conditions contrôlées.

Ce travail vise à élaborer un modèle capable de stimuler et de prévoir le comportement décisionnel de sujets évoluant dans un environnement dynamique d'une expérience basée sur les micromondes. La plateforme utilisée pour reproduire et simuler le comportement d'un opérateur est l'environnement intégré de modélisation des performances (EIMP). Le modèle EIMP reposait sur le réseau des objectifs élaboré avec l'analyse de buts hiérarchiques (ABH). La structure des objectifs de l'ABH a été transformée en un réseau dynamique de tâches EIMP. Les variables obtenues de l'ABH ont été utilisées comme paramètres libres pour s'harmoniser au rendement des opérateurs du modèle. Ces mesures du rendement d'équipe étaient étroitement liées aux sujets de décisions particulières prises pendant la poursuit3e de cet objectif.

Résultats : Le modèle EIMP a identifié avec succès les tendances générales du rendement d'équipe, prévoyant le temps requis pour accomplir la tâche de même que l'efficacité du rendement relativement au nombre d'incendies éteints. Le modèle était en mesure de prévoir de quelle façon certaines erreurs particulières dans le rendement d'équipe (p. ex., les retards dans les communications, ne pas fournir de rétroaction en temps opportun, sous-évaluer l'ampleur des incendies, etc.) auraient des répercussions sur le rendement dans l'ensemble.

Portée : Le modèle EIMP offre un nouveau cadre pour mettre à l'essai l'optimalité des décisions des sujets dans les expériences basées sur les micromondes. Il offre la possibilité de faire l'essai de nouvelles conditions expérimentales avant d'effectuer des expériences et des erreurs humaines prévues résultant de lacunes particulières dans le processus décisionnel.

Travaux futurs : Le modèle EIMP sera élargi par l'ajout de nouveaux modules cognitifs (semblables au Contrôle adaptatif de la pensée — Rationalité et Opérateur simulé pour les modèles de réseau) pour la réalisation de simulations enfichables, avec intervention humaine.

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1 Introduction

The Canadian Forces (CF) are engaged in domestic and international operations that require co-ordination within and between its own elements (e.g., navy, land, and air forces) as well as with allies, non-government organizations, and other groups. This interoperability requires geographically dispersed people with different specialties, skills, cultural backgrounds, and levels of authority, to work effectively in complex settings where decisions have to be constantly adjusted in response to a rapidly changing environment. In order to evaluate the decision-making (DM) in such settings and to anticipate possible flaws and errors in the decision process, new methods of analysis is required. One way to analyze the nature of DM is to observe human decisions in a controlled environment that would possess important characteristics of the real-world situations. Synthetic environments and microworlds are examples of such experimental platforms. The term “microworld” suggests a miniature copy of the real world. This characterization captures important characteristics of a microworld: it is an abstraction of the real world that attempts to replicate features that are important to the decision-making process without replicating the real world environment. Microworlds include some important characteristics of the real system—such as *complexity*, *dynamics*, and *opaqueness*–-which are selected and simulated in a relatively small and well-controlled model [2].

The nature of decisions that subjects face in microworlds is often characterized as dynamic decision-making (DDM). Edwards [3] pointed out that DDM has a number of important features: a series of decisions are necessary; these decisions are interdependent (i.e., the decision made at time t_i+1 depends on the decision made at time t_i); the environment changes both autonomously and as a function of the decision maker’s actions.

Nevertheless, these very benefits of the microworlds outlined above impose some limitations on experimental control that otherwise would be available in a standard laboratory experiment. For example, the subjects in microworld-based experiments are active agents who direct and control the unique trajectory that unfolds during their participation in microworld-based experiments. Consequently, the traditional methods of assessment of subject performance (such as accuracy rates, time to complete task, relation between stimuli and responses) are not as directly related to subjects’ decisions as they are in standard experiments. These shortcomings are associated with a lack of normative models that can characterize both optimal decisions and actions of subjects and that can be used as a benchmark to analyze observed performance. The goal of this work was to develop a model that can simulate and predict decision-making behaviour of subjects acting in a dynamic environment of microworld experiment.

The model presented in this work is based on the previous study of Zotov & Chow [4] who applied Hierarchical Goal Analysis (HGA) to evaluate cognitive systems in a distributed team environment. Specifically, two-member teams were tasked to control forest fires in C^3Fire microworld platform. The HGA is a method to define the required levels of team performance using goals as the main units of analysis [5]. In the analysis, the process of goal decomposition is a process of identification of the current points of perceptual reference, beginning with the top-level goal and then descending into the lower levels. HGA offers the evaluation of the of subject’s actions and specific requirements for interactions between subjects in the context in which they operate.

C^{3}Fire is a command, control, and communication simulation environment for analyzing, training, and experimentation of distributed decision-making [1]. The C^{3}Fire microworld is a fire-fighting scenario that requires subjects to make decisions on allocation of limited resources to control and extinguish the fire. The C^{3}Fire microworld has been used extensively in previous research on network based command and control [1][6][7][8] and it originates from a long tradition of microworld research on distributed decision making [2].

The experiment investigated the impact of voice communications on distributed two-person teams in a simulated tactical-level dynamic environment of C^{3}Fire. The type of voice communications allowed between subjects was manipulated in different communication conditions.

The Integrated Performance Modelling Environment (IPME, TM of The Alion MA&D Operation) model presented in this work uses the hierarchy of goals derived from two C^{3}Fire experiments (for a detailed description see [6][9]). The initial HGA was conducted with specific purpose of decomposing goal hierarchy of Jobidon et al.'s experiment [6]. Considering that Zotov & Hawton's experimental design [9] was similar to one of the conditions in Jobidon et al. work, the HGA was slightly modified to account for the differences between two experiments. The purpose of the Zotov & Hawton experiment was to investigate performance of two-member teams that were assigned to three different communication conditions, varied on amount of communication feedback between two team members. Each team member fulfilled its own unique role; thus, among other things, the success of the operation was dependent on the efficient and productive communication between the teammates. Team activities were analyzed using basic and enhanced measures of team performance. The basic measures included a set of general variables related to C^{3}Fire team performance—such as fire-fighting efficiency and the number of active fire cells at the end of a session. The variables for the enhanced measures were derived from a HGA that decomposed the overall goal of the experimental task into specific sub-goals and extracted variables that are specific to each of the goals. The experimental configuration was used as a basis of IPME model presented in this note. HGA-derived goal structure was converted into a dynamic model of team activities using Integrated Performance Modelling Environment

2 IPME model of C^3Fire

2.1 IPME platform

Integrated Performance Modelling Environment is discrete event simulation and modelling software designed to investigate and evaluate systems that rely on human performance. The platform enables simulation of complex tasks and evaluation of some characteristics of human performance, such as time to complete a task, workload distribution through the process, identification of possible bottlenecks in the process, etc. The software consists of five major components that jointly represent a system: environment model, a crew model, a task network, a performance shaping function model, and external models that can be optionally added to the main model.

