Agent-based Decision Support System for the Third Generation Distributed Dynamic Decision-making (DDD-III) Simulator*

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Agent-based Decision Support System for the Third Generation Distributed Dynamic Decision-making (DDD-III) Simulator*

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Abstract

In this paper, we discuss the design and application of a decision support system (DSS) based on the third-generation distributed dynamic decision-making (DDD-III) simulator and contingency theory to increase the organizational cognitive capacity and to facilitate the processes of adaptation. The role of the DSS is to provide mission-monitoring and re-planning information to human decision-makers (DMs) in order to manage the explicit and tacit knowledge, codify them into simple and meaningful formats, and facilitate rapid transfer of knowledge among the DMs. We present an overview of contingency notions that incorporate three relevant components affecting organizational performance: (1) environment, (2) organizational structure, and (3) strategy, and demonstrate that triggers for organizational adaptation require an integrated multi-dimensional concept of congruence ("fit between the organization and mission environment") incorporating structure-environment, strategy-environment, and strategy-structure matches. Due to the elusive nature of knowledge necessary for efficient and effective organizational adaptation, the knowledge management strategies for efficiently codifying and rapidly transferring the knowledge among DMs is central to achieving superior organizational performance. Our DSS is a suitable test-bed to investigate these processes, and thus provides a means for organizations to gain competitive advantage.

I. Introduction

CHANGE is the only certainty in the world of organizations. Changes in technology, social, economic, and political environment, and globalization drive organizations to reconsider the way they operate to cope with the changes. This also applies to military organizations. Many traditional adversarial assumptions, such as known threat, known doctrine, and known order of battle, are now obsolete. Asymmetric warfare, which, in essence, is a means for inferior forces to gain advantage over mightier opponents, is the new re-emerging form of threat. The focus has shifted from peer adversarial wars to major theater wars with small-scale contingencies.

Managing these changes requires a new kind of approach and analysis by the command and control (C2) organizations. In a stable competitive environment, a relatively simple and mechanical organization is adequate for success. However, in a rapidly changing and unpredictable environment, success requires an organization to be flexible, dynamic and to have the ability to renew itself and the capacity to innovate, viz., to adapt.

Contingency theorists (e.g., [Burton et al., 2002], [Chandler, 1962], [Galbraith, 1973]) have argued over the past forty years that the best way to organize depends on the nature of the environment in which the organization operates. That is, organizations whose internal features best match the demands of their environments achieve the best performance. Although the concept that a match, viz., congruence, has positive impact on organizational performance and that incongruence produces negative effects has

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long been accepted, the identification of incongruence conditions that trigger organizational adaptation to regain fit remains elusive. Among the challenges are determining the set of incongruence conditions that produce significant degradation in organizational performance, viz., triggers for adaptation, and recognizing when and how to regain the congruence state, i.e., when and how to adapt, and to assist the DMs in recovering organizational fit.

Organizational decision-making, including the process of recognizing when and how to adapt, is a complex, knowledge intensive process. A DSS is instrumental in facilitating the knowledge management (KM) processes, which, in turn, amplifies the cognitive capacity of human DMs. That is, by relaxing the bounded rationality constraints [Simon, 1982] of human DMs, DSS offers a competitive edge to organizations that use it.

In this paper, we discuss the design and application of a DSS as a means to enhance the organizational cognitive capacity and to facilitate the processes of adaptation from a contingency theory perspective. We employ an agent-based DSS by utilizing the third-generation distributed dynamic decision-making (DDD-III) simulator [Kleinman et al., 1996] as a test-bed. In section II, we present our contingency model, discuss conditions of incongruence that trigger adaptation, and outline knowledge management (KM) strategies to regain congruence. In section III, we begin with the structure and attributes of a mission (i.e., task environment) and of an organization, and we briefly describe the DDD-III simulator. In section IV, we outline the architecture of the DSS, and present the performance and congruence measures that serve as indicators for when and how to adapt. We present simulation results with a discussion in section V. The paper concludes with a summary of findings in section VI.

II. Triggers for Organizational Adaptation to Regain Congruence

A. *Multi-dimensional Contingency Theory*

THE contingency model for organizational design assumes that a match, i.e., congruence, among the relevant environmental, structural, and strategic factors, yields better organizational performance when compared to a mismatch, i.e., incongruence. An early evidence in support of the contingency theory is the study by Chandler in 1962 [Chandler, 1962], wherein he suggests that a functional structure is congruent with a low level of task diversification, and a divisional structure matches a high level of diversification. The study also suggests that the converse cases are also true. In 1978, Miles and Snow [Miles and Snow, 1978] suggest that the environment, structure, and strategy of organizations should fit together to achieve superior performance. Based partly on these models, in 2002, Burton and Obel [Burton et al., 2002] extend the contingency concepts to a multi-contingency model of organizational design, wherein a rule-based expert system is devised that relates organizational size, climate, strategy, technology, environment, and management style to organizational structure, and that can be used to (qualitatively) design an efficient, effective, and viable organization.

In this paper, we explore an integrated view of contingency notions by proposing the following contingency model for organizational design. We consider three components that have been proven to have relevant impact on organizational performance: (1) environment, (2) organizational structure, and (3) strategy. Our integrated multi-dimensional concept of congruence incorporates all three possible congruence conditions: *structure-environment, strategy-environment, and strategy-structure*.

B. *Triggers for Adaptation*

The extreme misfit hypotheses [Burton et al., 2002] state that extreme misfits are those incongruence conditions that have significant effect on organizational performance. Building on this idea, we develop the extreme incongruence conditions that necessitate organizational adaptation to regain congruence, viz., *triggers for adaptation*. Differing from the rule-based and qualitative nature of the extreme misfit hypotheses, our triggers for adaptation are *quantitative (analytical) measures* suitable for fast paced organizations facing highly dynamic mission environments.

We assert that there exist certain levels of incongruence, be it in the context of structure-environment, strategy-environment, or strategy-structure, that necessitate organizational adaptation to retain a satisfactory level of performance. That is, only when an extreme misfit in any of the pairs belonging to the multi-contingency model is coupled with significant drops in organizational performance below acceptable levels, triggers for organizational adaptation, in the form of strategy adjustment, structural reconfiguration, or both, are invoked to recover congruence. A detailed discussion on the quantitative measures of triggers for adaptation is presented in sub-sections IV-C through IV-E.

C. *Knowledge Management*

A key criterion in choosing a suitable form of organizational adaptation is effective organizational diagnosis and analysis. The organizational diagnosis and analysis involve identifying the symptoms, localizing the problems, generating hypotheses, and formulating relevant action strategies. Effectively managing the information related to the mission environment, organizational structure, and strategy is imperative for an effective and efficient organizational diagnosis.

The management of knowledge within the organization, however, is also dependent on the types of organizational changes being considered. As described in [Bloodgood and Salisbury, 2001], there exist two general classifications of knowledge, explicit and tacit. Explicit knowledge is one that is easily expressed, and transferred; such as documented knowledge regarding rules of engagement, evacuation procedures, etc. Tacit knowledge is one that is difficult to articulate and express; such as any unwritten rules within an organization. Knowledge management, which centers around how explicit and tacit knowledge may best be codified into specified formats, is operationalized through the use of three general knowledge management strategies [Bloodgood and Salisbury, 2001]: knowledge creation, knowledge transfer, and knowledge protection. Knowledge creation, which focuses on creativity, experimentation, and, to a significant extent, creating a shared understanding within the group to construct new knowledge, is suitable for creative and innovative organizations. Knowledge transfer, which stresses on rapidly disseminating knowledge through the organization in an effort to utilize it to its fullest extent as quickly as possible, is more suitable for fast paced organizations facing highly dynamic mission environments. Knowledge protection, which focuses on maintaining knowledge in its original and constructive state, i.e. not losing it or allowing it to become altered or obsolete and keeping knowledge from unauthorized transfer to other organizations, i.e., using security and legal measures, is more suitable for organizations, wherein secrecy is critical to the success or even the survival of the organizations.

In this study, we are focusing on military organizations facing the challenges of coping with the increasingly agile and uncertain environments. In general, the knowledge management strategies that are suitable for such organizations involve all or mixtures of the three types, viz., knowledge creation, transfer, and protection. However, due to limited organizational resources, emphasizing on all three knowledge management strategies simultaneously may be prohibitive. Thus, the nature of the missions dictates the optimal choice of knowledge management strategies. Here, we consider relatively fast paced missions with a high degree of uncertainty, which require the organizations to not only react quickly but also implement new strategies and/or structures to cope with the highly dynamic mission environments. We assume, for simplicity, that all communication channels are secure; thus, knowledge protection strategy already exists. Consequently, we will focus on the processes of knowledge creation and transfer as a means to gain and sustain competitive advantage.

