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Applying a Work-Centred Exploratory Design Framework to Joint Fires Coordination

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Abstract

Developing design requirements and associated design concepts for a future C2 capability requires analytical tools with the power to provide design insights for systems that are first of a kind. This paper provides an overview of the principal results from applying a work-centred, constraint-based design framework, that is sensitive to such design challenges, to develop requirements for a future Joint Fires Coordination (JFC) system for the Canadian Forces (CF). In this envisioned system, all services in a joint CF operation will be able to call for fires on targets of opportunity, and the JFC capability (JFCC) will effectively integrate these calls into a fire plan and coordinate delivery of fires. Five Cognitive Systems Engineering analyses in the framework were used to acquire knowledge about JFCC work functions, processes and tasks, decision and situation awareness requirements, and information exchange needs. Several hundred design requirements and concepts, related to technology, process and organizational structure of the future JFC system were then identified. This paper reviews the design framework, and discusses at a high level the analysis results and design concepts derived from its use. An example of how these concepts were used to develop recommendations for experimentation options for the JFCC is also elaborated.

1. Introduction

Joint Fire Support (JFS) is the application of shared resources from military component land, air or sea forces, including sensors, communications, targeting, decision aids, Command and Control (C2), weapons, and battle damage assessment, to provide force protection/projection. The JFS Technology Demonstration Project (TDP), being conducted by Defence R&D Canada, is investigating the development of an effective and efficient Canadian Forces Joint Fires model at the operational C2 level. The TDP is focusing specifically on Joint Fires Coordination (JFC), with the goal of establishing requirements for a future JFC capability (JFCC).

In land operations, the manoeuvre commander directs his[1] organic firepower to accomplish his mission or desired end state. There is also established CF, NATO and allied JFS doctrine, whereby at each level of field command from a battle group up, there is some form of Fire Support Coordination Centre (FSCC), headed by an artillery officer, to coordinate the use of additional firepower with a supported land force commander. Such fires, known as Joint Fires, involve the use of indirect fire and firepower resources external to the manoeuvre force.

With a JFCC as envisioned in the TDP, a spotter, observer or other legitimate non-firing service would be able to request “calls for fire” on emerging and/or time sensitive targets. The JFCC

[1] The use of the masculine pronoun throughout the paper is not intended to be gender specific.

would then designate and prioritize a target for engagement by the most appropriate weapon systems available within the joint force to optimize the use of its resources, while respecting the Joint Force Commander's objectives. Employment of two or more component forces' resources would be seamlessly integrated and coordinated to provide the needed fire support to the manoeuvre land force commander, by delivering fires (effects), on time, on target, and in accordance with his requirements.

The JFCC would provide an effective capability to the joint force, requiring advanced technological concepts and tools, organizational structures and processes to optimize the use of indirect fire and firepower resources. Its anticipated operational benefits include increased options to engage targets while deconflicting the use of weapon systems in the battle space, increased accuracy and timeliness of engagements, and reduced fratricide and collateral damage. Narrower in scope than the broader JFS system, a JFCC is seen as playing various roles, differentiated according to target type, summarized as follows:

Pre-planned targets: These are targets developed and selected for inclusion on a target list to support the Joint Force Commander's objectives. Fire responses to such targets are developed in advance, based on likely form, time and place, but may not be scheduled. Pre-planned targets may be time-sensitive, in the sense that they can only be engaged at particular times or are expected to be available for very brief time frames. Observers attached to manoeuvre forces, such as a Forward Observation Officer (FOO), a Forward Air Controller (FAC) or a Naval Operations Officer (NOO), direct and coordinate fire assets allocated to act upon targets in close contact with friendly troops. For pre-planned targets, JFCC would collect data related to the status of fire assets in order to maintain up-to-date knowledge about the use and availability of resources.

Mission support: In pre-planned target situations where the FOO, FAC or NOO requires additional assets to handle them, they would contact the JFCC with a "call for fire". The JFCC would then play a mission support role by allocating assets to meet those needs (often from reserves or a separate contingency pool).

Emerging targets: These are targets reported through "calls for fire" that are not pre-planned (not on a target list) or are included on a target list but appear in an unanticipated form, time or location and therefore require additional processing prior to engagement. They are typically time-sensitive, requiring immediate processing and response because they pose, or will soon pose, a danger to friendly forces, or are highly lucrative, fleeting targets of opportunity [1]. The JFCC would determine target legitimacy and identify appropriate and available resources that could be used if the target is to be engaged.

Time-sensitive targets: Time-sensitive targets (TSTs) may be pre-planned or emerging. If they are pre-planned and scheduled, then JFCC would function in its pre-planned role. If the TST is on a target list but appears at an unanticipated time and is called in by the FOO/FAC or NOO, then JFCC would participate in a mission support role, identifying and allocating available and appropriate resources. If the target is called in by a non-FOO/-FAC/-NOO, or it is not on a target list, the JFCC would perform similar processing as for emerging targets.

This paper provides an overview of the methodology and a summary of the principal results of using a work-centred, constraint-based design approach to identify design requirements and propose design concepts for the future JFCC. The particular approach to conducting requirements analysis and design activities that underpins the work is analytical in nature. It derives from the thesis that developing concepts for a future complex sociotechnical system capability like a JFCC requires an approach and supporting analysis tools with the power to provide design insights for systems that are first of a kind. In this type of system design problem, there may be limited preconceived specificity about key elements of that future capability. Our approach exploits Cognitive Systems Engineering (CSE) techniques for modeling work constraints of the JFS system. This enabled the identification of several hundred design requirements and design concepts related to technology, process and organizational structure for the future JFCC. The paper also describes some of these concepts, and gives an example of how they were used to develop preliminary recommendations for experimentation options for the future capability.