IPME allows hierarchical representation of tasks, thus the HGA goal hierarchy can be translated quite readily into an IPME task network that preserves the goal structure that was developed for C^3Fire. Among IPME's features, the ability to analyze and predict subject's performance in a dynamic environment was especially valuable for analyzing team performance in a dynamic environment of experimental microworlds. Specifically, IPME offers workload measurement, analysis of errors, time series analysis, and the ability to test and run "what if" scenarios, thus saving time and effort required to run different experimental scenarios. Additionally, IPME has a number of features that make it easier to integrate IPME with other simulations and models in a real-time environment. IPME's function library, user-defined functions, and an event catalogue allow dynamic events to trigger based on time or a condition within the simulation. These features would allow high fidelity testing of the properties of C^3Fire scenarios.

To summarize, the choice of IPME as a simulation platform was straightforward: the software network architecture that consists of linked tasks is an ideal platform for modelling a hierarchy of interlinked goals derived by HGA, making a relatively simple conversion from static network of goal structure into a dynamic simulation. The following section will elaborate on details of converting C3Fire HGA goal structure into IPME simulation network.

2.2 HGA to IPME

The initial step in the modelling process was to develop a general principles of converting a top-down, hierarchical goal structure into a dynamic network able to simulate human decision-making process. Figure 1 shows part of the C^3Fire goal hierarchy related to search and fire detection activities, while Figure 2 shows part of the goal hierarchy related to fire-fighting activities. Note that Figures 1 and 2 display different parts of the same goal hierarchy. Connections between goals show paths along which subjects can direct attention (e.g., from higher to lower level and vice versa) while controlling the system. The depth of the goal hierarchy varied from three to six levels.

To simulate C^3Fire in IPME at the level of DM, the simulation processing units were defined first. Considering that in the C^3Fire scenario operators controlled three types of units, a corresponding three groups of IPME tags—the main system units—were allocated and defined as four fire-fighting units, two water supply units, and two reconnaissance units. Another main property of the C^3Fire is fire itself, with the time of onset and speed of spread controlled by the simulation scenario. To simulate fires, an array of tags was defined, FF_i, where *i* defines number of fire at any moment during simulation. The rate of fire spread is controlled by an intrinsic fire-spread accelerating function. The fire-fighting units reduce the number of fires and are capable of complete extinction of all fires. The rate of fire spread and speed of fire extinction were set by a set of parameters, which replicate corresponding rates defined by the C^3Fire experiment (see Annex A). Considering that all decisions in C^3Fire related to manipulation of units in response to environment, each goal was activated by corresponding task in IPME network.

While there are numerous functions defined to control the simulation at different stages of execution (see description in Annex A), a short overview of IPME model flow would help to navigate the flow of the simulation in the model. The overall run can be divided into these stages:

1) Right after simulation started, IPME generates and allocate 8 tags to four fire-fighting units (FF), two water tank units (WT), and two reconnaissance units (RT). Then, to replicate functional allocations to two operators, FF units are assigned to Operator 1 and the remaining WT and RT units are assigned to Operator 2.

2) To replicate the initiation and spread of forest fires, two more tags are allocated to act as units that drive the fire dynamics. These units are triggered by time specified in the simulation scenario.

3) As a next step, a specific task/goal is assigned to each type of unit: at this stage in the simulation, all units are assigned to search for fires and evenly allocated to different location in the C^3Fire area.

4) The search task is interrupted when the first fire is discovered. All units are notified and re-allocation of units takes place: FF units are sent to fight fires, WT units are sent to supply water , one of the RT units is deployed to investigate the amount of fires, and the second RT unit continues with its search for new fires.

5) Once the spread of the first fire is estimated by one of the RT unit, it gets re-assigned to searching for new fires.

6) When a second fire is discovered, it is evaluated in terms of spread of fires and then FF and WT units get re-allocated to combat both fires.

7) If all fires are extinguished, all units are re-assigned to searching for new fires. The simulation terminates when the session time is over, which was set to.

