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Abstract

The *Edge* represents a fresh approach to organizational design, moving knowledge and power to the edges of organizations. But this raises issues in terms of comparative performance with respect to alternate organizational designs (esp. military C2). The research described in this article represents the first stage of a multi-disciplinary, multi-year investigation into the design and efficacy of Edge organizations for current and future, military, mission-environmental contexts. Specifically, we employ methods and tools of computational experimentation to compare empirically the performance of current and competing organizational forms. This first study begins by specifying computational models of Hierarchy and Edge organizations in the C2 domain. Rooted firmly in Organization Theory, yet cognizant of military operations, in this article we report the bases and results of such specification in considerable detail. We also design an experiment to compare explicitly the performance of both Hierarchy and Edge organizations across two, contrasting, mission-environmental contexts: Industrial Age and 21st Century. Preliminary, experimental results reveal insightful dynamic patterns and differential performance capabilities of Hierarchy and Edge C2 organizations. This work suggests immediate results amenable to practical application in the Military. And it suggests also an exciting agenda for continued research along the lines of this investigation.

Introduction

The *Edge* [1] represents a fresh approach to organizational design, which appears to be particularly appropriate in the context of modern military warfare. It proposes to capitalize upon fully connected, geographically distributed, organizational participants by moving knowledge and power to the edges of organizations. This highlights promising opportunities for enterprise efficacy. But it also raises issues in terms of comparative performance with respect to alternate organizational designs. Modern military organizations in general have adapted and evolved over many centuries and millennia, respectively. Hierarchical command and control (C2) organizations in particular have been refined longitudinally (e.g., through iterative combat, training and doctrinal development) to become very reliable and effective at the missions they were designed to accomplish. In contrast, the many putative benefits and comparative advantages proposed for Edge organizations remain untested hypotheses at best and naïve speculations at worst.

Current conceptualizations of Edge organizations [20, 38] are increasing the level of precision in defining important concepts for evaluating and comparing Edge and other organizational forms. They are beginning to identify key Edge entities and relations. And they are proffering self-report and like scales in attempt to operationalize measurable Edge constructs. But the "theory" underlying such conceptualizations remains as untested and speculative as in the original. Indeed, authors of these current conceptualizations call expressly for testing the claimed superiority of Edge organizations. The problem is, few research approaches exist at present to examine Edge propositions. For instance, it remains unclear even whether informative examples—much less exemplars—of Edge organizations in practice can be identified for study (cf. [44]). And attempting to test large-scale military organizations in the laboratory suffers from severe problems with external validity [7]. Likewise, modifying one or more operational military organizations in the field to take on Edge-like characteristics creates problems with internal validity [16].

Further, current conceptualizations of Edge organizations are limited largely to natural language descriptions (e.g., [1, 20]) and static models (e.g., [38]). Descriptions in natural language—even from the best writers—retain considerable ambiguity in terms of conceptual meaning and interrelations. Many people can use the same words and phrases to mean different things. And many different interrelations can be characterized to describe the same phenomena.

Plus, static models are unable to represent the kinds of rich, dynamic, often emergent behaviors that are important for understanding complex organizations and environmental interactions such as observed in military C2.

The research described in this article represents the first stage of a multi-disciplinary, multi-year investigation into the design and efficacy of Edge organizations for current and future, military, mission-environmental contexts. Specifically, it builds upon recent work in the C2 domain [15, 46] to employ computational methods and tools to represent complex, dynamic organizations via semi-formal models. Semi-formal, computational modeling can overcome substantial ambiguity inherent in natural language description. And it can represent and project dynamic behaviors of complex and adaptive organizations. This research stream also draws from the science of laboratory experimentation (e.g., see [3, 29]) to compare empirically the performance of current and competing organizational forms. In particular, we assess the relative performance of the Hierarchy—used to represent current military C2 organizations—and the Edge—purported to offer advantages in the 21st century C2 environment. Computational experimentation offers an approach to mitigate the limitations of both laboratory and field research [46]. And through dynamic performance emulation, it provides the means to evaluate and compare a variety of different organizations in practice—even with those that do not yet exist.