2. Work-centred exploratory design framework

Figure 1 shows a general design framework we have developed and exercised over a number of sociotechnical system applications, mostly for the naval tactical C2 domain (e.g., [2-5]). It incorporates a variety of activites usually found in (essentially linear) systems engineering frameworks. However, it also admits the non-linear explorations that are needed of the problem and solution spaces, and their complex inter-relations, as an increasing understanding of the work demands operators can face is developed and potential design solutions or design interventions are identified and investigated. The approach reflects a focus on explicitly dealing with ill-structured design problems in complex sociotechnical systems in an exploratory manner, by exploiting or adapting CSE work analysis techniques [6].

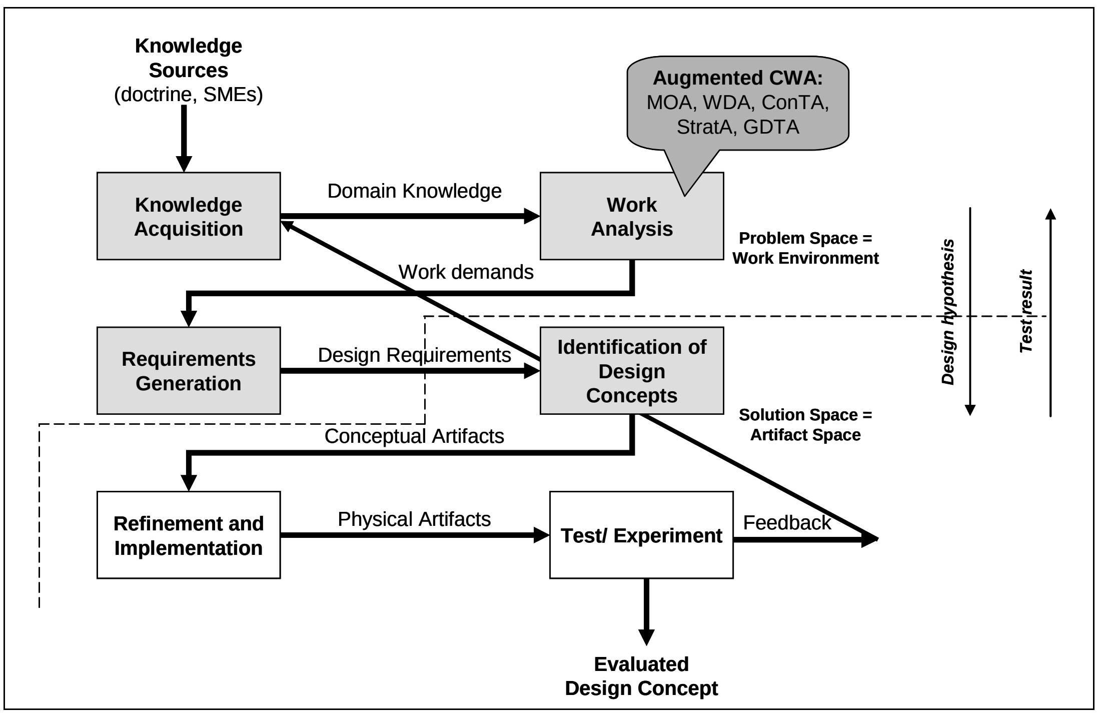

FIGURE 1. Work-centred exploratory design framework

In the framework, a *design requirement* determines an opportunity or need for a design intervention, stated from a solution-independent perspective. Such opportunities are identified from an understanding of the characteristics of operators, including, but not limited to, their work domain and context, their goals, activities and the strategies for achieving those goals. A *design concept*, on the other hand, is a proposed, or tentative, design intervention (i.e., it is a solution-specific design hypothesis) matched to one or more of these opportunities.

A specific top-down design trajectory is shown in Fig. 1. Its distinguishing characteristic is its reliance on a *work analysis* to generate design requirements and identify design concepts to address the requirements in a deliberative manner. However, bottom-up or opportunistic design trajectories (not shown in Fig. 1) are also accommodated. One example of a bottom-up trajectory involves sessions in which Subject Matter Experts (SMEs) are asked to discuss challenges in the current or “as-is” Joint Fires System and then analysts work directly with the SMEs to identify possible solutions; in another variant, analysts brainstorm among themselves, using knowledge acquisition results, to directly identify design concepts. We have not relied solely on bottom-up trajectories to enable their design outputs to be compared for consistency, validity and usefulness against design requirements derived from work analysis results. For example, this can help reduce the risk of producing design concepts resulting from incomplete SME understanding of the complex sociotechnical work system.

We have exploited these various types of design trajectories to generate requirements and identify suitable design concepts that can subsequently be fleshed out and assessed through testing and experimentation for their effectiveness. Only the specific activities of the framework shown shaded in Fig. 1 have been conducted to date in the work reported here.

3. Knowledge acquisition

The first step in applying the exploratory design framework consisted of acquiring domain-specific knowledge, which was achieved through a review of relevant literature and by interviewing SMEs. Given that an analysis can only be as strong as the knowledge it is based upon, it was necessary to review significant doctrine and documentation related to joint fires and interview a variety of SMEs.

Canadian and US doctrine documents dealing with joint fires, targeting, planning, firepower, artillery, close air support, naval gun support, and surveillance and target acquisition, were consulted to build a broad knowledge about the current joint fires system, including knowledge of its structural components, systems and processes. Six sets of SME interviews were also conducted, each over one or two days, including observing the battle phase of an artillery planning and execution exercise, at the brigade and division levels, in a simulated setting. SMEs included members of the surveillance, targeting and acquisition training team at CFB Gagetown, New Brunswick, Canada, as well as two SMEs with recent Afghanistan combat experience, one a brigade level Task Force Fire Support Officer and the other a division level HQ Chief Joint Fires and Targeting Officer. SME interviews used a semi-structured knowledge elicitation method encompassing flexible, open-ended questions.