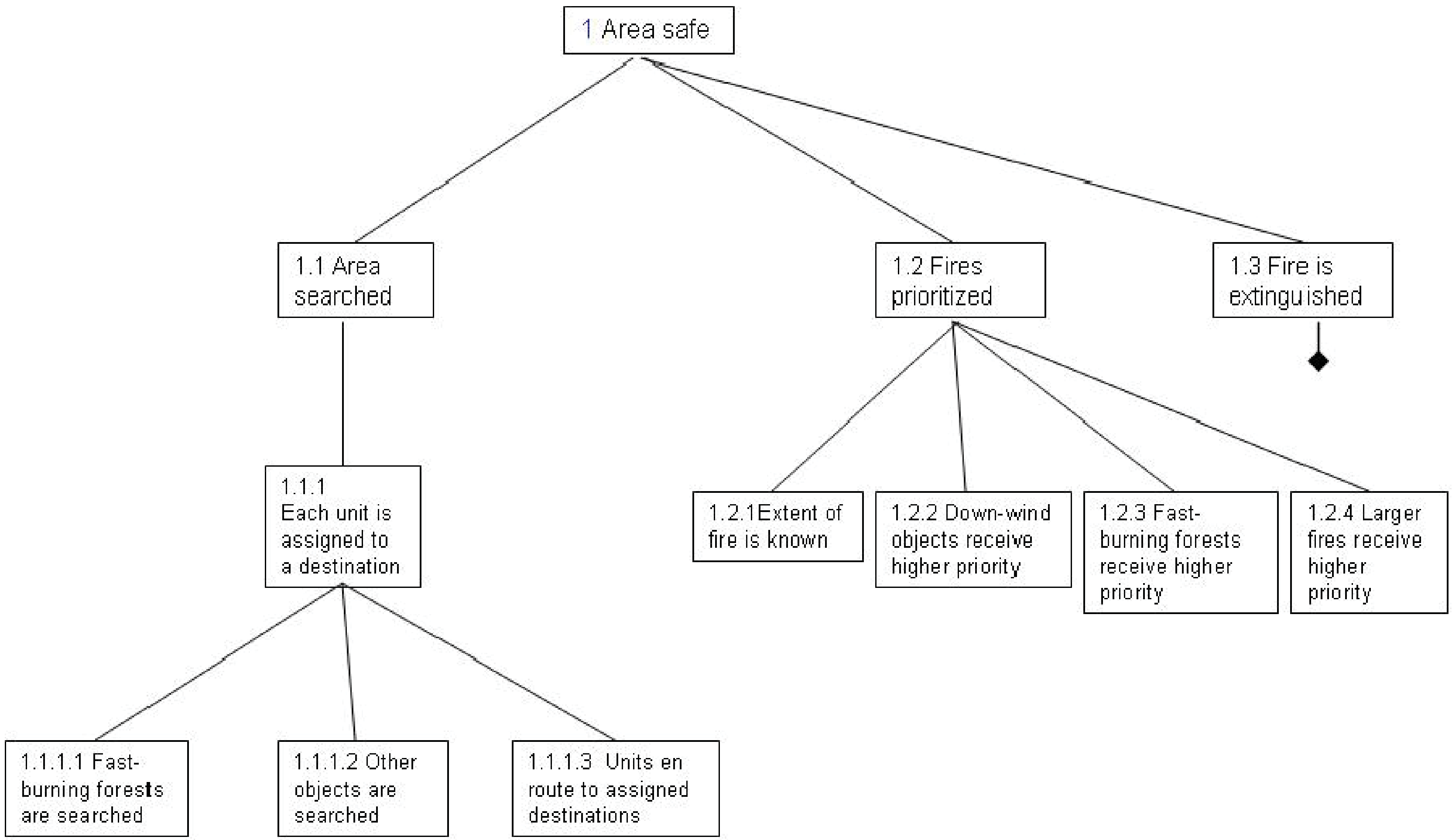

Figure 1. First part of the goal hierarchy. Filled diamond indicated a hidden part of tree (shown in the next figure)

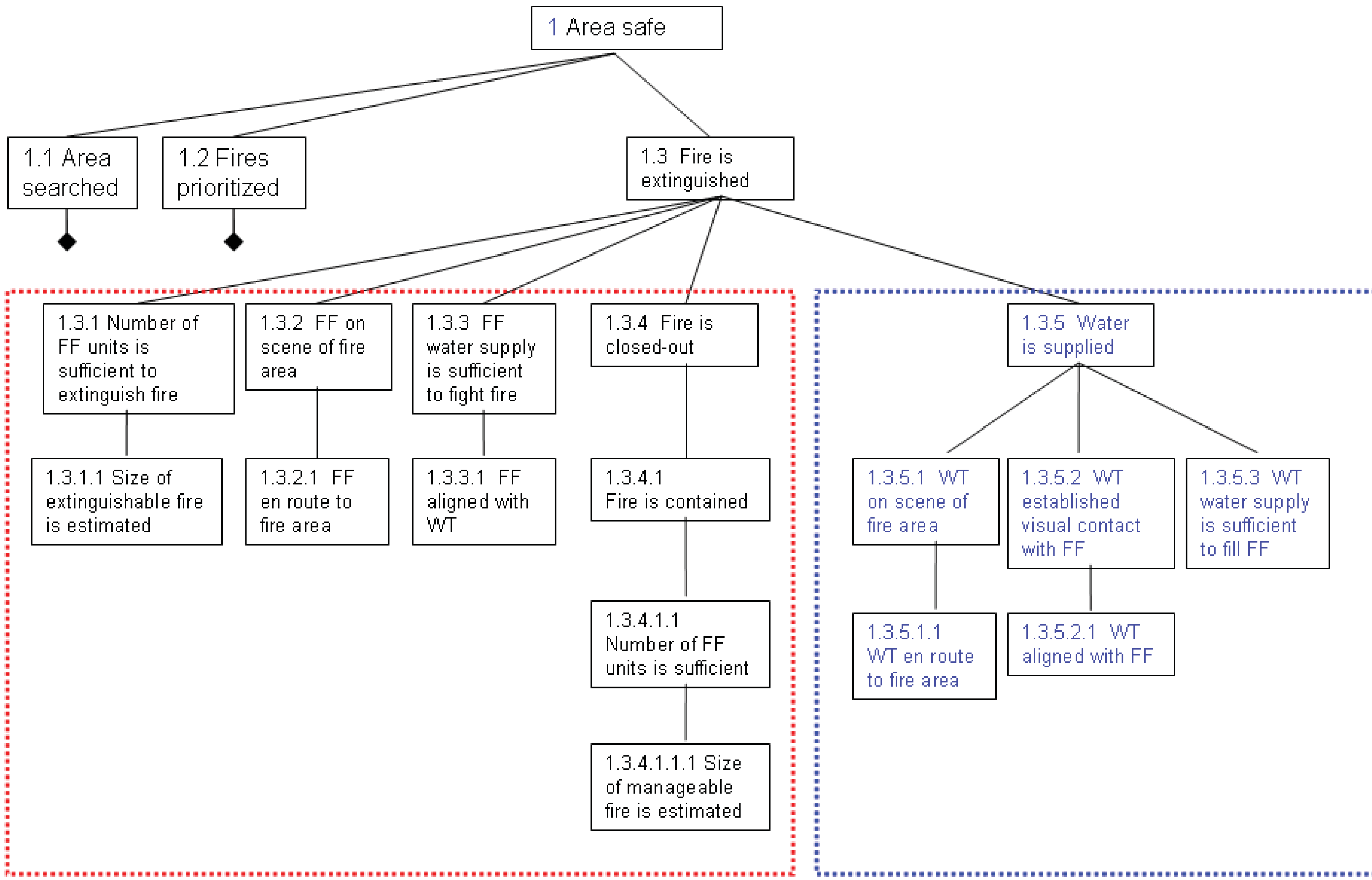

Figure 2. Second part of the hierarchy. The left red-dotted area demarcates a fire-fighting activities while right blue-dotted area represents water-supplying activity.