III. Modeling Missions and Organizations

A. *Structures and Attributes of Missions and Organizations*

A mission task T_i (or simply i) is characterized by the following basic attributes: (i) task arrival time, a_i (time at which the task appears in the mission scenario); (ii) task processing time window, t_{a_i} (maximal time available from the start of task execution to its finish; this time window is used to synchronize assets assigned to this task; (iii) estimated task processing time, t_i (the interval between the time the first asset starts executing the task and the time at which the last asset finishes the task; the task processing time must not exceed the task processing time window, $t_i \leq t_{a_i}$); (iv) accuracy of task processing, α_i, which depends on how well the resource requirements of a task are matched by the resources allocated to the task; (v) task start time, s_i (the time that a task execution is started, which is obtained during mission execution); (vi) geographical location of task, (x_i, y_i); (vii) resource requirement vector $[r_{i1}, r_{i2}, ..., r_{iL}]$, were r_{ij} is the number of units of resource of type l required for successful processing of task i (l =1,. . . ,L, where L is the number of resource types); this vector defines the resources required to successfully process (attack) the task; and (viii) task value, ω_i (task value reflects the fact that not all tasks are equally important). In addition, there exists a dependency diagram that details the interrelationships among tasks: (i) task precedence; (ii) inter-task information flow; and (iii) input-output relationships between tasks, i.e., the *task graph*. This directed acyclic task-precedence graph represents a plan to execute the mission.

A platform (asset) represents a physical entity of an organization that provides resource capabilities used to process the tasks. Each platform P_m (or simply m) ($m = 1, \ldots, K$) has several attributes that uniquely define this platform: (i) sub-platforms, i.e., additional assets that reside on-board a parent platform that only become active after being 'launched' from the parent; (ii) ownership, i.e., only owners of the platforms are able to move, carry a pursuit or attack with them, or launch sub-platforms; owners of parent platforms are not necessarily owners of the sub-platforms; (iii) sensors, i.e., specify effectiveness ranges for task detection, measurement, and identification or classification; (iv) geographical location, i.e., (x_m, y_m); (v) maximum velocity v_m, defines how fast a platform can travel; and (vi) resource capability vector $[\hat{r}_{m1}, \hat{r}_{m2}, ..., \hat{r}_{mL}]$, where $\hat{r}_{ml}$ specifies the number of units of resource type l available on platform m. A platform can be used to attack any task, but the ranges of the platform's weapons depend on the task type or class. Assets must be routed among task locations to execute the assigned tasks. Assets can begin to process the same task at different times, but must be synchronized to complete a task in a specified task processing window. For each asset-task pair, the asset-task engagement time, e_{mi}, is specified. Further details on the DDD-III structures to model tasks and platforms can be found in [Kleinman et al., 1996].

A decision-maker (DM), DM_j (or simply j), is an entity with information-processing, decision-making, and operational capabilities that can control the necessary resources to execute mission tasks, provided that it does not violate the concomitant capability thresholds. As a consequence of decentralization in large-scale systems, each DM only has access to a portion of organization's resources. The operational capabilities of a DM is defined by assets he owns. The DM-asset allocation matrix is defined by

$$w_{jm} = \begin{cases} 1, \text{ if asset } P_m \text{ is allocated to } DM_j \\ 0, \text{ otherwise} \end{cases} \tag{1}$$

We assume that each asset is assigned to a single DM, and cannot be shared during the mission so that $\sum_{j=1}^{D} w_{mj} = 1$.

The processing of a mission by an organization is identified by specifying asset-task assignment, and the corresponding DM-task allocation matrix:

$$y_{mi} = \begin{cases} 1, \text{ if asset } P_m \text{ is assigned to task } T_i \\ 0, \text{ otherwise} \end{cases} \tag{2}$$

$$u_{ji} = \begin{cases} 1, \text{ if asset } DM_j \text{ is assigned to task } T_i \\ 0, \text{ otherwise} \end{cases} \tag{3}$$

The asset-task assignment matrix specifies the necessary interaction among assets when processing a task. This interaction necessitates coordination among DMs that have ownership of these assets; the DMs serve as information/decision/action carriers.

B. The Third-generation DDD Simulator

The third generation distributed dynamic decision-making (DDD-III) simulator [Kleinman et al., 1996] provides a flexible, controllable research paradigm, which allows researchers to examine the interactions between the task (or mission) structure, and the way in which the organization tasked to execute the mission is structured. The DDD-III allows for constraints and manipulations of organizational structures, such as authority, information, communication, resource ownership, task assignment, etc., as well as mission and environmental structures, such as air, sea, and ground environment, a variety of task

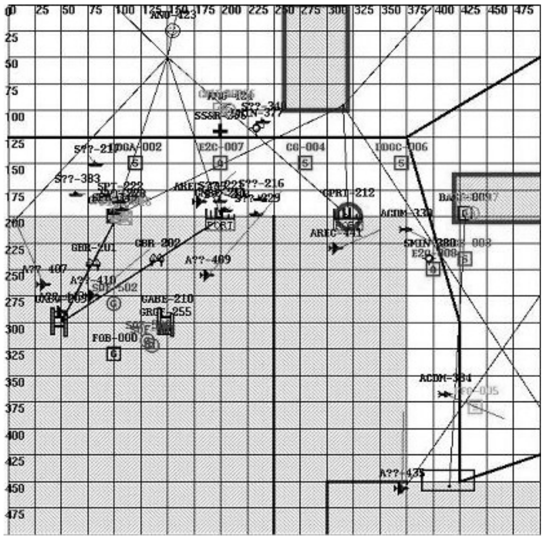

Fig. 1. A Screen-Shot from the A2C2 Experiment 8

classes, and controllable platforms with sub-platforms, sensors, and weapons via a scripted organizational structure and mission scenario.

A typical experiment within the DDD-III framework involves a group of subject matter experts, who act as a team of DMs – in a hierarchical or networked organization, in an environment that simulates a military operation. During the real-time playout of an experimental run, tasks appear, move (maneuver), and disappear according to the scripted mission scenario. The characteristics of each task – its class, attributes, precedence constraints, and resource requirements – can be tailored to specify a threat (such as a hostile fighter, minefield, etc.) and to create intra-team conflicts for assets needed in the execution of those tasks. A DM, through the use of his asset capability, is able to detect, measure, identify, pursue, and eventually process tasks. The DDD scenario requires the players to follow a set of predefined mission requirements, while simultaneously defending one or more 'penetration zones', and possibly their own assets, against potential land, sea, and air adversaries. Through the scenarios, the designers craft an experiment to uncover key issues in the organization's decision-making and coordination processes. A typical screen-shot of a DDD-III experiment is shown in Fig. 1. The use of DDD simulator in conducting model-driven C2 experimentation is described in (e.g., [Kleinman et al., 2003] and [Kleinman et al., 1996]).

IV. The Decision Support System

A. Architecture of the Decision Support System

THE extant of information and processes to be monitored, re-evaluated, and communicated during the course of mission execution can be overwhelming for human DMs having bounded rationality constraints. The role of the DSS is to provide synthesized information to human DMs in terms of managing the explicit and tacit knowledge, codifying them into simple and meaningful formats, and facilitating rapid transfer of knowledge among the DMs.

The first aspect of embedding a DSS into the DDD simulator is to enable experimentation within information-rich environments. The current DDD simulator module is very limited in its information dimension, i.e., static attributes of the objects are merely numbers whereas the more realistic and informative graphical data are needed. However, the necessary extensive patching to DDD module to improve its capabilities is not feasible. Therefore, linking the DDD simulator with a web-based DSS is seen as a value-added solution that enables numbers (i.e., DDD-attributes) to be transferred to the DSS and re-interpreted from points to imagery, historical data, plans, templates, etc. This allows modification

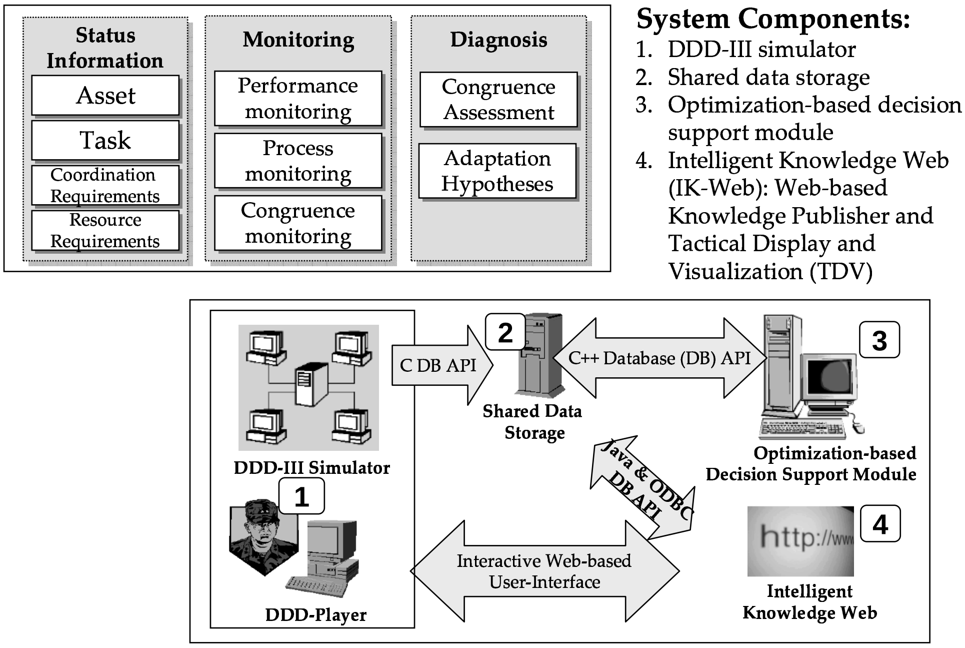

Fig. 2. The Architecture of the Decision Support System

of the information in the C2 experiments as a multi-dimensional concept, and allows it to be perusable via a web interface (along with all of the structures that a web-based DSS brings, e.g., [SPAWAR, 2003]). The second aspect is to increase the cognitive elements of the C2 experiments. This is linked to some extent with immersing players in a richer information environment/context (more content) that must be assimilated to understand possible options, paths through the task (mission) graph, asset requirements, etc. The third, and perhaps the most important aspect, is to enable human DMs, facing a highly dynamic and uncertain environment, to recognize when and how to adapt in order to cope with the demands of the mission environment.