This first study begins by specifying computational models of Hierarchy and Edge organizations in the C2 domain. Rooted firmly in Organization Theory for background, yet cognizant of military operations for application, in the following section we report the bases and results of such specification in considerable detail. We describe then the design of an experiment to compare explicitly the performance of both Hierarchy and Edge organizations across two, contrasting, mission-environmental contexts: Industrial Age and 21st Century. Preliminary, experimental results are reported subsequently. They reveal insightful dynamic patterns and differential performance capabilities of Hierarchy and Edge C2 organizations. In the closing section, we note multiple contributions to C2 research. We also suggest several insights and results that are amenable to immediate practical application. And we reveal several parts of an exciting agenda for continued research along the lines of this investigation.

Background

In this section, we draw from Organization Studies to conceptualize theoretically how the Edge organization would compare to other archetypes discussed in the literature. This reflects our purposeful, two-step approach to specifying Edge organizations via computational models. In this first step, we draw from current conceptualizations of Edge organizations (esp. [1, 20, 38]) and look to extant organization theory to root such conceptualizations in the rich and well-established literature. Once rooted as such in theory, we identify the organizational archetypes that match most closely current conceptualizations of the Hierarchy and Edge organizations for comparison. In the second step, we use characterizations of such archetypes for guidance in specifying model parameters for representing the organizations computationally. We then revisit and recapitulate key propositions of current Edge "theory" that can be used to develop a set of hypotheses for testing. This sets the stage for computational experimentation.

Organizational Archetypes

A great many, diverse organizational forms have been conceived and articulated, over a relatively long period of social science investigation. By *organizational form*, we mean a class of organizations with distinguishing characteristics. No single instance of an organization within a class matches exactly all class characteristics. But in coherent and discriminating classification systems, all instances within a given class share many characteristics with others in the same class, and all instances within a given class are more similar to one another than they are to instances in different classes. Indeed, in many respects, organizational forms can be viewed taxonomically [39], in a manner analogous to how cattle, fish, plants, insects and people can all be viewed as very different classes of biological organisms. This enables us to abstract away from the details of individual organizations (e.g., Wal-Mart, General Motors, The US Navy) in a class and to concentrate instead of common characteristics (e.g., large numbers of employees, numerous geographical locations, many levels of management hierarchy) shared by organizations in such class.

Modeling at the class level as such—through organizational archetypes—increases the generalizability of our research. Senge [54, p. 94] describes additional benefits of viewing a complex world via abstraction to classes and archetypes.

> These ‘systems archetypes’ or ‘generic structures’ embody the key to learning to see structures in our personal and organizational lives. The systems archetypes—of which there are only a relatively small number—suggest that not all management problems are unique, something that experienced managers know intuitively. … Just as in literature there are common themes and recurring plot lines that get recast with different characters and settings, a relatively small number of these archetypes are common to a very large variety of management situations. … [They] reveal an elegant simplicity underlying the complexity of management issues.

Key among such additional benefits is the relatively small number of comparable, class-level archetypes that can be used effectively to represent and learn about a very large number of diverse, instance-level organizations.

Table 1 Sample of Organizational Forms from the Literature

Organizational Form
Bureaucracy [62]
M-Form & U-Form [9]
Rational & Natural, Closed & Open [53]
Markets & Hierarchies [63]
Simple, Machine Bureaucracy, Divisional, Professional Bureaucracy, Adhocracy [41]
Clans [49]
Hunters, Temples, Producers & Palaces [39]
Network [40]
Heterarchy [26]
Federated [30]
Interactive [25]
Virtual [17]
Technocracy [5]
Internal Market [37]
K-linked [2]
Multidimensional Matrix [51]
Interstitial [42]
Platform [12]
Shamrock [22]
Social Network [34]
Cluster [23]
Chaotic [61]
Organizational Democracy [13]
Pop-up [27]
Loose Hierarchies & Democracies [36]
Knowledge-Flow [43]
Laminar & Turbulent [18]
Edge of Chaos [4]
Power to the Edge [1]