Assigned Operator	HUMAN				WORLD
1	**INPUT**	**CENTRAL PROCESSING**	**OUTPUT**		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.1.1 Each unit is assigned to destination	<u>**Declarative:**</u> **General guidelines for assigning units to fires based on units' capabilities:** -speed of movement; -time to extinguish fire; -water supply required to sustain fire-fighting (WT)	**Visual** -central; **Cognitive** -spatial pattern recognition; -reasoning **NON-IPME categories** -memory (Memorization)	D_{xy} set for all units;		EV1: --- $D_{x,y}$ (Assignments of each unit FF_j, WT_k, & RT_m to a destination)
	<u>**Situational:**</u> **Situation assesment:** -fire extent and shape of fire, -location of houses relative to wind direction, -location of forests relative to wind direction, -number of units available, -distance from fire(s) to nearest unit(s) **Information updates between O1 & O2: (Functional condition only)** -current locations of units, -assigned locations				
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	D_{xy} is not set	* AssignTagToUnit; * GetUnitCoordinate; * AllocateUnit	Status of units assignments		Once assignments are completed, operators concentrate on monitoring of fire-figting and recon info

Figure 3. Goal template for goal 1.1.1 “Each unit is assigned to destination”.

2.3 Utility of the model: initial findings

2.3.1 Tested performance measures

The IPME model of C^3Fire allows users to manipulate the flow of dynamics of the simulation by changing parameters defined in the scenario event. Considering the non-linear and interactive character of C^3Fire simulation, it is impossible to generate analytical model that can accurately predict team performance. Thus, simulation is the only way to anticipate the effect of different scenario values on team performance, which is achieved by generating a distribution of possible performance outcomes.

While the present simulation program can be used to predict some general measures of human performance (e.g., time to extinguish fires, number of extinguished cells, number of houses saved, etc.), these general measures can miss important team performance characteristics thus obscuring the proper evaluation of team effectiveness, as Zotov, Smith, & Chow (2008) showed in another work [10].

To illustrate these deficiencies, consider a couple of examples. At the beginning of the experiment, each member of C^3Fire team assigns units to a destination. Considering that the location of new fire is unknown, it is to player's advantage to spread units uniformly and systematically browse the area in search of new fires. Overall, such approach does work. Occasionally, by chance, the time required to locate fires is considerably longer than average. Compare such a team to another one that opted to send all their units into the same area and accidentally discover fire much quicker than average. Due to non-linear nature of fire spreading, the second team will be very efficient at extinguishing fires as there will be only a few of cells caught on fire; but it would be a mistake to evaluate this team efficiency by some general measure of performance such as time required to extinguish fires. One way to reduce the effect of randomness is to repeat experimental sessions numerous time—an approach that is very difficult to test empirically due to time and resource limitations. In such circumstances, some other team measures (e.g., index of unit spread and proportion of search coverage) are more effective in capturing team efficiency. A simulation is another solution since it can be re-run for multiple sessions, thus cancelling the effect of stochastic dynamic simulation.

Another example is team communication. Co-ordination between two teammates can be evaluated in the context of the information exchange to test if all necessary information related to units' and fire locations were fully exchanged between two teammates. Any omissions in information flow would result in incomplete and outdated team situational awareness. By running simulations, different aspects of communication deficiency can be predicted.

The examples above indicate that instead of relying on a single, generalized variable (e.g., the number of burned cells), it is necessary to define new measures of performance related to performing on specific tasks or goals. For example, one way to evaluate and compare performance of individual units is to look at the total amount of time units were left idle (i.e., unassigned to any destination); a shorter time would corresponds to superior performance. Another measure is the average distance between the FF units; a longer distance would indicate better utilization of resources (i.e., "Units spread index" in Table 2). These measures differ from the more conventional measures in that they are not affected by prior decisions and the stochastic elements of the microworld. That is, even if the subjects initially concentrated their units in one area, they could still re-distribute these units later on to attain reasonable overall levels of performance, without being severely penalized in terms of “time to detect second fire” if the second fire happened to occur very early in the trial or took place far away from the initial locations of their units.

Therefore, the simulation was set to estimate a limited set of general measures of performance, such as proportion of fires extinguished, as well as specific measures that help to evaluate the effect on performance when some task are underperforming, replicating some typical errors that many teams in C^{3}Fire experiment made (for detailed results of the experiment see [9]). Among these typical error are underestimation of the non-linear tendencies (e.g., spread of fires), inappropriate allocation of resources, and inefficient communication and coordination between team members, uneven distribution of attention among different tasks, effects of errors of individual members on team performance.

The predicted results were compared to observed results of C^{3}Fire experiment where teams in three different communication conditions varied on amount of communication feedback between two team members: Full Feedback, Partial Feedback 1, and Partial Feedback 2. In Full Feedback condition, there was unlimited voice communication between two teammates. In Partial Feedback 1, there was no communication between participants during session breaks, and, in Partial Feedback 2, communication was allowed only during session breaks. As expected, the best performance was observed in Full Feedback condition followed by Partial Feedback 1, and Partial Feedback 2. Considering that in Session 1 participants were still learning to perform the task, only results from Session 2 were used. The model was run optimized for best performance—in other words, all task were set to be completed as efficient as possible without any error. This efficiency was achieved by setting the completion times for all tasks in the simulation to the same time obtained empirically by the best performing teams in Zotov & Hawton experiment [9]. The only delays were coming from the stochastic nature of dynamic simulation where randomly placed sources of fire required tie to detect.

2.3.2 Results

The results of IPME predictions are reported in general and goal-specific measures of team performance. The predictions of the general measures show how well the model can capture the team performance in terms of the total number of extinguishing fires, counted by number of cells. The number of extinguished cells is, in a way, a final product of team effort, requiring detection of fires, deployment of units, and coordination of participants. The goal-specific predictions demonstrate IPME’s ability to account for more refined aspects of team performance related to completion of goal-related tasks. The goal-specific measures, which IPME was tested against, were the fire-fighting (FF) unit’s efficiency and communication delays. FF unit efficiency was measured by counting the proportion of time the units were active; the measure is related to many goals encountered in C^{3}Fire; among them are “Units are deployed”, “Search is conducted”, “FF units have sufficient water supply” etc. Communication delays were counted as time passed from the moment a new fire is detected by one of the units to the moment this information is conveyed to the teammate. While these reported measures represent only a small subset of all observed results, they were critical in overall team performance as results of the experiment showed [10].