In view of these observations, the objectives of our DSS are to facilitate effective knowledge creation (codification) and presentation (distribution of value-added information) within a team setting, so as to augment human decision-making in highly dynamical uncertain mission environments. We operationalize the process of codifying both the explicit and tacit knowledge by embedding an agent-based decision support module, which employs optimization models and algorithms described in ([Levchuk et al., 2002a], [Levchuk et al., 2002b], and [Meirina et al., 2003]), within the DDD. The effective transfer of knowledge is operationalized via a web-based graphical user interface, which displays the monitoring data and decision support information; it is an intermediary between the DDD simulator (”the environment”) and the human DMs (”the organization”). The DSS enables human DMs to generate and analyze various options and strategies to successfully achieve their mission objectives.

The agent-based DSS for the DDD-III simulator consists of four component modules: (1) the DDD-III Simulator, (2) Shared Data Storage, (3) Optimization-based Decision Support Module (Agent), and (4) Intelligent Knowledge Web (IK-Web): Web-based Knowledge Publisher and Tactical Display and Visualization (TDV), as shown in Fig.2. This interlinked architecture enables the DSS to provide an effective on-line support for the human DMs during the course of mission execution.

The web-based displays are organized into three categories: (1) *Critical Information on Tasks and Assets*, which is intended to provide a quick look at the most urgent tasks, e.g., five most critical tasks (ordered according to time-criticality, distance-based threat level, etc.) and current asset information; (2) *Decision Support Information*, which is designed to: (a) provide the team with information on current tasks and

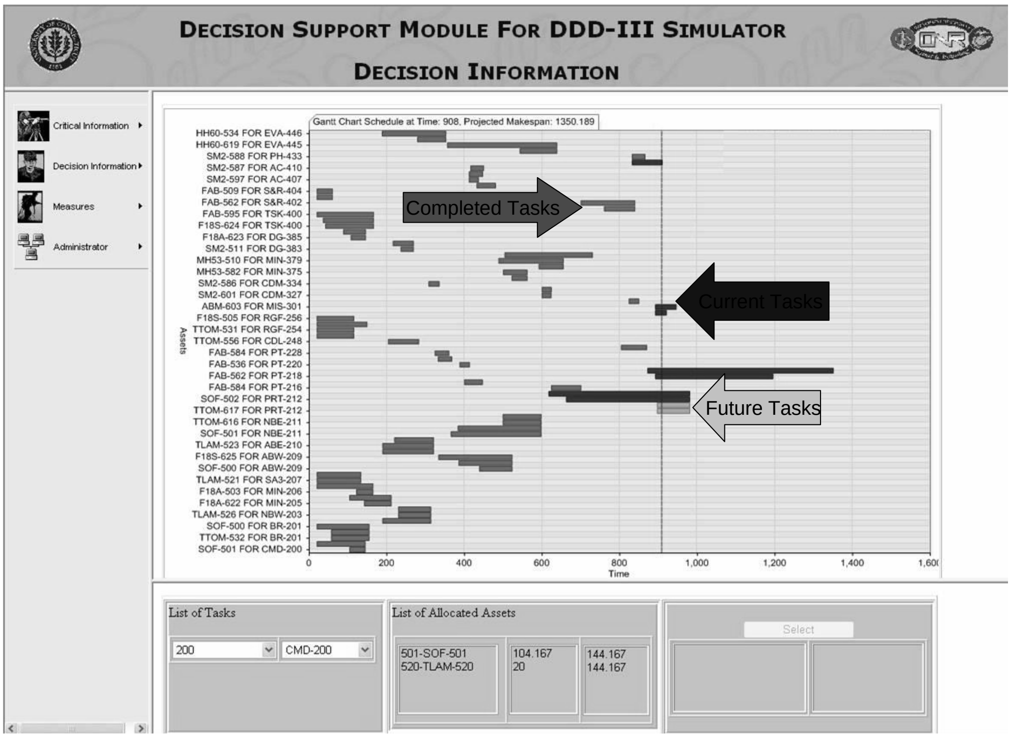

Fig. 3. Gantt-chart Display in the Decision Support System

available assets, (b) aware of task dependencies (i.e., precedence constraints), (c) provide near-optimal dynamic schedule (in terms of time, asset efficiency, accuracy, etc.), (d) provide alternative asset-packages for each task, and (e) monitor the status of weapons and assets; and (3) *Measures*, whose goals include: (a) provide the team with performance measures (e.g., accrued task gain, task completion) and process measures (e.g., internal and external workload), (b) assist the team in recognizing potential problems (e.g., unbalanced workload, high rate of attrition of re-usable assets, low task completion rate), and suggest corrective actions.

An example of a display to facilitate the re-interpretation from data points to imagery of organizational plans, is the Gantt-chart display. This display shows the information of 'who should do what, when, and with which assets'; see Fig.3. One example of a display designed to increase the cognitive element of C2 experiments is the overall asset availability display covering not only the assets owned by a single DM, but also those of other DMs within his range of operation; see Fig.4. Results on the integrated congruence assessments or their derivatives, which are detailed in the following sub-sections, assist the human DMs in recognizing when and how to adapt to recover the desired organizational performance; see Figs. 5, 6, 7, and 8. These displays are organized in the *Measures* category.

B. An Integrated Congruence Concept: An Overview

We believe that the key to successful organizational adaptation to recover congruence is one of relating congruence assessment with performance measures. In [Donaldson, 2000], Donaldson argues that performance degradation drives organizational change to regain acceptable performance. We agree, in substance, with this observation. What is lacking, is a causal link, which connects a drop in organizational performance with the source of the degradation. We propose an organizational diagnostic framework that relates the symptoms with the causes; viz., by concurrently monitoring both the metrics of performance and congruence assessment, we can link certain performance drops with specific incongruence conditions. Subsequently, we can prescribe organizational change to remedy the incongruence and, thus, regain satisfactory performance. In the following, we quantify the multi-dimensional concept of congruence that relates the structure-environment, the strategy-environment, and the strategy-structure fit.

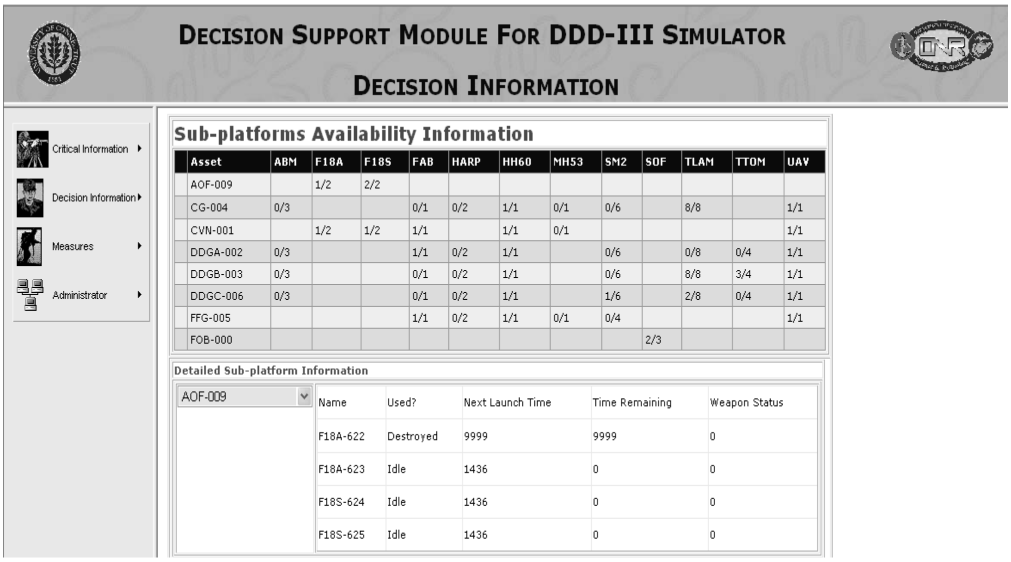

Fig. 4. Asset Availability Display in the Decision Support System

By environment, we mean all factors outside the organization that have potential impact on the organization. For our purposes, the task structure, i.e., resource requirements, task interdependencies, and the spatial-temporal loading (locations, trajectories, and arrival times) of tasks, describes the environment. We represent the environment by a two-dimensional attribute-vector for the task structure: complexity (e.g., number of tasks, types of resources, resource requirements), and uncertainty (e.g., uncertainty in resource requirements, task dependencies). By organizational structure, we wean formal arrangements of structures and processes, which include the decision-making structure, e.g., hierarchy, matrix, heterarchy; the allocation of assets and functions to DMs, e.g., functional, divisional; and the communication structure, e.g., hierarchy, network. By organizational strategy, we mean a stream of decisions about how assets are allocated to meet mission demands and opportunities subject to organizational constraints. The strategy variables include, for example, the DM-task allocation, the task execution schedule, and so on.