A sample of diverse organizational forms reported in the organization studies literature is presented in Table 1. The interested Reader is directed to the literary citations and references for elaboration. Notice the last entry denotes the Edge organization representing the focus of our present investigation. Within the entries presented in this table, different levels of granularity are evident in terms of how general versus specific each particular entry is. For instance, the Bureaucracy refers to a single class of organization, as do the Clan, Heterarchy, Technocracy and others. A single class as such is useful for modeling only so long as the organizations of interest in our study conform to that particular class. Although the Hierarchy, for example, may conform relatively well to the class *Bureaucracy*, the Edge probably will not. Hence a single class is likely to be too narrow for our purposes. As another instance, the Open organization refers to a broad collection of diverse organizational forms that share characteristics only at a very high level. A broad class such as this is useful for modeling only so long as the organizations of interest in our study vary across classes. However, both the Hierarchy and the Edge, for example, conform to the class *Open*. Hence a high-level class is likely to be too broad for our purposes.

Alternatively, some entries presented in this table fall in between these levels of granularity. Some even include rubrics for differentiating between different organizational classes, in addition to characterizing multiple classes within such rubrics. Such approaches include mini-taxonomies of classes as well as instances of organizational forms, in addition to specifying the rules for classifying and differentiating various organizations and forms into and between the multiple classes. For instance, Mintzberg [41] develops a rubric for classifying and analyzing a wide variety of organizational forms. This rubric centers on the number *5*. It includes a typology of five organizational archetypes: 1) Simple Structure, 2) Machine Bureaucracy, 3) Professional Bureaucracy, 4) Divisionalized Form, and 5) Adhocracy. It also characterizes organizations in terms of five elements: 1) operating core, 2) strategic apex, 3) middle line, 4) technostructure, and 5) support staff. And it outlines five basic mechanisms for coordination: 1) mutual adjustment, 2) direct supervision, and standardization of 3) work processes, 4) outputs, and 5) skills. This scheme includes also eight design factors: 1) job specialization, 2) training and indoctrination, 3) behavioral formalization, 4) unit grouping, 5) unit size, 6) planning and control systems, 7) liaison services, and 8) decentralization. This rubric and the associated archetypes provide a suitable level of granularity for our modeling purposes.

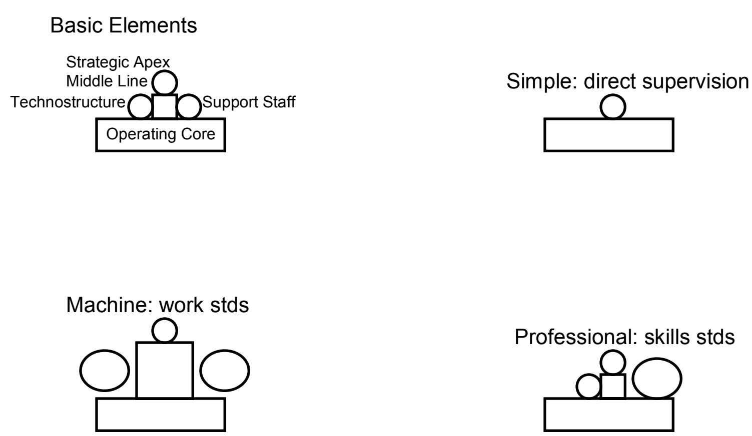

Figure 1 Organizational Elements and Archetypal Examples

Figure 1 summarizes these organizational elements in the upper-left quadrant. The *strategic apex* is shown as a circle at the top of the organization. This is where senior management and leadership are accomplished. The *middle line* is shown as a square below the apex. This is where line management takes place. The *operating core* is shown immediately below the middle. This is where the basic product and service outputs of the organization are accomplished. On either side of the middle line is the *technostructure* and *support staff*. Like the middle line, these two elements both sit between the strategic apex and the operating core. But as staff organizations, they are not part of the direct line between the apex and core. The technostructure is responsible for direct support such as planning, analysis and technology. The support staff is responsible for indirect functions such as accounting, legal counsel and building maintenance.