Considering that the outcomes of the IPME runs were under full experimenter control, the variance of the model's outcomes was fully controlled by the parameters of the IPME model. Thus, all reported analyses are descriptive in nature providing a degree of fit of the model to the observed data. At the same time, the model parameters were held constant and their values were taken from the configuration settings of the C^3Fire experiment [10]. As such, the model was not fitted to replicate individual team results. The purpose of simulation was to investigate whether the model can predict team performance relying only on the set of original configurations. A more comprehensive simulation would include fits to individual team performance using some sort of degree of correspondence between observed and predicted measures, such as root mean square deviation or maximum likelihood ratio. Thus, the model predictions were close to what would be an optimal level of team performance. In other words, the model shows how well would team do if they were always maintaining a perfect situational awareness of all controlled units, instantly communicate all relevant information to their teammates, and anticipating well all future needs of each unit and situation in general. The stochastic part, which introduces variability of predictions, originated from the random nature of time needed to search and detect fires and the units' proximity to fires and water source at the time when the fire-fighting task has started. Thus, for the first two analyses ("Number of fire cells extinguished" and "Effectiveness of fire-fighting units"), the optimized, fixed-parameter IPME model was tested against all three conditions in Zotov & Hawton experiment [9]. It would be a very speculative simulation case if the model was set to replicate performance in Partial Feedback 1 condition, considering that the only difference between Full- and Partial 1 Feedback conditions was the ability of teammates to communicate during session breaks. After analyzing the content of communication during the session breaks, Zotov & Hawton suggested that the superior performance in the Full-feedback condition was achieved by participants discussing past mistakes and engaging in strategic planning. In order to replicate these subtle differences, the IPME model would have to be fundamentally revised; it would require adding human-like processes accounting for planning and decision-making, which is beyond the scope of this work.

Nevertheless, the model was evaluated in its ability to account for delays in communication feedbacks in the last analysis reported ("Communication dealays"). The analysis was performed for Partial Feedback 2 condition, where only text-based communication was allowed. The teams in this conditions suffered significant deterioration in performance when a new notification was delayed by one of the teammates. In order to observe how the model would account if some of the tasks get delayed and to evaluate how well it will replicate performance deterioration in human subjects to as would happen with human subjects.

2.3.2.1 Number of fire cells extinguished

Figure 4 summarizes predicted versus observed performance in terms of proportion of fire cells extinguished (the higher the number, the better the performance). As it is clear from the figure, the model's predictions were close to those results achieved by the best-performing group in Full Feedback condition, thus confirming that the teams in full feedback condition functioned close to the optimal level.

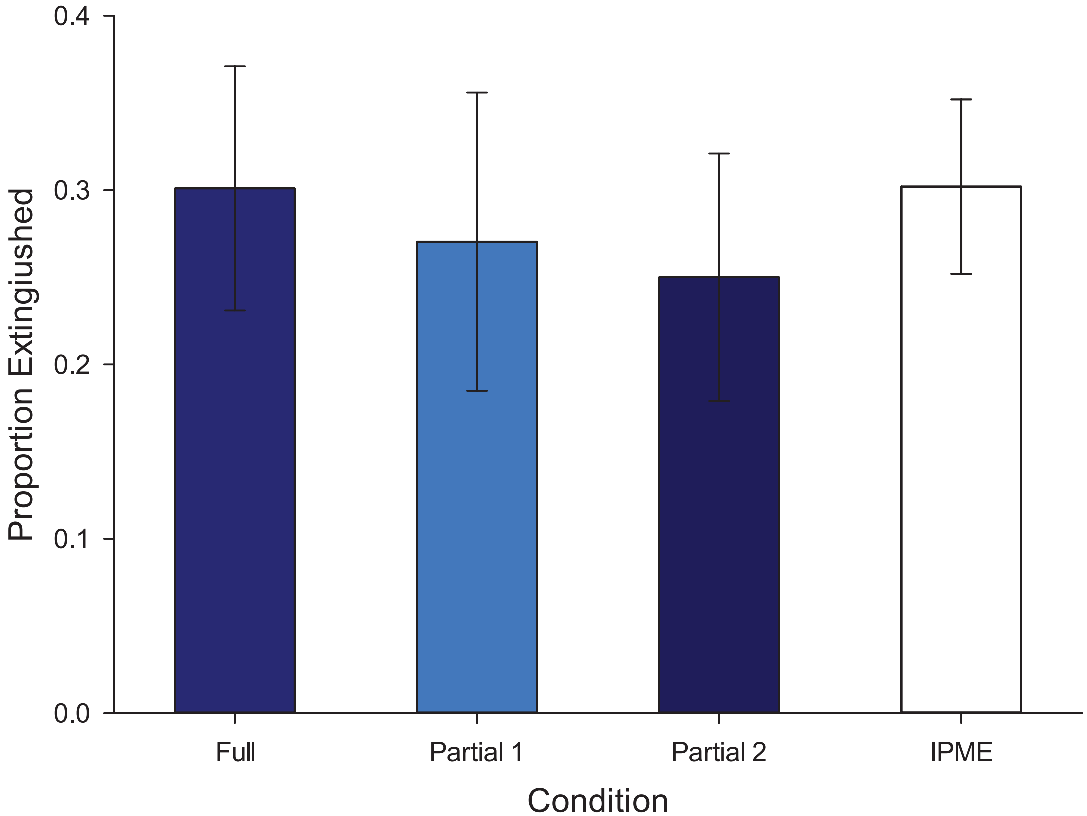

Figure 4. Observed versus IPME-predicted performance in terms of proportion of fire cells extinguished. The error bars represent SE.

2.3.2.2 Effectiveness of fire-fighting units

In C^3Fire experiment [10], inefficient allocation of WT units resulted in time delays of water supply to FF units, causing them to halt their fire-fighting activities. Considering that there are only two WT units and four FF units, it is impossible to provide uninterrupted supply of water to all FF units, but positioning of WT units close to the FF units can reduce these time delays to minimum. Better performing C^3Fire teams were able to minimize these delays, while less efficient teams were not as successful at engaging FF units. In order to quantify the efficiency of water supply, the overall idling time of FF units was calculated. Figure 5 shows total idling time of FF units in three conditions as well as IPME-predicted time. Considering that team performance in IPME model is optimized, it is no surprise that the IPME-predicted delays are shorter observed in participants, even in the Full Feedback condition. At the same time, these predicted results are not totally unrealistic considering that some teams in the Full Feedback and the Partial Feedback 1 did achieve similar results.