C. *Performance Measures*

1) Accrued task gain: A combined measure that reflects the task accuracy and timeliness tradeoff is the task gain. The gain of a task T_i is defined as the execution accuracy multiplied by the task value:

$$g_i = \alpha_i \cdot \omega_i$$

To visualize the dynamic pattern of total gain achieved by an organization over time, we define the accrued task gain, $G(t)$, as an aggregate of task gains achieved by time t. We increment the gain function when each task T_i completes its execution (at time $s_i + t_i$) with a task gain of g_i. Therefore, the accrued task gain is computed as follows:

$$G(t) = \sum_{i=1}^{N} g_i \delta_i(t) \tag{4}$$

where

$$\delta_i(t) = \begin{cases} 1, \text{ if the task } T_i \text{ has been completed by } t \\ 0, \text{ otherwise} \end{cases}$$

2) Aggregate Loss of Reusable Assets: One measure of organizational effectiveness is its aggregate loss of reusable assets during the course of mission execution. It is defined as:

$$L(t) = \sum_{m=1}^{M} \gamma_m(t) \tag{5}$$

where M is the number of assets, and

$$\gamma_m(t) = \begin{cases} 1, \text{ if the asset } P_m \text{ is a reusable asset and is lost by time } t \\ 0, \text{ otherwise} \end{cases}$$

An effective organization accomplishes more at a smaller price, viz., the lower is the reusable asset loss, the more effective is the organization.

D. Congruence Measures

1) Congruence between DM-resource allocation and task-resource requirements: One measure of structure-environment congruence is the closeness between the DM-resource allocation and the task-resource requirements. Let $\mathrm{R}(t) = [r_{il}(t)] \in I^{N(t)\times L}$ (I is the set of non-negative Integers) be the task-resource requirement matrix at time t, where r_{il} is as defined in III-A, and L denotes the number of resource types. $N(t) = \sum_{i=1}^{N} \mathrm{u}(t - a_i)$ represents the number of tasks at time t, where

$$\mathrm{u}(x) = \begin{cases} 1, \text{ if } x \geq 0 \\ 0, \text{ otherwise} \end{cases}$$

Let $\hat{\mathrm{R}}(t) = [\hat{r}_{ml}(t)] \in I^{M\times L}$ be the asset-resource allocation matrix at time t, where $\hat{r}_{ml}$ is as defined in III-A, and M is the number of assets in the organization. Let the matrix $\mathrm{W}(t) = [w_{jm}(t)] \in I^{D\times M}$ define the DM-asset allocation at time t (presumably, the organization can shift its DM-asset allocation structure during the mission), where w_{jm} is as defined in Eq. (1). Thus, the matrix $\tilde{\mathrm{R}}(t) = \mathrm{W}(t) \times \hat{\mathrm{R}}(t) = [\tilde{r}_{jl}(t)] \in I^{D\times L}$ defines the DM-resource allocation matrix at time t, where $\tilde{r}_{jl} = \sum_{m=1}^{M} w_{jm} \cdot \hat{r}_{ml}$ (w_{jm} and $\hat{r}_{ml}$ are as defined in III-A), and D is the number of DMs in the organization. The measure of closeness, i.e., the congruence between $\tilde{\mathrm{R}}(t)$ and $\mathrm{R}(t)$, at time t, is defined by:

$$C^{OE,1}(t) = \tilde{f}(t) - f(t) \tag{6}$$

where $f(t)$ defines the average value of the number of resource types required across all tasks at time t:

$$f(t) = \frac{1}{N(t)} \sum_{i=1}^{N} \xi_i(t)\mathrm{u}(t - a_i)$$

Here

$$\xi_i(t) = \begin{cases} 1, \text{ if } r_{il}(t) > 0 \\ 0, \text{ otherwise} \end{cases}$$

and $\tilde{f}(t)$ denotes the average number of resource types allocated across all DMs at time t:

$$\tilde{f}(t) = \frac{1}{D} \sum_{j=1}^{D} \tilde{\xi}_i(t)$$

where

$$\tilde{\xi}_i(t) = \begin{cases} 1, \text{ if } \tilde{r}_{il}(t) > 0 \\ 0, \text{ otherwise} \end{cases}$$

If the average resource types required per task, $f(t)$, is significantly higher than the average resource types allocated per DM, $\tilde{f}(t)$, the DMs are expected to coordinate among themselves during task execution. Excessive DM-DM coordination is undesirable due to excessive delays it might cause. On the other hand, if the value of $f(t)$ is consistently much smaller than $\tilde{f}(t)$, the distance between them, i.e., $C^{OE,1}(t)$, indicates a high degree of excess organizational capability for the given mission, viz., inefficiency. Thus, the smaller the value of $C^{OE,1}(t)$ is (as long as $C^{OE,1}(t) \geq \overline{C}^{OE,1}(t)$, where $\overline{C}^{OE,1}(t)$ denotes an adequate margin on $C^{OE,1}(t)$), the better is the congruence match between the structures of the DM-resource allocation and the task-resource requirements.

Congruence between the organizational structure and the task structure, i.e., the environment, can also be measured by surrogate measures such as the external coordination workload. External coordination, one of the indicators for coordination-related overhead in an organization, is the inter-DM dependence that results from cooperative (synchronized) processing of a task by multiple DMs. This direct DM-DM coordination between two DMs DM_j and DM_k is the aggregated time associated with simultaneous processing of the same set of tasks (see Eq. (3)):

$$\hat{e}_{jk}(t) = \sum_{i=1}^{N(t)} \min\left(u_{ji}, u_{ki}\right) t_i \tag{7}$$

The external coordination workload of DM_j at time t is the sum of its direct coordination with other DMs:

$$e_j(t) = \sum_{k=1, k\neq j}^{D} \hat{e}_{jk}(t)$$

We define a surrogate measure for the structure-environment congruence at time t as the root-mean-square of external coordination measures of all DMs in the organization:

$$C^{OE,2}(t) = \sqrt{\frac{1}{D}\sum_{j=1}^{D} e_j^2(t)} \tag{8}$$

This measure accounts for both the mean and the variance of external coordination, and, consequently, provides a measure of balance of the aggregated external coordination of DMs at time t. The better an organizational structure is matched to its task structure, i.e., mission, the better will be its external coordination balance among the DMs.

2) Congruence between spatial-temporal-loading of organization and mission: The changes in arrival times, locations and trajectories of tasks require the organization to adjust its spatial-temporal-loading mechanism among its DMs. The closeness between the two can be used as a measure of strategy-environment congruence. Let $\underline{a}(t) = [a_1, a_2, \cdots, a_{N(t)}]$ be the vector of arrival times and let $\underline{s}(t) = [s_1, s_2, \cdots, s_{N(t)}]$ be the vector of start times of all tasks at time t. A measure of temporal strategy-environment congruence, at time t, is the distance between $\underline{a}(t)$ and $\underline{s}(t)$ as operationalized through latency:

$$\tau_i = s_i - a_i$$

The latency of a task T_i is the time from the appearance of a task to the time when its execution begins. Thus, temporal strategy-environment congruence is the average task latency, at time t, as defined by:

$$C^{SE,1}(t) = \frac{1}{N(t)}\sum_{i=1}^{N} \tau_i \mathrm{u}(t - s_i) \tag{9}$$

where $N(t)$ is as previously defined. The smaller is the value of $C^{SE,1}$, the better is the congruence match between the temporal organizational strategy and the temporal demand of the environment. However, since this measure does not account for missed tasks, too small a value for $C^{SE,1}$ can also indicate potential problems.