4. Work analysis

We adapted various methods from Cognitive Work Analysis (CWA) [6] to perform the work analysis shown in Fig. 1. According to [6], CWA is used to analyze the cognitive, social and physical constraints that shape behaviour in complex sociotechnical systems. This enables determining how work *can be* done (i.e., a formative approach), rather than how it *should be* done (i.e., a normative approach) or how it *is* done (i.e., a descriptive approach). CWA therefore provides a design lens to view the future JFCC from a perspective that is not unnecessarily clouded by normative or descriptive views about current work practices. The work constraints captured in a CWA include those related to values and priorities of the system (e.g., minimize fratricide, minimize response time-line to calls for fire, laws governing mass and energy) which should be relevant regardless of the situation. Growing evidence of the robustness and extensibility of CWA methods to real-world, large-scale system design problems in diverse sociotechnical domains (e.g., military, aviation, healthcare) appears in [7].

We exploited three CWA methods [6] to model the JFCC work environment: a Work Domain Analysis (WDA), a Control Task Analysis (ConTA), and a Strategies Analysis (StratA). These were augmented with the inclusion of a Mission and Organizational Analysis (MOA) and a Goal Directed Task Analysis (GDTA) [8]. The intent of each work analysis method was as follows:

1) MOA: to establish and record the boundary, context, high-level system constraints, and goals of the current JFS system, based on the established body of knowledge and instruction (doctrine, formalized processes, etc.) about how joint fires are executed and integrated.

2) WDA: to model in an event-independent manner the JFS systems' functional and decompositional structure, from its intentional to its physical context, and from its whole system level to the level of its elemental system components.
3) ConTA: to decompose the work activities in a JFCC into a combination of critical work functions for achieving the JFS's functional purposes, and, for a selected subset of those functions, to model the cognitive information processing and resulting knowledge states of the critical control tasks involved.
4) StratA: to investigate and model the different ways in which various control tasks detailed in the ConTA could be performed.
5) GDTA: to determine key decision and situation awareness requirements for a JFCC as a whole, rather than being restricted to a particular organization of JFCC, work position or role in its organization.

TABLE I. Abstraction levels with examples from the JFS ADS

Abstraction Level	Definition	Examples
Functional Purposes	Purposes of the system and indications of its performance	See the definitions of the purposes for the whole JFS system and each component subsystem (Section 3.1.1)
Abstract Functions	Underlying laws, principles, constraints, values and priorities	• Kill chain timeline optimization (JFS) • Balancing accuracy and speed in the production of intelligence products (Intelligence) • Conservation of capabilities (e.g., by ensuring only minimum force is used to produce desired effects) (C2) • Resource management (Logistics) • Concealment of force and/or weapon movement (Manoeuvre)
Purpose-Related Functions	Processes by which Abstract Functions are carried out	• Vetting/validation of calls for fire as needed (e.g., an emerging taget not on a target list) (C2) • Synchronize resources of all operational units in accordance with asset authority (Coordination) • Evaluate plan (Planning) • Processing of order to fire (Delivery of fires) • Determination of communication needs and management of communication networks and resources (Communication)
Object-Related Processes	Capabilities and limitations related to achievement of Purpose-Related Functions	• Data acquisition systems (e.g., surveillance and target acquisition systems, weapon locating systems) (Intelligence) • Ordnance tracking systems (Logistics) • Scheduling tools (Coordination) • Weapon systems (Delivery of fires)
Physical Objects	An inventory of example objects and/or inputs used to meet the capabilities of the Object-Related Processes level.	• Maps and target overlays (JFS) • Air traffic control facilities (Intelligence) • Communication and data links (Communication) • Weapon effectiveness table (Planning) • Attack Guidance Matrix (C2)

With the exception of the MOA, and in keeping with the formative focus of this work, all other analyses considered the JFS system irrespective of existing organizations, processes and structures. The WDA modeled the JFS work domain as a whole, to allow developing a better understanding of the functional role of a JFCC within JFS. This approach also identified JFCC with an aggregate of specific subsystems within JFS. However, the subsequent analyses (i.e., ConTA, StratA, GDTA) focused on JFC rather than considering JFS in its entirety.

It was recognized that a future JFC system in the Canadian context will need to account for the multi-national or coalition nature of operational deployments. However, to limit the scope of the analyses at this stage, we purposely did not include considerations of multi-national forces. It was also felt that a broader knowledge acquisition effort than what was conducted would be needed to incorporate the multi-national constraints and do proper justice to the wider coalition context.

4.1 Results

In this section, we give an overview of the principal analytical results. For brevity sake, we only discuss the CWA-specific analyses, i.e., WDA, ConTA, and StratA. We omit the methodological details of each analysis. Some of these details can be found in [9].

4.1.1 Work Domain Analysis (WDA)

The WDA built a structural, activity-independent, map of JFS that captures the functional and decompositional structure of the JFS in the form of an Abstraction-Decomposition Space (ADS). The abstraction dimension of this ADS map represents the system's functional structure, at various levels of abstraction (see Table I above), from its intentional to its physical context, with mean-ends links (not shown in the table) between functions in consecutive levels of abstraction. In the decomposition dimension of the ADS, on the other hand, the whole JFS system was decomposed into a set of eight subsystems: Intelligence, Planning, C2, Coordination, Communication, Delivery of Fires, Logistics and Manoeuvre. While this decomposition is finer than found in the JFS literature, it was required due the clear divergence at the subsystem level of their Functional Purposes. In addition, each subsystem has quite different constraints and will certainly require different metrics to evaluate their performance. In developing the ADS it was also useful to include the functional elements that are relevant to all subsystems at the system level, while elements relevant to one or more subsystems, but not all, were allocated to the relevant abstraction levels of the appropriate subsystems. This allocation is illustrated in parentheses for each of the examples given in Table I. The final ADS map contained over 500 functional nodes.