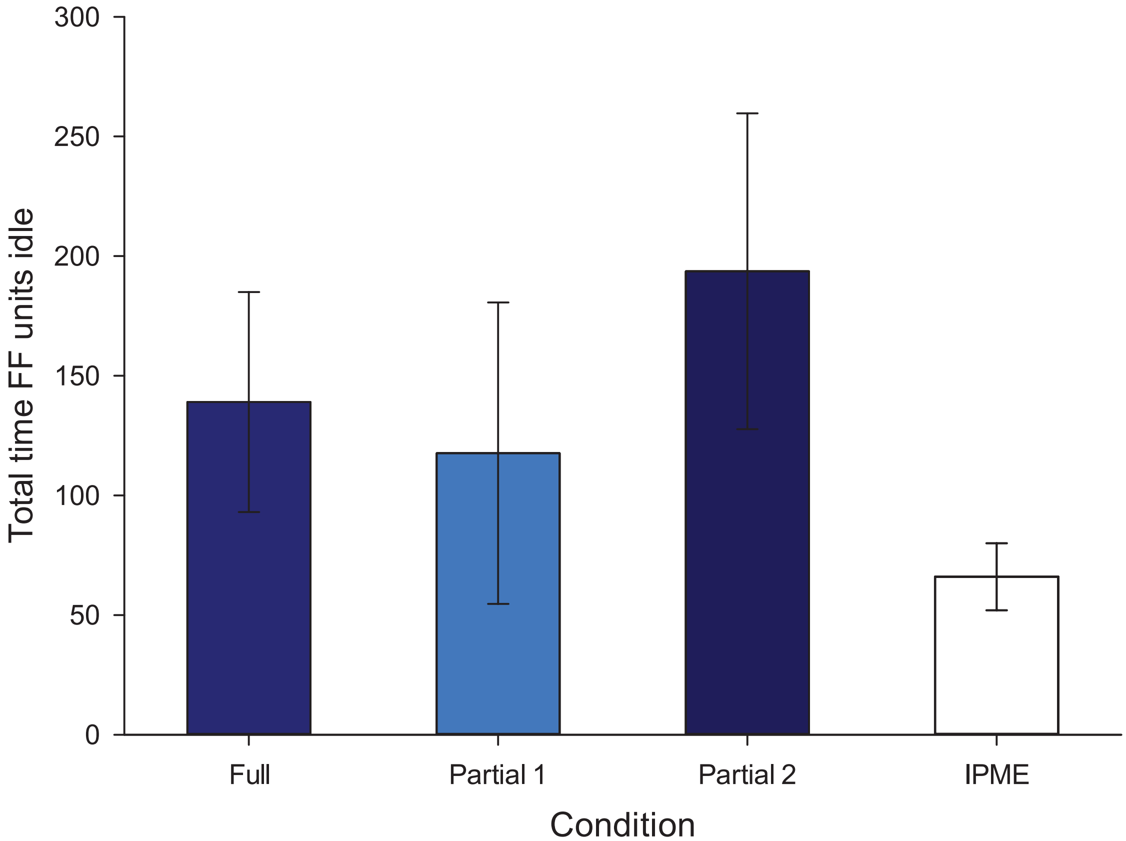

Figure 5. Sum of idling time of FF units observed and IPME-predicted.

2.3.2.3 Communication delays

A common and typical error observed in the experiment [10]. was related to delays in information exchange related to discovery of new fires. For example, if the operator who controls FF units discover a new fire, but does not share the information, the water supply will be delayed. These errors were most evident in Partial Feedback 2 conditions, where no voice communication was allowed during experimental sessions. The teams that failed to immediately exchange fire information were also teams who performed the worst. In order to replicate such error in the model, the parameter that controls timing of information was delayed and corresponding drops in performance were recorded and then compared with similar delays in human participants in Partial Feedback 2. Figure 5 shows the relation between performance and communication delays for five teams in C^{3}Fire experiment and IPME-predicted. The model-predicted values were higher than those of human participants, but the relations between communication delays and performance were very similar. To normalize predicted and observed sets of data, the predicted values were scaled down by multiplying each predicted value by the same coefficient.

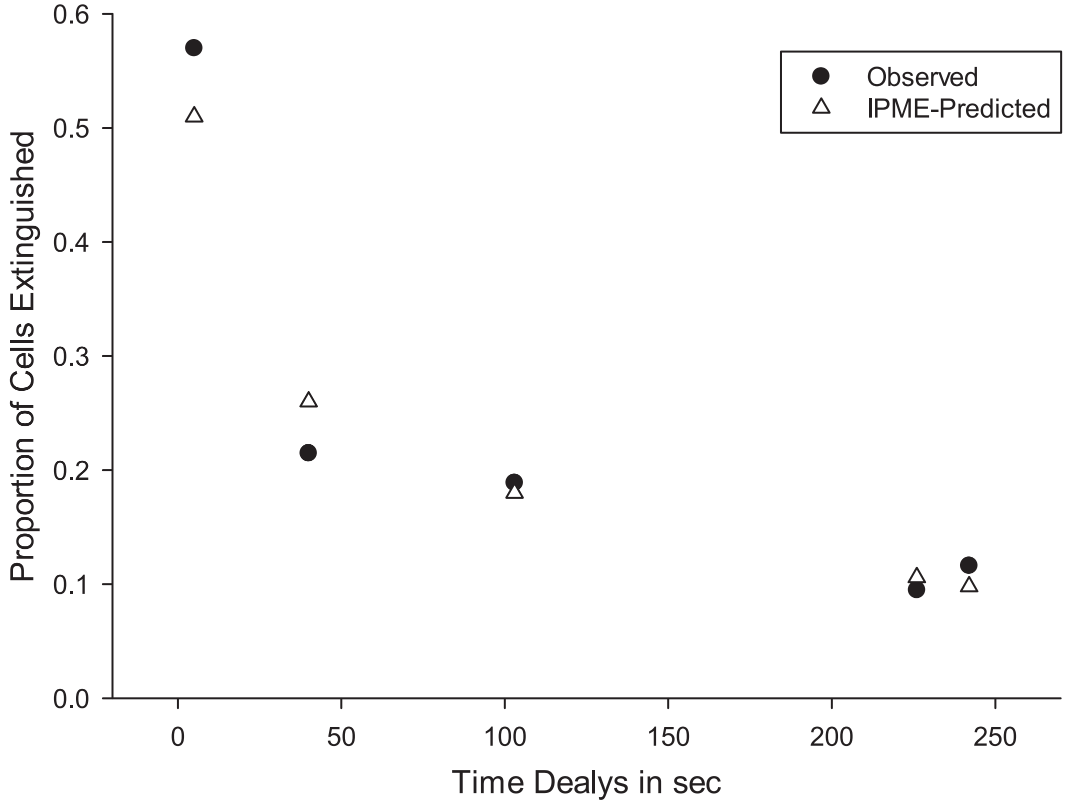

Figure 6. Effect of delays in communication on team performance observed in Partial Feedback 2 and IPME-predicted. Observed data represent communication delays of individual teams

3 Summary and future plans

The stochastic, non-linear nature of events unfolding in a dynamic distributed decision field has a significant impact on human performance. Subsequently, many standard measures of performance including both individual and team-based measures (e.g., time to complete task, error rate, or subject's workload) are often affected by environmental factors, obscuring the evaluation of subject's decisions. To analyze the cognitive system of the C^3Fire microworld, a Hierarchical Goal Analysis [5] was used to analyze the subjects and the environment with which they interacted. The goal hierarchy and the completed goal templates of the HGA process was converted into an IPME task network to create a dynamic model of participants' decisions and actions.