The average traveling distance of assets involved in the execution of task T_i is defined as:

$$\overline{d}_i = \frac{1}{M_i}\sum_{m=1}^{M_i} \|\underline{z}_i - \underline{\hat{z}}_m\|_2$$

where M_i is the number of assets involved in task execution, and $\underline{z}_i = (x_i, y_i)$ and $\underline{\hat{z}}_m = (\hat{x}_m, \hat{y}_m)$ denote the locations of task T_i and the asset P_m, respectively, at the time of task-asset allocation. The measure of spatial strategy-environment congruence, at time t, is defined as:

$$C^{SE,2}(t) = \sqrt{\frac{1}{N(t)}\sum_{i=1}^{N(t)} \overline{d}_i^2} \tag{10}$$

The smaller is the value of $C^{SE,2}$, the better is the congruence match between the spatial organizational strategy and the spatial demand of the environment.

3) Congruence between DM-resource utilization and DM-resource allocation: One measure of strategy-structure congruence is the closeness between the DM-resource utilization and the DM-resource allocation, i.e., $\tilde{\mathrm{R}}(t) = [\tilde{r}_{jl}(t)] \in I^{D\times L}$ matrix as previously defined. Let $\mathrm{U}(t) = [u_{ji}(t)] \in B^{D\times N(t)}$ ($B \equiv (0,1)$) be the DM-task assignment matrix, where D is the number of DMs in the organization and $N(t)$ is the number of tasks at time t, and u_{ji} is as defined in Eq. (3). Recall that $\mathrm{R}(t) = [r_{il}(t)] \in I^{N(t)\times L}$ matrix defines the task-resource requirements at time t. Therefore, $\tilde{\mathrm{U}}(t) = \mathrm{U}(t) \times \mathrm{R}(t) = [\tilde{u}_{jl}(t)] \in I^{D\times L}$ is the matrix that defines the DM-resource utilization, where $\tilde{u}_{jl}(t) = \sum_{i=1}^{N} u_{ji} r_{il} \mathrm{u}(t - a_i)$. Thus, the distance between $\tilde{\mathrm{U}}(t)$ and $\tilde{\mathrm{U}}(t)$ defines a measure of closeness between the DM-resource utilization and the DM-resource allocation at time t. However, a direct comparison yields a bias towards $\tilde{R}(t)$, since typically $\|\tilde{\mathrm{U}}(t)\|_F \gg |\tilde{\mathrm{R}}(t)\|_F$, where the Frobenious norm is utilized to measure the matrix size. The following equalizes $\tilde{\mathrm{U}}(t)$ and $\tilde{R}(t)$:

$$\tilde{\tilde{\mathrm{U}}}(t) = \frac{\|\tilde{\mathrm{R}}(t)\|_F}{\|\tilde{\mathrm{U}}(t)\|_F}\tilde{\mathrm{U}}(t)$$

where the Frobenious norm is defined as:

$$\|\tilde{\mathrm{R}}\|_F = \sqrt{\sum_{j=1}^{D}\sum_{l=1}^{L} \tilde{r}_{jl}^2}$$

Thus, the closeness between the DM-resource utilization and the DM-resource allocation is measured as:

$$C^{SO,1}(t) = \left\|\tilde{\mathrm{R}}(t) - \tilde{\tilde{\mathrm{U}}}(t)\right\|_F \tag{11}$$

The smaller is the value of $C^{SO,1}(t)$ (as long as $C^{SO,1}(t) \geq \overline{C}^{SO,1}(t)$, where $\overline{C}^{SO,1}(t)$ denotes an adequate margin on $C^{SO,1}(t)$), the better is the congruence match between the strategy of the DM-resource utilization and the structure of the DM-resource allocation.

Congruence between organizational strategy and structure can also be measured by surrogate measures such as the internal coordination workload. The internal coordination workload of DM_j is defined as the aggregated workload of operating assets assigned to the DM:

$$c_j(t) = \sum_{m=1}^{M} w_{jm}\left(\sum_{i=1}^{N(t)} y_{mi}\right)$$

where the DM-asset allocation w_{jm} and the asset-task assignment y_{mi} are as defined in Eqs. (1) and (2), respectively. Here, without loss of generality, we assume that the workload associated with executing task T_i using asset P_m is 1. We define a surrogate measure for the strategy-structure congruence at time t as the root-mean-square of the internal coordinations of all DMs in the organization:

$$C^{SO,2}(t) = \sqrt{\frac{1}{D}\sum_{j=1}^{D} c_j^2(t)} \tag{12}$$

This provides a measure of balance of the aggregated internal coordinations of DMs at time t. The better an organizational strategy is matched to its structure, the better will be its internal coordination balance among the DMs.

E. Congruence as a Relative Measure

Given two organizations $\mathbf{O}_1$ and $\mathbf{O}_2$ that operate on the same mission $\mathbf{M}$, we say that organization $\mathbf{O}_1$ is structurally more congruent with this mission than $\mathbf{O}_2$, if $|C^{OE,1}(\mathbf{O}_2) - C^{OE,1}(\mathbf{O}_1)| > 0$ and $|C^{OE,2}(\mathbf{O}_2) -$

$C^{OE,2}(\mathbf{O}_1)| > 0$. The differences in the degrees of the structure-environment congruence between $\mathbf{O}_1$ and $\mathbf{O}_2$ is defined by:

$$\Delta^{OE,m} = \begin{cases} 1, \text{ if } \psi > 1 \\ \psi, \text{ if } -1 \leq \psi \leq 1 \\ -1, \text{ if } \psi < -1 \end{cases} \tag{13}$$

Here

$$\psi = \frac{C^{OE,m}(\mathbf{O}_2) - C^{OE,m}(\mathbf{O}_1)}{C^{OE,m}(\mathbf{O}_2)}$$

where $m = 1$ or 2. This definition also applies to determining the differences in the degrees of strategy-environment and strategy-structure congruence between the two organizations, i.e., $\Delta^{SE,m}$ and $\Delta^{SO,m}$. Furthermore, let the difference in the performance between $\mathbf{O}_1$ and $\mathbf{O}_2$ be:

$$\Delta^{\theta} = \begin{cases} 1, \text{ if } \varphi > 1 \\ \varphi, \text{ if } -1 \leq \varphi \leq 1 \\ -1, \text{ if } \varphi < -1 \end{cases} \tag{14}$$

where

$$\varphi = \frac{\theta(\mathbf{O}_2) - \theta(\mathbf{O}_1)}{\theta(\mathbf{O}_2)}$$

and $\theta \equiv \tau, \tau_m, G$ or L define the various performance measures defined in IV-C.

Continuing on the discussion of triggers for adaptation from II-B, we say that large values of $\Delta^{OE,m}$, $\Delta^{SE,m}$, or $\Delta^{SO,m}$ warrant organizational adaptation, in the form of strategy adjustment, structural reconfiguration, or both, when the following is true:

$$|\Delta^{\theta} - \overline{\Delta}^{\theta}| \gg 0 \tag{15}$$

where $\overline{\Delta}^{\tau}$, $\overline{\Delta}^{\tau_m}$, $\overline{\Delta}^{G}$, and $\overline{\Delta}^{L}$ are allowable performance decrements in organization $\mathbf{O}_2$. Thus, the values of $\Delta^{OE,m}$, $\Delta^{SE,m}$, or $\Delta^{SO,m}$ matter only when the organization $\mathbf{O}_2$ fails to satisfy its performance targets. That is, only, when its average task latency, defined in Eq. (9), significantly increases beyond an acceptable level, i.e., $\Delta^{\tau}(\mathbf{O}_2, t) \gg \overline{\Delta}^{\tau}$, or when its accrued task gain, defined in Eq. (4), significantly falls below an intended target at time t, i.e., $\Delta^{G}(\mathbf{O}_2, t) \ll \overline{\Delta}^{G}$, or when it suffers from an alarmingly high loss of reusable assets, defined in Eq. (5), i.e., $\Delta^{L}(\mathbf{O}_2, t) \gg \overline{\Delta}^{L}$, etc., it becomes necessary to recover the desired organizational performance, i.e., $|\Delta^{\theta} - \overline{\Delta}^{\theta}| \approx 0$ via organizational adaptation. Thus, the extreme misfits in the sense of C^{OE}, C^{SO}, C^{SE}, or any combinations of the three, that occur concurrently with a significant degradation in performance, specify the types of organizational adaptation needed to regain the congruence, and consequently, the desired organizational performance.

V. Results and Discussion

To illustrate our congruence concepts, we utilize the divisional (**D**) and functional (**F**) structures from the A2C2 Experiment 8 ([Kleinman et al., 2003] and [Levchuk et al., 2003]) executing a divisional (**d**) scenario from the same experiment. In a divisional organization, each DM controls multiple types of resources, whereas in a functional organization, each DM controls a single resource type. Tasks, in a divisional scenario, require multiple types of resources to complete. Thus, the divisional scenario was designed to create a matched situation, in a structure-environment sense, for the **Dd** (divisional structure and divisional scenario), and to create a mismatch for the **Fd** (functional organization and divisional scenario) case. Unlike, the A2C2 experiment, wherein a human-in-the-loop experiment was conducted, in this paper, we utilize a computational agent, described in [Meirina et al., 2003], to run the mission scenario in the DDD-III simulator.