The JFS system level and its subsystems were defined by their functional purposes as follows:

Joint Fire Support (system level):

- Optimize kill chain process in support of commander's intent
- Determine in a timely manner whether, when, and how to deliver requested effects
- Safely deliver desired effects on time and on target
- Manage joint fires to assist forces to manoeuvre and control territory, populations, airspace and key waters
- Enhance breadth and depth of effects available to manoeuvre force

Functional Purposes for Subsystems:

Intelligence:

- Collect, maintain, integrate and analyze all relevant data/information to promote and maintain situational and battlespace awareness for support of land combat operations through joint fires

Planning:

- Prioritize and plan fires that will put into effect Commander's Intent and optimize resource allocation

C2:

- Make decisions and provide guidance to enable joint fires to support land combat operations
- Implement plans and direct units to achieve Commander's Intent as expressed by planning objectives.
- Develop Commander's Intent based on political and operational goals

Coordination:

- Synchronize fires (lethal and non-lethal) in time, space and purpose between land, sea and air units to support land combat operations

Communication:

- Enable information to be exchanged between system components to support situational and battlespace awareness, as well as action execution

Delivery of Fires:

- Deliver fires with accuracy in accordance with Commander's Intent

Logistics:

- Manage ordnance and resources (including personnel) to support delivery of fires.

Manoeuvre:

- Enable assets to move into position to achieve desired effects

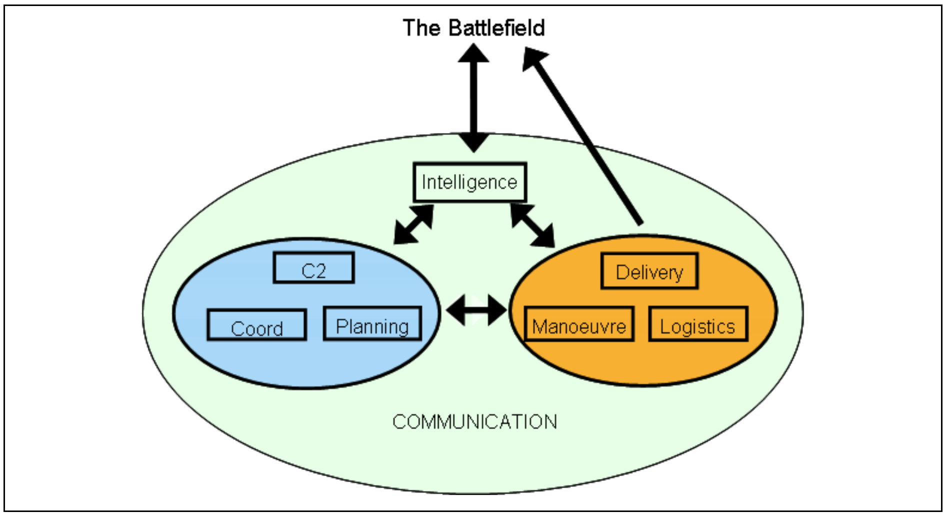

FIGURE 2. JFS subsystems

Figure 2 shows the subsystems grouped to illustrate their interactions (at functional purposes level). We found that JFC could be identified with more than just the Coordination subsystem of JFS. JFC includes integrating calls or requests for fire within Planning and C2 to achieve effective delivery of fires through scheduling and synchronization and resource allocation, requiring target engagement decisions and target prioritization to support land combat operations. The need to maximize the effect on the enemy while protecting blue forces and neutrals also requires Coordination functions related to information exchange between components and up and down the command chain, and attaining and maintaining situation and battlespace awareness by interacting with Intelligence, all of which must be managed throughout the targeting process. As such, JFC principally includes functions within the C2, Planning, Coordination, and Intelligence subsystems.

4.1.2 Control Task Analysis (ConTA)

TABLE II. Description of work functions (according to target types)

Target Type	Work Function	Description
Pre-Planned	Target Development and	Categories of pre-planned targets are developed and selected for inclusion on target lists to meet the commander’s intent and operational objectives.

Target Type	Work Function	Description
	Selection	
Pre-Planned/Emerging	Capabilities Analysis	Targets are matched with capabilities expected to produce the desired effects. Several capabilities may be applicable to each target, which should be rated based on effectiveness and efficiency. This process is accelerated when emerging targets are highly time-sensitive. When an emerging target is already on a target list, but not expected at that particular time or place, a capabilities analysis may have already taken place. However, it may be out of date depending upon the difference between the expected and actual circumstance in which the target is observed.
Pre-Planned/Emerging	Force Assignment	Force assignment takes the theory (planning of target lists) and puts it into action based on currently available resources. This function deals with resources at a system-level rather than dictating precisely which specific weapon should be used, resulting in a tasking order at the tactical level. Resource allocation for emerging targets must be considered in relation to resources allocated for scheduled pre-planned targets. It is necessary to determine whether resources should be reallocated from pre-planned to emerging targets in the event that an emerging target is prioritized above pre-planned targets.
Pre-Planned (Mission Support)	Force Assignment for Mission Support	Calls for mission support are made when insufficient resources are available to handle scheduled, pre-planned targets. This may occur when resources are damaged (e.g., plane is shot down), originally designated resources have been reallocated to other targets, or the desired effect is not achieved on a first attempt (e.g., poor force assignment decision, or firing error). Force assignment involves allocating resources to calls for support from reserves or when necessary and appropriate, from other scheduled, pre-planned targets.
Emerging	Process (Vet and Validate) Emerging Targets	When a call for fire is received, the target must be both vetted and validated before it can be further processed for engagement. This requires assessing the target in the context of the operation, commander's intent, Rules of Engagement, Law of Armed Conflict, and allied concerns. The emerging target may be identified as unplanned (not on target list) or pre-planned but appearing in an unexpected form, time or place. The emerging target may also be time-sensitive.
All	Outcome Assessment	An outcome assessment may be conducted after a target is fired upon. It is conducted to determine whether or not the desired effect is achieved. The assessment process requires gathering, weighing and aggregating information about damage to the target and its surroundings. This aggregate is compared against the desired effect to determine whether or not re-attack is necessary. This decision must be considered in terms of the available resources and future plans.
All	Coordination of Components	The coordination function is related to ensuring teamwork between components when it is necessary that a joint effort be employed against a target. Deconfliction is required to ensure the safety of all military components.
All	Management of JFC	The overall JFC process must be managed appropriately and continuously in order to maintain availability and awareness of real-time information including location and availability of resources, current and future plans, taskings and workload of JFCC personnel, and mission progress.