The IPME model was tested against observed performance of two-member teams participating in the task of managing and controlling forest fires in C^3Fire simulation platform. To evaluate human performance, both general and more specific, HGA-generated variables, were used. The IPME model was able to capture key performance measures of C^3Fire teams, showing its preliminary predictive power to replicate team decision-making process in the context of dynamic simulation.

The IPME model was designed using three-levels deep HGA hierarchy, that is, the model was a mid-range in terms of its fidelity level. The level was sufficient to replicate and predict many details of the human decision-making process. However, the level of fidelity of the C^3Fire platform was not very detailed. For example, no actual two-dimensional representation of the area (as in actual C^3Fire platform) was used; the time estimates for unit movements to and from their destinations were obtained empirically and used as averages. To overcome these deficiencies, a more powerful model is needed. Such a model would either replicate the two-dimensional mapping of C^3Fire or to act as a "piggybacked" plug-in to the actual C^3Fire simulation. The obvious drawback of such a model would be the cost and time associated with programming efforts. Nevertheless, in situations where a set of experiments is planned, such an approach might still outweigh the cost associated with modelling effort, providing good estimates of potential "what if" scenarios and validating simulated data in human-in-the-loop experiments. Considering that the model's hierarchy starts from global, general goals and then descending into more specific, task-like goals, the model can be generalized to other C^3Fire experiments with only a few changes related to individual participants' assignments (e.g., more than two players, different number of units, different unit assignments, etc.) and different scenario events (e.g., speed of fire spread, layout of villages and forests, direction of wind, etc.).

Another deficiency in the model is a very simple DM process mostly deterministic and driven in response to environmental conditions. Such an approach assumes that human DM process is reactive and rigid rather than proactive and flexible (for review, see [12]). A more elaborated and human-like DM mechanism might address this deficiency. One possibility is to use a dynamic human decision model, such as a Busemeyer and Townsend's Decision Field Theory (DFT) [12]. DFT-based model takes into consideration a rapidly changing environment of dynamic simulation and makes on-the-fly adjustment in a way humans do in similar conditions. The recent work of Xu and colleagues 0 adopted DFT to model a Sugar Factory supervisory control system, where operators' reliance on automation was modeled and enhanced.

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Annex A List of parameters, varaibles and functions

PARAMETERS (CONSTANTS)		
NAMES OF PARAMETER	CATEGORY	DESCRIPTION
AREA_SEARCHED	Double	A parameter that sets time limit for searching fires (set to 100 sec)
BALLANCED_FF	Integer	A parameter that sets max number of FF units fighting in the same area (set to 1)
BALLANCED_WT	Integer	A parameter that sets max number of WT units supplying water in the same area (set to 1)
BURNED_OUT_CONST	Integer	A parameter that sets time to burn a single cell (in sec, set to 8)
IGNITE_TIME	Double	A parameter that sets time to ignite new cell (set to 60 sec)
N_UNITS_TOTAL	Integer	A parameter defining total number of units (set to 8)
N_WT	Integer	A parameter defining total number of WT units (set to 2)
SEARCH	Integer	A parameter that defines numerical value of search state
SIMULATION_TIME	Integer	A parameter that defines the total time of simulation (set to 20min)
SINGLE_FF_CAPACITY	Integer	A parameter that defines the number of fires FF unit can fight (set to 4)
VARIABLES		

NAME OF VARIABLE	TYPE	CATEG ORY	DESCRIPTION
ContainedEstStarted	Boolean	Var	A variable that triggered by the beginning of the fire containment estimation task
DownwindFirePrioritySet	Boolean	Var	A variable that is set to TRUE after wind and location of houses are established
ExtentFireKnown	Boolean	Var	A variable that is set to TRUE after the area affected by fire is defined
ExtFireEstStarted	Boolean	Var	A variable that set to TRUE when the process of estimation of fire extend is started
FF_Reallocate	Integer	Array	An array of integer that contain information related to allocation of FF units
FF_WaterSupply	Integer	Array x 2	An array of integer that keeps track of water level of each FF unit and state of re-fill (e.g., low, assigned to refill, started, etc.)
FireChiefAvailable	Integer	Array	An array of integer that controls unit assignments to fire chief 1 and 2 (1- 4 FF units; 2 – 2 WT units and 2 RT units)
FireExtinguished	Boolean	Var	A variable that is set to TRUE when all fires are extinguished
FirePrioritized	Integer	Array	An array of integer that controls which of two fires needs a priority
FirstFire	Integer	Array	An array of integers that counts number of first fire cells types (total, active, burned, extinguished)
FirstFireCounter	Integer	Var	A variable keeps track of first fire

FirstFireDeployed	Boolean	Var	A variable that is set to TRUE when units deployment in response to the first fire finished
FirstFireDetected	Boolean	Var	A variable that is set to TRUE when the first fire is detected
FirstFireExtinguished	Boolean	Var	A variable that is set to TRUE when the first fires is extinguished
FirstFirePrioritizationStart ed	Boolean	Var	A variable that is set to TRUE when the process of allocation of resources for the first fire started
FirstSearch	Integer	Array	An array that assigns search task to all units
FireContained	Boolean	Var	A variable that is set to TRUE when the number of new fires remains constant or getting smaller
FireFightingStarted	Boolean	Var	A variable that is set to TRUE on onset of fire fighting
LargeFirePrioritySet	Boolean	Var	A variable that is set to TRUE when a larger fire is detected
MOVING	Integer	Var	A variable that assigns numerical value to moving unit (set to 2)
MultipleFires	Boolean	Var	A variable that is set to TRUE when more than one fire are active
ManagableFireEstimated	Boolean	Var	A variable that is set to TRUE when number of required units estimated
N_FF	Integer	Var	A counter of FF units fighting fires
N_Search	Integer	Var	A counter that keeps track of number of units involved in the search of fires