The underlying assumption in [Levchuk et al., 2003] states that, although the DM-DM coordination is essential to achieve good organizational performance due to the distributed nature of the information required for decision-making, excessive DM-DM communication and coordination are harmful to performance due to increases in task processing workload/overhead. The structure-environment pairs

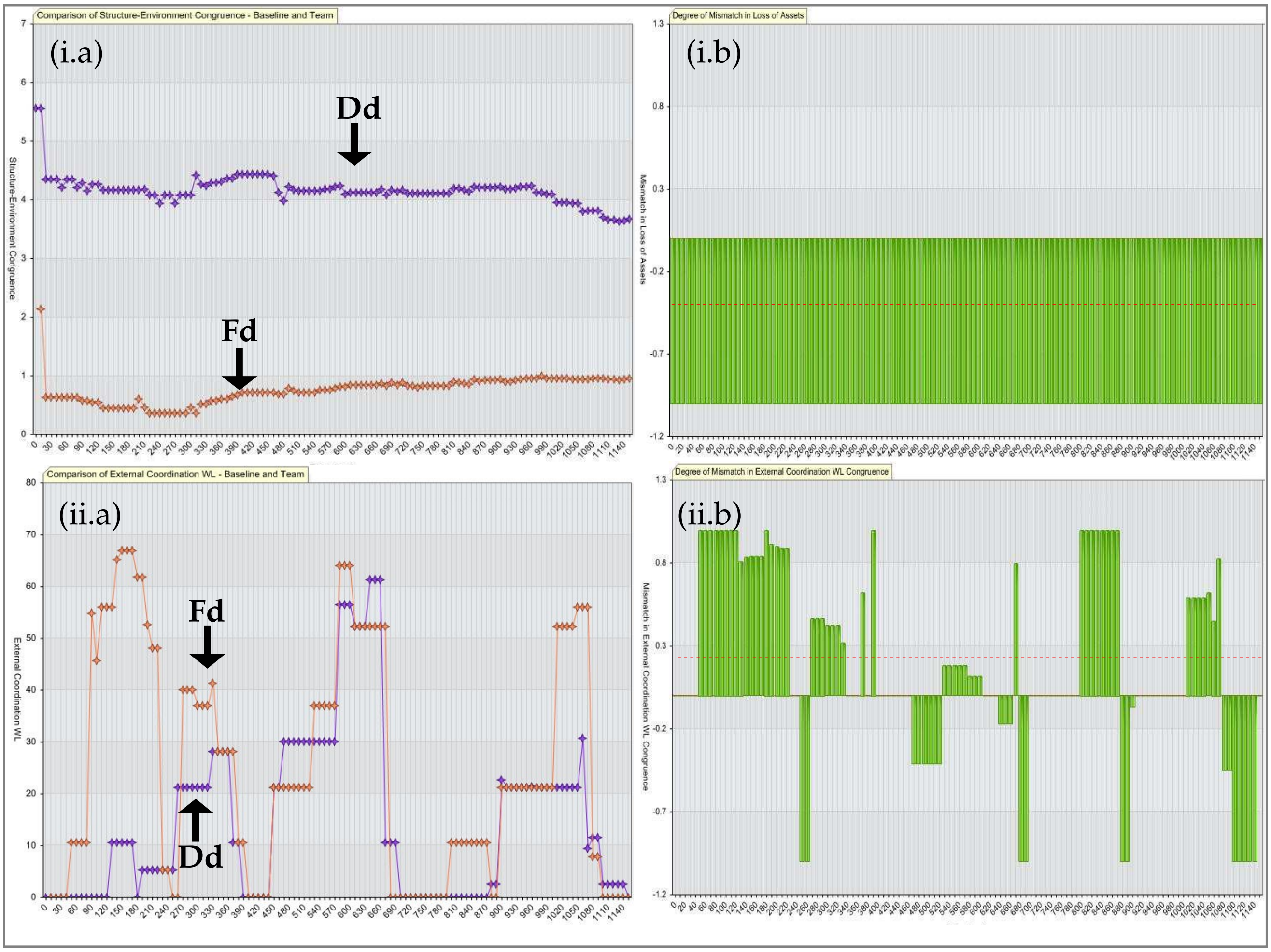

Fig. 5. Structure-Environment Congruence:
(i.a) Degree of Congruence between the DM-resource Allocation and the Task-resource Requirements, $C^{OE,1}(t)$,
(i.b) Degree of Structure-Environment Congruence Difference between the **Dd** and the **Fd** Pairs, $\Delta^{OE,1}(t)$,
(ii.a) External Coordination Workload, $C^{OE,2}(t)$, and
(ii.b) Degree of External Coordination Workload Difference between the **Dd** and the **Fd** Pairs, $\Delta^{OE,2}(t)$.

in the **Dd** and the **Fd** cases manipulate the DM-DM coordination requirements, thus, prompting the structure-environment incongruence for the **Fd** case. Experimental results show that, indeed, the **D** structure out-performs the **F** structure on mission **d**, in terms of accrued gain, as well as the workload balance. In this example, we show that by minimizing the cost to coordinate via a DSS, the superiority of the **D** structure over the **F** structure is also mitigated. By doing so, we have shown that structure-environment incongruity alone does not warrant structural adaptation. That is, triggers for organizational adaptation have to emerge from an integrated multi-dimensional concept of congruence that incorporates structure-environment, strategy-environment, and strategy-structure conditions, instead of a one-dimensional structure-environment match.

A. Structure-Environment Congruence Assessment

We measure the structure-environment congruence in terms of the closeness between the organizational DM-resource allocation and the task-resource requirements demanded by the mission scenario, i.e., $C^{OE,1}(t)$ (Eq. (6)), and the external coordination workload of the organization, i.e., $C^{OE,2}(t)$ (Eq. (8)). Results in Fig. 5.i.a and 5.i.b indicate the structure-environment mismatch, as expected from the experimental design. Fig. 5.i.a indicates that the multi-resource tasks in scenario **d** pose no challenge to multi-resource DMs in organization **D**; i.e., the difference between the average resource types allocated per DM and the average multi-resource types required per task is small. On the other hand, the (nearly-)