The ConTA was an analysis of the information processing activities that would need to occur in a future JFCC in terms of its decision-making related work functions. These functions, also referred to as control tasks, are the recurring problems that a future JFCC must be capable of solving. The first step of the analysis therefore focused on identifying an appropriate set of JFC work functions. They were identified by assessing the Purpose-Related Functions in the ADS for relevance to JFC and by interviewing SMEs. In particular, SME interviews were instrumental in the selection and validation of work functions along with the identification of goals and information that could require processing by each function. Work functions were identified primarily in the C2, Planning, Coordination, and Intelligence subsystems and are described in Table II above. Six of the eight final set of JFC work functions that were selected are also shown in Fig. 3 along with their process flow linkages (according to target type).

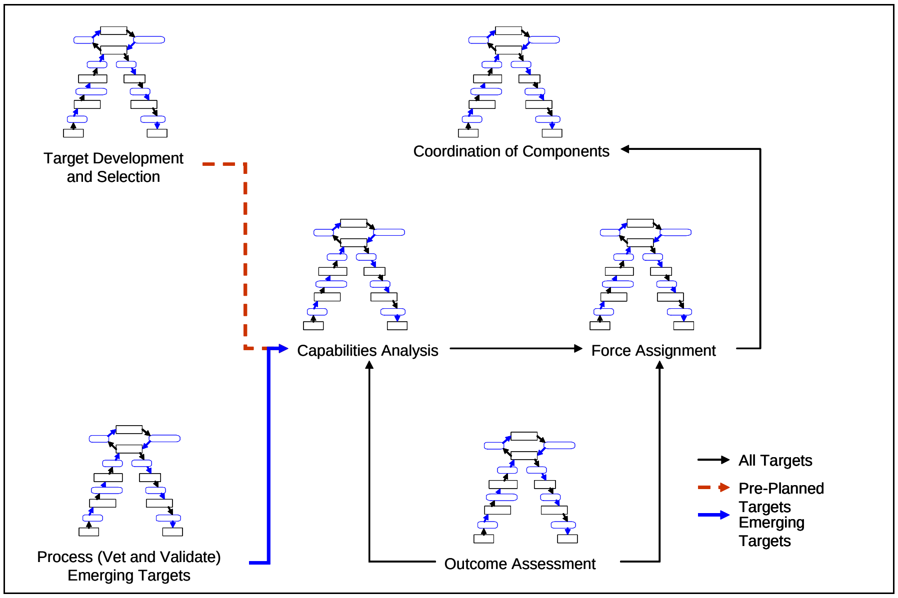

FIGURE 3. Process flows among JFC work functions

The second step of the ConTA was completed by developing a decision ladder (DL) model [6] of each work function based on information acquired from SME interviews and from reviewing the JFS literature. A DL is a template on which to formatively map the potential cognitive transformations involved in terms of what cognitive or information-processing tasks are potentially involved and their resulting states of knowledge.

4.1.3 Strategies Analysis (StratA)

In CWA, a strategy is a category of cognitive task procedure that transforms one cognitive knowledge state into another [6]. Whereas the ConTA identified the work functions and their cognitive processes for a future JFCC, the StratA identified ways in which those processes could be achieved. Strategies are not all-or-none, nor are they mutually exclusive. In other words, multiple strategies might be used in practice, and multiple strategies could be combined in principle into a hybrid strategy when a cognitive process is performed. There are also many different factors that could determine which strategy would be chosen by personnel in the future JFCC and, specifically, by whom. As a simple example, some factors that might influence the choice by someone to display spatial information on a computer versus using a paper map could include their location, the availability of each type of representation, their task, and their personal preference.

TABLE III. Strategy categories and derivations

Strategy category	Derived from:	Examples
General	Strategies that occurred in multiple ConTA work functions; bottom-up data from SME interviews	• Analytical versus intuitive decision making • Use of paper maps versus computer displays to display spatial information
Coordination	Coordination of Components to synchronize actions (ConTA work function)	• Physically locate resources organically with units versus holding them externally to units • Deconflict the use of resources in space or in time • Request additional resources according to the specific resources required, or in terms of the required effect
Target development	Target Development and Selection (ConTA work function)	• Create a master list of targets or separate lists for component forces (land, air, navy)

		• Continuous review of target lists, or according to a pre-determined schedule
Capabilities analysis	Capabilities Analysis (ConTA work function)	• Determine capabilities to achieve desired target effects from memory, technical documents, or by seeking advice
Force assignment	Force Assignment (ConTA work function)	• Consider all joint force resources to make an optimal force assignment or make assignments from restricted subsets of component resources
C2	Bottom-up data from SME interviews	• Centralized versus decentralized C2 • A task-based versus a goal-based command style
Commander's Intent	Bottom-up data from SME interviews	• Brief commander at set times or on demand

There are few documented examples of Strategies Analyses in the literature, and there is no standard data collection, data analysis, or general representational template, to formatively map out all strategies in a complex sociotechnical system. This work required us to develop new procedures for conducting the StratA for JFC [9]. In addition, flow charts were developed as a general graphical method for presenting information about a strategy. Because strategies generally represent different ways of making a decision in support of a specific goal, the goals and decisions associated with strategies were generally included in the flow chart representation to provide their context.