OnScene	Integer	Array	An array that keeps track of units at their designated positions
QuadrantNUnits	Integer	Array	An array that keeps track of units locations
RtExtentSearch	Integer	Var	A counter keeps track of RT units that evaluating extent of fire
SearchStarted	Boolean	Var	A variable that is set to TRUE when the search for fires initiated
SecondFire	Integer	Array	An array of integers that counts number of second fire cells types (total, active, burned, extinguished)
SecondFireCounter	Integer	Var	A variable keeps track of second fire
SecondFireDetected	Boolean	Var	A variable that is set to TRUE when the second fire is detected
SecondFireExtinguished	Boolean	Var	A variable that is set to TRUE when the second fires is extinguished
SecondFirePrioritizationStarted	Boolean	Var	A variable that is set to TRUE when the process of allocation of resources for the second fire started
StartingFire	Boolean	Var	A variable that is set to TRUE by scenario events related to first fire
StartingFire2	Boolean	Var	A variable that is set to TRUE by scenario events related to second fire
SINGLE_FF_CAPACITY	Integer	Constant	A parameter that defines the number of fires FF unit can fight (set to 4)
TagsSearching	Integer	Array	An array that tracks searching units
TimeToAllocateUnit	Integer	Array	An array that records time to allocate each unit

TimeToDetectFire	Integer	Array	An array that records time spent ot detect fires (in sec)
UnitsAssigned	Boolean	Var	A variable that is set to TRUE when all units assigned to destinations
UnitCoordinateState	Integer	Array x 2	A two-dimensional array that keeps track of units locations and states
UnitID	Integer	Array	An array that assigns TAGs to units
UnitOpAssigned	Integer	Array	An array that keeps assignments of units to operators (OP1, OP2)
UnitStates	String	Array	An array that keeps text information related to states of units
WtAligned	Integer	Array	An array that keeps track of WT-FF units alignment for water supply
WtReallocate	Integer	Array	An array of integer that contain information related to (re)allocation of WT units
WtWaterSupply	Integer	Array x 2	A two-dimensional array that keeps track of WT water level and FF requests for water supply
X_Coordinate	Integer	Array	An array that supplies initial X-coordinate of each unit
Y_Coordinate	Integer	Array	An array that supplies initial Y-coordinate of each unit

FUNCTIONS		
NAME	RETURN	DESCRIPTION
Allocate	Void	Control the unit allocation process

AssignXY	Void	Assigns units to their initial coordinate (defined by X_Coordinate and Y_Coordinate parameters)
CheckReadyToSupply	Integer	Checks whether WT unit is ready to supply water to FF
FF_Need_Water	Integer	Checks whether any FF unit is soon to be out of water
FillWithWater	Void	Check the unit type and fills it with water according to user-set parameters
GetEmtyFF_ID	Boolean	Checks whether any FF unit has run out of water
GetUnitID	Void	Assigns operators to units
GetUnitQuadrantXY	Void	Takes and process unit Y and X coordinates converting coordinates to quadrants of C3Fire gaming space
SpreadUnitsFF_WT	Void	Spreads units evenly over the 4 quadrants
SCENERIO EVENTS		
NAME	TRIGGERED BY	DESCRIPTION
FireContainedEstimation	Event	Event triggered by starting of fire-fighting and initiates the estimation of fire spread
FireExtinguishableEstimation	Event	Event triggered when fire fighting contained fires so that the estimation of fire extinguishing process can start
FirstFire	Time	Initiation of the first fire triggered by scenario timing (4 min)
SecondFire	Time	Initiation of the second fire triggered by scenario timing (8 min)
StartPrioritizingFirstFire	Event	Event triggered by detection of the first fire; initiates the process of prioritizing resources

StartPrioritizingSecondFire	Event	Event triggered by detection of the second fire; initiates the process of prioritizing resources

Notes. FF is a fire-fighting unit, WT is a water-tank unit, and RT is a reconnaissance unit.

List of symbols/abbreviations/acronyms/initialisms

CF	Canadian Forces
DDD	Dynamic Decision-Making
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
FF	Fire Fighting unit
HGA	Hierarchical Goal Analysis HGA
IPME	Integrated Performance Modelling Environment
MEA	Means Ends Analysis
PCT	Perceptual Control Theory PCT
R&D	Research & Development
RT	Reconnaissance unit
WT	Water Tank unit

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence R&D Canada – Toronto 1133 Sheppard Avenue West P.O. Box 2000 Toronto, Ontario M3M 3B9	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED NON-CONTROLLED GOODS DMC A REVIEW: GCEC APRIL 2011

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

IPME model of dynamic decision-making in C3Fire platform:

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

Zotov, Vlad

5. DATE OF PUBLICATION (Month and year of publication of document.) March 2012	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 34	6b. NO. OF REFS (Total cited in document.) 13

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Memorandum

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – Toronto
1133 Sheppard Avenue West
P.O. Box 2000
Toronto, Ontario M3M 3B9

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC Toronto TM 2011-169	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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Recent developments in microworld-based experiments provide researchers with an opportunity to conduct complex and dynamic experiments in laboratory-controlled environments, thus narrowing the gap between laboratory-based and field experiments. The performance assessment in a dynamic decision making environment, however, requires new methods for evaluation and analysis of data and cognitive systems. This memorandum discusses the application of Hierarchical Goal Analysis (HGA) to evaluate cognitive systems in a distributed team environment.

The process of conducting HGA involves the following steps: a) derivation of goal hierarchy, b) assignment of goals to subjects, c) identification of controlled variables, and d) completion of templates that specify goal attributes. The HGA-derived controlled variables provide additional measurements of performance that are closely related to subjects' decisions. We conducted upward information flow and stability analyses to evaluate the system that the subjects were functioning in. The analyses helped to identify a number of situations that might impede subjects' performance during task execution.

Finally, this memorandum discusses the potential benefits of applying HGA in the context of distributed and dynamic simulations and proposes future work to use the HGA outputs as the basis for the development of a computational model for predicting subject performance under specific task conditions.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS

Dynamic decision making, Controlled variables, Hierarchical Goal Analysis; microworld; IPME; Dynamic decision making; Controlled variables;

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