Using these elements arranged as such, different organizational archetypes can be depicted and differentiated graphically. For instance, the Simple Structure is depicted in the upper-right quadrant. It includes only two of the five elements: 1) strategic apex and 2) operating core. Coordination is attained principally through direct supervision. Many small businesses are organized as such. In contrast, the Machine Bureaucracy is depicted in the lower-left quadrant, as another instance. It includes all five elements, with three elements emphasized in terms of large prominence. Specifically, the middle line is depicted using a relatively large square, and both the technostructure and support staff are depicted similarly using relatively large circles. This depiction represents the relatively many layers of middle management and relatively large size and influence of technical and support staffs. Coordination is attained largely through standardization of work processes. Many large firms and government agencies organize along these lines.

A third instance includes the Professional Bureaucracy, which is depicted in the lower-right quadrant. It includes all five elements also. But only the support staff is emphasized in terms of a relatively large circle for representation. Here standardization of skills provides the principal means of coordination. Many professional corporations (e.g., legal firms, medical offices, consultancies) organize in these terms. Using Mintzberg's rubric for classifying organizational archetypes helps us to identify and differentiate a relatively small number of common patterns that pertain to a very large diversity of organizations. In this article, we focus exclusively on the Hierarchy and Edge: two alternate and contrasting organizational forms conceptualized currently for military C2 (see esp. [1]).

Edge Specification

Here we employ Mintzberg's classification rubric to specify the Hierarchy and Edge organizational forms. These specifications are useful in their own right to ground current conceptualizations in organization theory and to indicate similarities and differences with other organizational forms through archetypal classification. Table 2 summarizes our classification of the Hierarchy and Edge organizations according to this scheme. The first column includes the coordination mechanism and eight design factors listed above. Two subfactors are included for *specialization*: horizontal refers to (low) job breadth; vertical refers to (little) job control. The second column lists the manner in which the Hierarchy organization corresponds with each design factor. For instance, coordination is listed as "work standards." This suggests that organizational policies, standard operating procedures, task checklists, detailed work instructions, technical specifications, and like approaches to standardization of work processes play the principal role in C2 coordination. Clearly other approaches (e.g., direct supervision, standardization of skills) play an important role too. But classification and analysis at the archetypal level seeks to identify the *principal* role.

Other entries in the Hierarchy column follow similar logic. For instance, horizontal specialization is listed as "high." This depicts the highly specialized, relatively narrow job descriptions associated with most military positions. Likewise, vertical specialization is listed as "high" also. This depicts the highly controlling nature and detailed focus of military leadership and management. High training and indoctrination mirrors the extensive formal training and acculturation provided to military personnel, as well as the tremendous internal norming forces associated with an organization with negligible avenues for lateral entry. High formalization in the next row corresponds with coordination through work standards and the extensive specification of policies, procedures and interactions.

Table 2 Classification of Hierarchy & Edge Organizations

Design Factor	Hierarchy	Edge
Coordination	Work standards	Mutual adjustment (Adhocracy)
Specialization – H	High	Low (Simple Structure)
Specialization – V	High	Low (Professional Bureaucracy)
Training & indoc	High	High (Professional Bureaucracy)
Formalization	High	Low (Simple Structure, Professional Bureaucracy, Adhocracy)
Grouping	Function	Market & function (Adhocracy & Professional Bureaucracy)
Unit size	Large	Small (Adhocracy)
Planning & control	Action planning	Limited action planning (Adhocracy)
Liaison	Few	Many throughout (Adhocracy)
Decentralization	Centralized	Selective decentralization (Adhocracy)
Archetype	*Machine Bureaucracy*	*Professional Adhocracy*

Unit grouping is principally by function in the Military. At a very high level, the Military reflects a divisional structure (e.g., separate Services for Army, Navy, Air Force; distinct commands such as Central Command, Seventh Fleet, Strike Group 3). But within each structure, the various units—across all services and commands—are grouped by Napoleonic function (e.g., 1 – Administration, 2 – Intelligence, 3 – Operations). Further, when examining the organization and processes in context of wartime C2, the most appropriate unit of analysis becomes the *joint task force* (JTF; see [43, 44]), which is organized functionally even across Service lines.