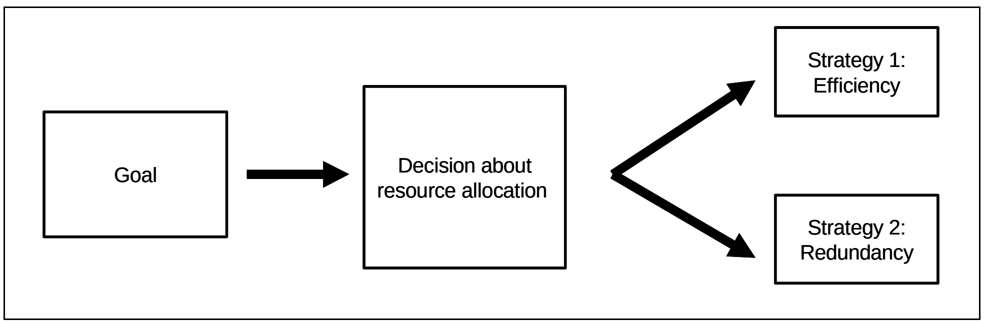

FIGURE 4. General resource allocation strategies

Almost 100 strategies were identified, grouped into categories according to Table III. General strategies included those that applied to many of the JFC work functions. Generally, however, strategies were derived from specific JFC work functions as indicated in Table III. SME data contributed solely to the last 2 strategy categories. A simple flow chart of a general strategy for making a resource allocation decision is illustrated in Fig. 4: the efficiency strategy assigns the fewest resources; and the redundancy strategy maintains backup reserves of resources.

5. Requirements generation and identification of design concepts

The various work analysis methods represented the captured knowledge specific to the goals, functions, decisions, tasks, situation awareness (SA) requirements and strategies associated with JFC. By performing the top-down analyses and also recording in a bottom-up manner design concerns and insights from SMEs, we were able to identify design opportunities and propose potential design solutions for the future JFCC. In addition, consistent with the design framework in Fig. 1, the approach allowed this to be done in traceable manner, spanning knowledge acquisition, work analysis, and design activities. This provided a significant capability to inspect each analysis for details about its associated design threads, i.e., knowledge acquisition → analysis → design, and even to suitably aggregate threads across the various analyses into a number of overall, general design concepts, when exploring ideas for developing experiments to evaluate the efficacy of the concepts.

The top-down design process consisted firstly of a detailed examination of the work demands captured in the work models developed in the WDA, ConTA, StratA, and GDTA analyses. This was aimed at extracting the design requirements implied by those demands. As examples, working with the ADS required a systematic assessment of each of the functional elements in the ADS to determine their information requirements; a similar technique applied to the decision ladders for the various work functions developed in the ConTA identified each function`s decisions and associated information requirements. The requirements produced in this manner were then analysed further to identify design concepts categorized as one or more of the following:

- Technology – concepts related to support tools or visualization (independent of modality such as electronic, paper, etc);
- Organization – concepts related to team structure, roles or expertise; and,
- Process – concepts related to training, policies, tasks or protocols.

Additional details about the methods used to develop the full design threads can be found in [9]. Instead, we concentrate here on the design outcomes.

5.1 Results

Eight overarching design themes were present across all analyses and therefore identified as significant in the design landscape of the future JFCC. These themes are described in Table IV, along with some high-level examples of the design requirements and design concepts identified under each theme and their analysis → design threads to show the range of design outcomes. The process was in fact instrumental in identifying several hundred design requirements and matching design concepts for the JFCC. In the manner treated in this work, the results of the StratA were used primarily to identify the diversity of information processing and decision making methods that would need to be supported by a JFC system.

TABLE IV. Design themes and examples of design outputs

Analysis → design thread	Design requirement	Technological design concept	Organizational design concept	Process/policy/training design concept
Theme: Decision, Planning and Coordination Support				
Analyses revealed the importance of the planning process during JFC where emerging and pre-planned targets, resources and personnel must be coordinated effectively within the context of a variety of circumstances to develop Courses of Action(COAs) that meet operational objectives. Support for COA development, evaluation and selection should be available and incorporate many different aspects of the current and future plans. All analyses offered insight into design concepts to ease this process (e.g., warnings when conflicts affect plans).				
WDA	Need to identify conflicts associated with plans (e.g., due to weather or terrain constraints), and to update plans when changes are required.	Automated support tools to provide alerts of plan interdependencies and conflicts		Processes to track the effects of reactive operations on plans.
GDTA	Need to understand how long a sensor will be able to provide information about a specific target.	Decision support tool with templates and baseline information for making time estimates.		
Strategies Analysis	Systems and/or processes must accommodate both analytical and intuitive decision making.			
Theme: Availability of Baseline and Real-Time Information				

Analysis → design thread	Design requirement	Technological design concept	Organizational design concept	Process/policy/training design concept
Analyses revealed the importance of having access to baseline information (e.g., pattern of life, target and surroundings before delivery of fires), in addition to real-time tracking of changing information to inform decision making (e.g., decision to re-attack, combat identification, resource allocation).				
WDA	Need real-time information tracking for calls for fire, targets, resource allocation, environmental conditions, Blue Force locations and mission progress.	Visualizations that track calls for fire, targets, Blue Force movements, changes to inventory based on availability and location; changes to terrain and weather.		Processes to track calls for fire, targets, resource allocation, environmental constraints, status of Blue Force,s and mission progress.
ConTA	Need record of timing associations (e.g., time since call for fire was received, time target list was last updated, time since resource inventory was updated).	Provide timing associations with information in appropriate format (e.g., length of time since call for fire was received, time until delivery of fires is expected).		Processes for monitoring time associated with information and events.
Theme: Data/Information Fusion Data/information fusion is required to achieve a complete representation of the situation (e.g., enemy and Blue Force locations, current and planned Blue Force locations, current target locations and likely path of movement, target location and geographic characteristics). Data/information fusion involves linking relevant data/information together to ease decision making.				
GDTA	Need to understand how long it will take to prosecute a target based on a proposed COA.	Fuse information about time latencies in decision support tools for engagement planning so that time information is automatically generated when generating COAs.		
Bottom-up	Need ability to link target information with the context of the target (e.g., relationships with other targets, target environment).	System or process that enables the acquisition, and communicating of better contextual information about targets.		
Theme: Information Presentation The presentation of information was a primary theme across the analyses because of its relevance to decision making. Information should be presented to act as a memory aid and to foster establishment of situational awareness (SA). Information presentation should be customizable. In particular, information overload can be minimized by offering opportunities to customize the visible information in the Common Operating Picture (COP). The COP should offer access to information related to all military components.				
WDA	Need ability to code data/information using multiple parameters.	Icons and coding representing multiple parameters (e.g., use colour, size, shape, order and/or position to represent urgency, reliability, credibility, relevance, time-sensitivity, location, authority).		Processes to rate information (e.g., urgency, reliability) upon receipt so that it can be coded accordingly.
ConTA	Need awareness of targets requiring force	Inputs next to targets to specify allocated		