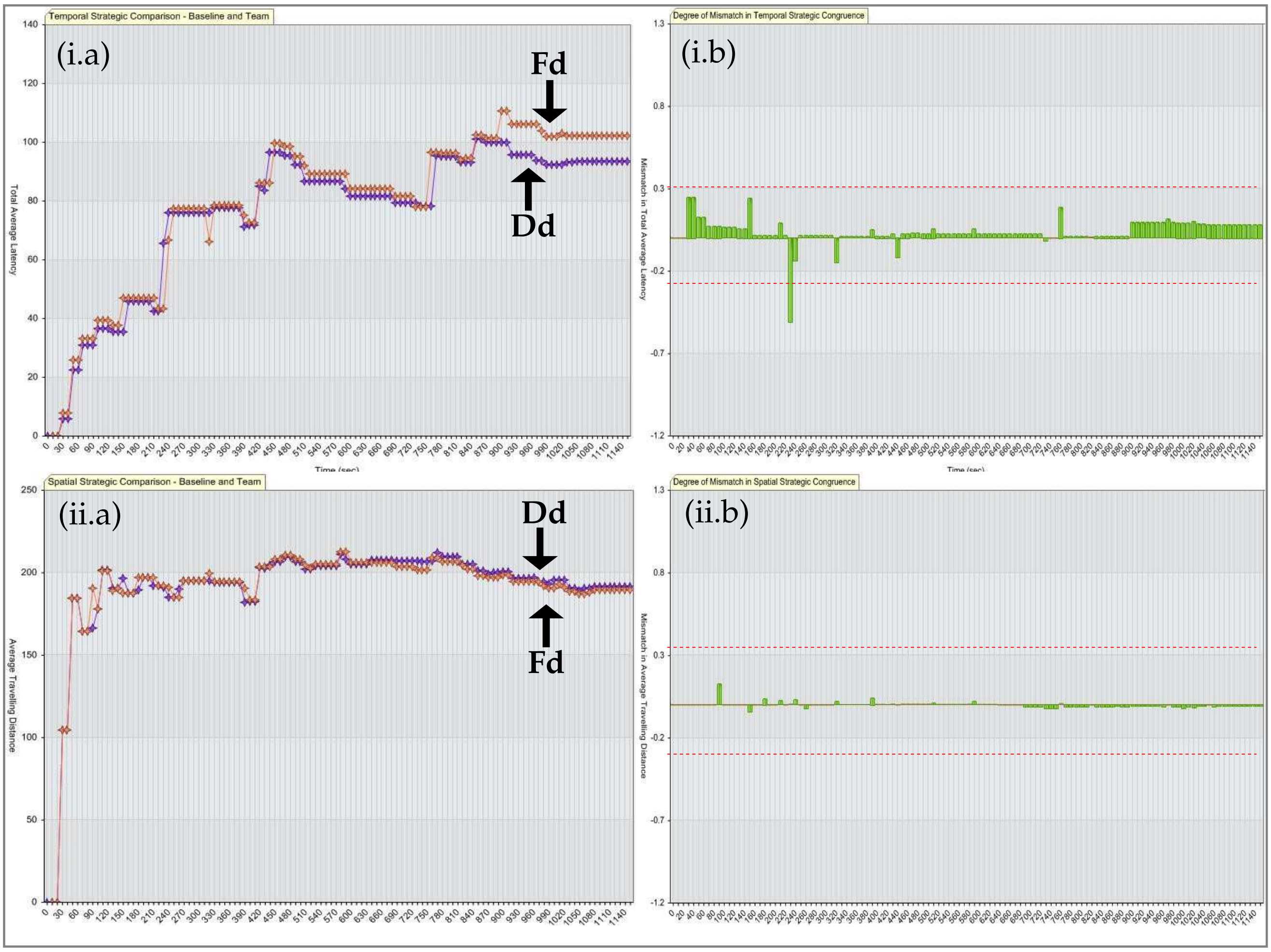

Fig. 6. Strategy-Environment Congruence:
(i.a) Degree of Temporal Strategy-Environment Congruence, $C^{SE,1}(t)$,
(i.b) Degree of Temporal Strategy-Environment Congruence Difference between the **Dd** and the **Fd** Pairs, $\Delta^{SE,1}(t)$,
(ii.a) Degree of Spatial Strategy-Environment Congruence, $C^{SE,2}(t)$, and
(ii.b) Degree of Spatial Strategy-Environment Congruence Difference between the **Dd** and the **Fd** Pairs, $\Delta^{SE,2}(t)$.

single-resource ownership by DMs in organization **F** has a very small margin to cope with the multi-resource tasks in scenario **d**. The extreme misfit in the structure-environment congruence between the **Dd** and the **Fd** cases over the course of the mission is shown in Fig. 5.i.b. Since the organizational structure remains the same throughout the mission (due to the absence of structural adaptation from the options), the DM-resource allocation and the task-resource requirements mismatch, $\Delta^{OE,1}(t)$, remains large $(= -1)$ for the duration of the mission.

The results for a surrogate structure-environment measure, the external coordination workload, is in agreement with $C^{OE,1}(t)$ measure. Fig. 5.ii.a shows that the **Fd** pair has higher external coordination workload when compared to the **Dd** pair for the duration of the mission. This supports the finding in [Levchuk et al., 2003].

B. Strategy-Environment Congruence Assessment

The strategy-environment congruence is measured in terms of the organization's temporal and spatial loading mechanisms as specified in Eqs. (9) and (10), respectively. The measure for temporal strategy-environment congruence, $C^{SE,1}(t)$, indicates that both organizations utilize congruent strategies, in a temporal sense, to the demands of the mission. This is evidenced from results shown in Figs. 6.i.a and 6.i.b, wherein the differences in the average task latency, defined in Eq. (9), between the **D** and the **F** structures are within the allowable margins.

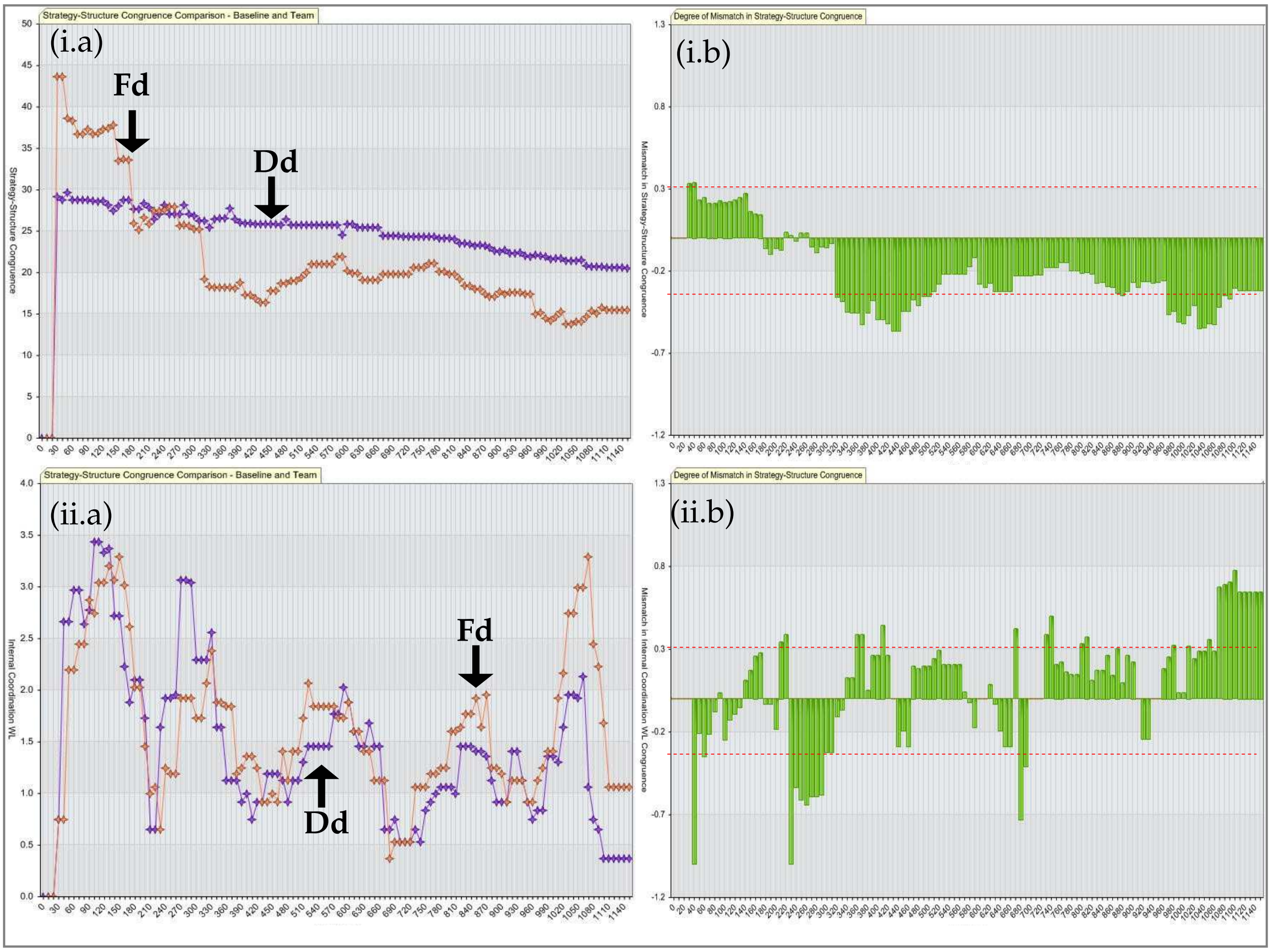

Fig. 7. Strategy-Structure Congruence:
(i.a) Degree of Congruence between the DM-resource Allocation and the DM-resource Utilization, $C^{SO,1}(t)$,
(i.b) Degree of Strategy-Structure Congruence Difference between the **Dd** and the **Fd** Pairs, $\Delta^{SO,1}(t)$,
(ii.a) Degree of Internal Coordination Workload Congruence, $C^{SO,2}(t)$, and
(ii.b) Degree of Internal Coordination Congruence Difference between the **Dd** and the **Fd** Pairs, $\Delta^{SO,2}(t)$.

Similarly, the spatial strategy-environment congruence assessment, $C^{SE,2}(t)$, indicates congruence in a spatial sense between the **D** and **F** structures. This can be inferred from Figs. 6.ii.a and 6.ii.b.

C. Strategy-Structure Congruence Assessment

One measure of strategy-structure congruence is the closeness between the DM-resource allocation and the DM-resource utilization, $C^{SO,1}(t)$ defined in Eq. (11). Results in Fig.7.i.a indicate that the **F** structure is as efficient if not more efficient in its resource utilization when compared to the **D** structure. However, the degree of strategy-structure incongruence between the two pairs is not significant. From Fig.7.i.b, it can be observed that only in a small period of the mission does the incongruence margin reach a significant value. The difference in $C^{SO,1}(t)$ between the two structures is partly due to the fact that the **D** structure has a higher degree of excess in organizational capability when compared to the **D** structure.

A surrogate measure for strategy-structure congruence, the internal coordination workload, $C^{SO,2}(t)$, defined in Eq. (11), is in agreement with the finding from $C^{SO,1}(t)$. Although there exists a persistent advantage of **D** over **F**, the difference is generally acceptable. That is, DMs in the **F** organization have to work harder than the DMs in the **D** organization due to structural differences between the two organizations. This is evidenced from Figs. 7.ii.a and 7.ii.b.

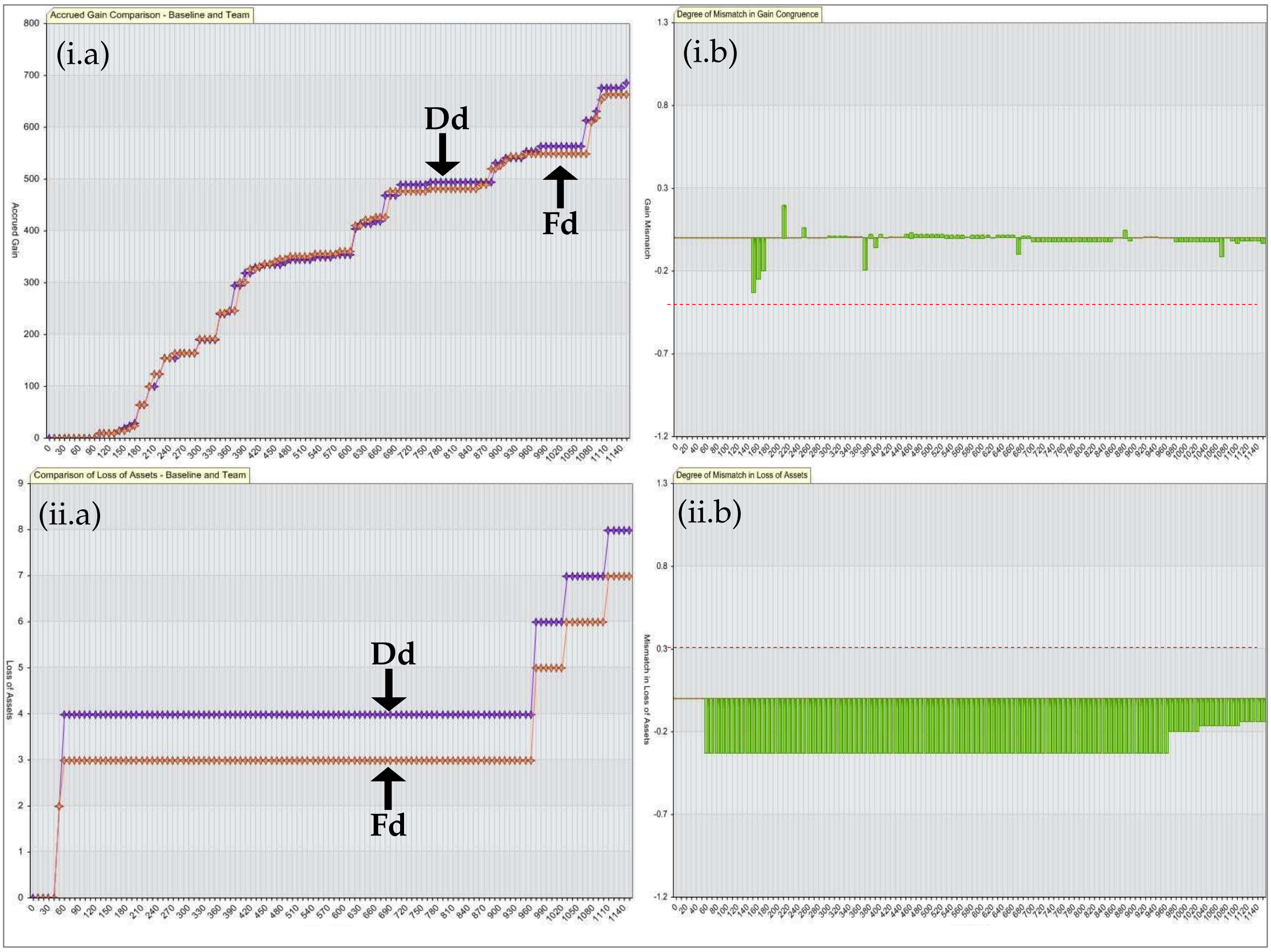

Fig. 8. Performance Assessment:
(i.a) Accrued Gain, $G(t)$,
(i.b) Degree of Accrued Gain Difference between the **Dd** and the **Fd** Pairs, $\Delta^G(t)$,
(ii.a) Aggregate Loss of Reusable Assets, $L(t)$, and
(ii.b) Degree of Difference in the Aggregate Loss of Reusable Assets between the **Dd** and the **Fd** Pairs, $\Delta^L(t)$.

D. Organizational Performance

The organizational performance is gauged via the accrued task gain, $G(t)$ defined in Eq. (4), and the aggregate loss of reusable assets, $L(t)$ defined in Eq. (5). The results, in Figs. 8.i.a and 8.i.b, indicate that there is no significant difference in the accrued task gain over the course of the mission between the **D** and the **F** structures. This finding differs from the one in [Levchuk et al., 2003]. This major difference is due to the lowered cost to coordinate in our simulation. That is, by using a computational agent, that has an overall picture of the mission and organization, in essence, the structure-environment incongruence is drastically reduced. This, in turn, makes the organizational performance insensitive to resource-allocation mismatches.

The same also applies to the aggregate loss of reusable assets. There exists no significant difference between the two structures with regard to the aggregate loss of reusable assets. The **D** organization looses one asset more than the **F** organization. This can be inferred from the results shown in Figs. 8.ii.a and 8.ii.b.

E. Discussion

The first lesson learned from the example is that triggers for organizational adaptation involves an integrated multi-dimensional view of congruence that incorporates structure-environment, strategy-environment, and strategy-structure matches. The second lesson learned is that by relaxing the bounded rationality constraints of human DMs (e.g., by minimizing the cost of DM-DM coordination), an organization gains a competitive advantage.

We have argued that the process of recognizing when and how to adapt, is a complex, knowledge intensive process, wherein the bounded rationality constraints [Simon, 1982] of human DMs, can potentially become an obstacle for achieving competitive advantage. From a knowledge management perspective, the type of knowledge necessary for efficient and effective organizational adaptation falls into the tacit knowledge category. Due to the elusive nature of tacit knowledge (i.e., the difficulty in articulating and expressing it), the knowledge management strategies that codify this type of knowledge are central to achieving superior performance. The DSS architecture, outlined in IV-A, is a suitable platform to transfer the codified tacit knowledge, i.e., the performance monitors and the congruence assessments, to human DMs.

We have also demonstrated that by utilizing a single computational agent having a bird's eye-view of the entire organization, viz., by relaxing the bounded rationality constraints of human DMs, the structure-environment incongruity of the **F** structure on mission **d** can be mitigated without undergoing structural adaptation. By proposing to utilize a computational agent at the heart of the DSS to facilitate the knowledge creation and transfer processes, we can potentially increase the organizational cognitive capacity and facilitate the process of adaptation.

VI. Conclusion

Organizational decision-making, including the process of recognizing when and how to adapt, is a complex, knowledge intensive process, wherein a DSS plays an instrumental role in achieving competitive advantage. The role of the DSS is to provide mission monitoring and re-planning information to human DMs in terms of managing the explicit and tacit knowledge, codifying them into simple and meaningful formats, and facilitating rapid transfer of knowledge among participating DMs. In this paper, we operationalized a DSS as a means to increase the organizational cognitive capacity, and to facilitate the processes of adaptation via an agent-based DSS by utilizing the third-generation distributed dynamic decision-making (DDD-III) simulator as the test-bed, assuming knowledge security.

To cope with the environmental demands in a relatively fast paced mission, such as in the multi-resource divisional mission scenario, which requires the organization to not only react quickly but also to implement proper coordinating strategies, especially for the functional structure, the knowledge management strategies focused on the knowledge creation and transfer. The web-based displays, that are designed to facilitate effective and efficient knowledge management, are organized into three categories: (1) Critical Information on Tasks and Assets, (2) Decision Support Information, and (3) Measures. Displays belonging to the first two categories are designed to support rapid transfer of knowledge by providing simple, succinct, meaningful formats. The contents of various displays belonging to the Measures category are in the form of either created knowledge that is not readily available to DMs without a DSS, or of codified tacit knowledge that is not easily articulated nor expressed otherwise. These displays are crucial to facilitate effective organizational diagnosis and analysis, and ultimately to the process of recognizing when and how to adapt.

In this paper, we have demonstrated, by a counter-example, that triggers for organizational adaptation emerge from an integrated multi-dimensional concept of congruence incorporating structure-environment, strategy-environment, and strategy-structure matches. This observation is derived from an integrated view of contingency notions that incorporate three relevant components affecting organizational performance: (1) environment, (2) organizational structure, and (3) strategy. Building on the rule-based extreme misfit hypotheses [Burton et al., 2002], we presented *quantitative* measures to identify when and how to adapt in fast paced organizations facing highly dynamic mission environments. We showed that only when an extreme misfit in any of the pairs belonging to the multi-contingency model is coupled with a drop in organizational performance below an acceptable level, organizational adaptation, in the form of strategy adjustment, structural reconfiguration, or both, is needed to recover the congruent state.

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