Analysis → design thread	Design requirement	Technological design concept	Organizational design concept	Process/policy/training design concept
	assignment.	resources; empty fields indicate resources have not been allocated; use coding to indicate high priority targets.		
GDTA	Need to understand how long the target will remain in a location.	Provide an estimate of remaining time (e.g. countdown display).		
Bottom-up	Need to coordinate between the big picture (i.e., information required at the division level) and what the brigades and battle groups see.	Provide a COP that is customizable according to role and context.		Policy about what information is standard in a COP and what is customizable. Training on how to customize information in the COP.
Theme: Streamlined Communications Analyses repeatedly indicated the need for communications to be streamlined by eliminating unnecessary redundancies or nodes or providing information in an efficient, concise manner through processes such as standardization and/or use of communication tools. The direction of information flow also affects communication streamlining (e.g., flow from strategic/operational to tactical levels)				
WDA	Need to ensure information is transferred across levels of command.		Team structure (e.g., decentralized) and connectedness suitable for information flow.	
GDTA	Need to decide which communication method is most appropriate for a specific communication.	Provide real-time information about communication methods and factors affecting use of communication resources.		Provide memory aids regarding the pros and cons of different communication methods.
Theme: Training While training was not a main area of investigation in the analyses, bottom-up SME feedback gave insight into training requirements (e.g., need for up-dated lessons learned). Several process-related design concepts developed through the other analyses also offered examples of training needs for the JFC system.				
ConTA	Need awareness of effect of information on target selection.	Automated or semi-automated information aggregation procedures.		Training to instruct decision makers regarding how information should be weighted when making decisions about target selection.
Theme: Measurement of Effectiveness and Performance Several concepts related to performance tracking also became apparent throughout the analyses, particularly with regards to measuring planning functions (e.g., prioritization effectiveness, coordination evaluation, evaluation of planning execution) and outcome assessment.				
GDTA	Need to evaluate execution of plans.			Provide MOEs and MOPs for evaluating how well plans were executed.
Bottom-up	Need process for effective prioritization of calls for fire, including adequate understanding about main effort, priority of fire, and when priorities should be switched. Need to ensure that decision aids properly	System or process to ensure that calls for fire are prioritized satisfactorily. System that tracks this type of info and makes it available on demand.		Communication of main effort, priority of fire, shifting of priorities, etc., from strategic/operational to tactical levels. Processes that ensure that strategic long term objectives and Commander's Intent are known and considered when

Analysis → design thread	Design requirement	Technological design concept	Organizational design concept	Process/policy/training design concept
	reflect commander's intent.			making tactical decisions and incorporated into tactical decision aids.
Theme: Team structure Analyses revealed the importance of identifying the costs and benefits associated with centralized versus decentralized C2. Team heterogeneity was also a consistent theme as revealed by the need for specialized information and expertise (e.g., legal, political and cultural information and assessments).				
GDTA	Need an organization for assigning and requesting capabilities and understanding what capabilities are required that will facilitate a high degree of collaboration between resources used to make the relevant decisions.		Different teams responsible for resource monitoring and allocation in different physical areas. Different teams responsible for different resources based on resource type. Different teams responsible for different resources based on mission (resource allocated by mission).	

6. Developing options for experimentation

A design concept produced using the design framework of Fig. 1 is essentially a design hypothesis for structuring, supporting, or facilitating work in the complex sociotechnical system under consideration [4]. Testing the validity of a design hypothesis could, in principle, range from initially obtaining subjective Subject Matter Expert (SME) feedback to the concept to conducting objective performance tests with it. In addition, within this exploratory design process, increasingly detailed and realistic mockups and prototypes of concepts could be iteratively developed, refined, integrated, and tested, incrementally producing knowledge that can contribute to the development of a coherent and effective capability.

One goal of this work was to propose ideas for experimentation within such a design process, based on the design requirements and design concepts identified for the future JFC work domain. Of course, because of the extremely large number of design requirements and design concepts, not all could be practically elaborated. Thus, it was necessary to develop a method to enable the selection of a manageable number of options. To achieve this, the entire list of design requirements and design concepts was presented to SMEs who were then requested to offer input in terms of which ones they felt were the highest priority for elaboration for experimentation purposes. The resulting subset of design requirements and design concepts were then elaborated in several ways. First, all analyses (i.e. WDA. ConTA, GDTA, etc.) were reviewed for design requirements and concepts related to those selected. Aspects of the analyses in which these design requirements were found were recorded in a traceability matrix to illustrate the way in which each analysis offered insight for similar design requirements. The traceability matrix was then expanded to show the actual design concepts. Finally, the design concepts were examined as an aggregate as they related to each design requirement in order to identify promising ones for experimentation.

Aggregated design concepts were rarely taken verbatim from the elemental design threads identified in Table IV, but rather, those threads were generalized by abstracting the main ideas across the aggregate of concepts in order to reduce redundancy and focus on the main points. Table V elaborates, in high-level terms, an experimentation strategy for one of the design requirements that resulted. The example given relates to one of the requirements identified under the Decision, Planning and Coordination Support design theme (see Table IV).

A proposed experimentation strategy dealt with the experimental conditions for assessing a design concept, determining possible metrics or measures to be used for the assessment, and proposing some design hypotheses around which to structure an experiment. The strategy also categorized experiments according to whether they would likely fit into a short-term (e.g., within 1 year to 18 months), medium-term (e.g, in 2-5 years), or long-term (longer than 5 years) implementation schedule. Factors considered in subjectively placing design concepts into these time categories included: whether additional work would be needed to develop the experiment (e.g., whether additional knowledge acquisition would need to be conducted, whether additional analyses would have to be performed), the likely level of effort required for prototype development (e.g., how much development would be required), and the likely level of effort and time required to develop a prototype into a functional system. Future research will need to focus on selecting appropriate, specific design hypotheses and metrics or measures, including threshold or objective values in their formulation (e.g., time required to develop and change plans).

TABLE V. An example of an experimentation strategy for a design requirement

Design Requirement	Short Term	Medium Term	Long Term
Need to update plans when changes are required.	**General Design Concept:** Alert indicating that plans need to be changed (e.g., plans for targeting, engagement priority, etc.) (Technology) **Experimental Conditions:** Alert present or absent Varying amounts of information present with alert (e.g., explanation as to why changes are required is present or absent) Varying degrees of reliability/ credibility of alert **Metrics/ Measures/ Evaluation Criteria:** Response time to choose to change plans Appropriateness of plan changes implemented Trust associated with alerts Utility ratings (including usefulness, timeliness) **Design Hypotheses:** Operators change plans faster when alerts are present compared to when they are absent Operators change plans more appropriately when an explanation regarding the need for change is present compared to when absent; Fewer planning errors are made when an explanation is provided with the alert Trust in alerts is increased when	**General Design Concept:** Specialized teams with different responsibilities, such as monitoring different resources or locations, developing MOEs and MOPs versus evaluating plans using the MOEs and MOPs (Organization) **Experimental Conditions:** Divide team responsibilities associated with planning and updating plans in a variety of ways (e.g., functional versus divisional team structures) **Metrics/ Measures/ Evaluation Criteria:** Team and team member responsibilities Time required to develop and change plans Appropriateness of plans given circumstances **Design Hypotheses:** Operators will develop and evaluate plans faster and more appropriately when teams have specialized responsibilities (e.g., work together regarding same locations and resources, but with specialized roles)	**General Design Concept:** System that tracks real-time changes in weather, terrain, battlefield dynamics , resources, etc., and indicates how they pertain to plans (Technology/ Process) **Experimental Conditions:** Varying degrees of human control over the tracking of information changes (all manual, semi-automatic, all automatic) Manipulations associated with algorithms designed to match information changes with plans (degree of change required to initiate an indicator/ alert that plans may be affected) **Metrics/ Measures/ Evaluation Criteria:** Baseline information Changes to information Sensitivity of system to change (e.g., how much information change is required to lead to an indicator/ alert that plans may be affected) **Design Hypotheses:** Operators change plans faster and more appropriately when changes are tracked automatically and when the system is highly sensitive providing indicators/ alerts upon minimal information change

Design Requirement	Short Term	Medium Term	Long Term
	alerts are highly reliable and credible		

It is worth noting that a subsequent experimentation study conducted in the JFS TDP, and reported in [10], has quantified the impact of selected design concepts listed in Table IV on human performance in JFC. For example, the effect of incorporating blue force tracking (related to the Availability of Baseline and Real-time Information theme in Table IV) in a common operating picture (related to the Information Presentation theme in Table IV) has been studied, by comparing performance in a system with these enhancements with that on a legacy system using only in-service C2 systems in a non-integrated manner. It was found that operator performance in a Joint Fire Support Coordination Cell (JFSCC) with blue force tracking and a common operating picture improved in two tasks: Dissemination of Targeting Information and the Request of Airspace Clearance. Furthermore, there was improvement in terms of the JFSCC operators' confidence in their SA, the trust of the operators in the adequacy and reliability of the system, and lower risk of human error.

7. Conclusions

JFC is a complex process with many different values, priorities, goals, functions and information requirements, all aimed at maximizing the protection and projection of the CF through the sharing of engagement assets and resources during the targeting process. The ability of the CF to effectively and efficiently coordinate fires across and even within military components to support land force operations is a necessity as the battlespace becomes more dynamic, distributed and asymmetric.

Overall, by applying the work-centred exploratory design framework to the future JFC work domain, we were able to identify a multitude of design requirements, which led to the development of an inventory of hundreds of design concepts. While the work was limited in the number of requirements that could be assessed for experimentation potential and further developed into experimental hypotheses and measures, there is an abundance of opportunities for research exploration in the JFC work domain.

Future work is recommended in a number of directions. First, the experimentation proposals generated by the approach described in this paper offer many options for follow-on work to develop detailed plans for conducting human-in-the-loop (HITL) experiments to refine and prove out concepts for optimizing the JFC process through design interventions directed at improvements in technological tools, processes and organizational structure. Such work could also conduct an even fuller examination of the cognitive analysis results to develop a more comprehensive set of options for HITL experiments that fit into a variety of time frames for developing a JFC capability. Second, although some organizational and training requirements have resulted from the work analyses conducted so far, additional analyses are needed to properly develop requirements for the future JFCC in these domains. Such work could look at extending the existing analyses to include: a social-organizational analysis [6] of a JFCC in the context of newly emerging concepts for C4ISR architectures in a net-centric operating environment; and a worker competencies analysis [6] to develop training requirements for operators in the future JFCC. Finally, as a pragmatic measure adopted for restricting the scope of the work to date, the cognitive analyses have not included considerations of coalition or multi-national operations employing a future JFCC. Given the significant multidimensional impact of such operations on the development of an effective JFC system for the CF, it is important to extend the scope of the analyses to include the effects of this broader operating context.

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