Unit size refers to managerial span of control, which is notably large within the operating cores of most military organizations. This is consistent with coordination by standardization of work processes and formal behavioral interaction. Mintzberg's categories for planning and control are matched best by *action planning* in the military C2 context. Many militaries include a specific functional organization devoted solely to planning. When considering Galbraith's [19] perspectives on various liaison approaches (e.g., informal, task teams, matrix) in the context of the JTF, few such approaches are notable in military C2. Most interfunctional coordination and integration takes place within the strategic apex of JTF organizations. For the Military as a whole, Mintzberg's categories for decentralization are matched best by *limited vertical*, which corresponds with our comments above pertaining to the divisional structure. But for our JTF unit of analysis, decision-making is very centralized.

Based on these classifications of the Hierarchy in terms of design factors, the final row in the Hierarchy column labels the organizational archetype that corresponds most closely with the kind of military C2 organization associated with a JTF: *Machine Bureaucracy*. As suggested above, this ideal type does not represent a perfect fit. For instance, other C2 coordination mechanisms associated with the Hierarchy include direct supervision and standardization of skills, which fit better with Simple Structure and Professional Bureaucracy, respectively. As another instance, high levels of training and indoctrination also fit the Professional Bureaucracy archetype better. And we note above how the Military as a whole fits well with the Divisionalized Form. But overall, most entries in the table for Hierarchy above correspond closely with those associated with the Machine Bureaucracy archetype, and none of the entries is grossly inconsistent with such classification. Our classification of the Hierarchy is consistent also with common perceptions articulated in the management and popular press (e.g., the pervasive and somewhat pejorative term *military bureaucracy*). Hence this classification appears to be relatively clear and clean.

Classification of the Edge organization is more difficult. This is in part because the military does not organize currently for C2 in terms of *edge*, and in part because the properties of an Edge organization draw from multiple archetypes. Indeed, few examples of Edge organizations can be identified in practice (cf. university research, open-source software development, soccer teams; see [44]). Further, there is some tension in classifying Edge organizations regarding the level at which *edgeness* applies. For instance, *edge* clearly does not apply to the Military as a whole. Yet several, very small military units today (e.g., SEAL and Special Forces teams) depict many *edge* characteristics. But when we focus on the JTF unit of analysis, we are able to complete the classification table with good representational validity and fidelity.

The first entry under the Edge column depicts coordination through mutual adjustment. Thompson [58] indicates mutual adjustment as the appropriate coordination approach when tasks are reciprocally interdependent. This matches well the nature of how Edge organizational units are purported to self-synchronize and adapt agilely to novel environments and varying missions. As noted parenthetically in the table, mutual adjustment corresponds most closely with the Adhocracy form. But as above, clearly direct supervision will play a part in coordination of Edge organizations, as will other approaches (e.g., work standardization, standardization of skills). Yet the Edge organization calls for emergent leadership: “Exactly who ‘takes charge’ will differ as a function of the characteristics of the individuals and the situation. When the most well suited or situated individual or organization is in charge, then the organization can be said to be a meritocracy” [1, pp. 184-185]. Combined with self-synchronization and other *edge* properties, mutual adjustment appears to represent the best fit.

In terms of other design factors, notice that many Edge entries in the table contrast with their Hierarchy counterparts. For instance, specialization in both horizontal and vertical dimensions is likely to be relatively low. Warriors will be required to exhibit more generalism and will be granted greater autonomy and discretion over their tactics and actions. Low behavioral formalization follows as well, with standardized jobs unlikely at the operating core of Edge organizations. As another instance, unit size will be relatively small, as discrete fighting modules combine, synchronize, and recombine in different dynamic patterns in response to varying environments and missions.

Alternatively, some Edge design factors are relatively more consistent with those pertaining to the Hierarchy. Training and indoctrination, for instance, is likely to be high in Edge organizations, as many aspects of military warfare require knowledge-intensive skills and involve a unique organizational culture. In terms of grouping, some functional groups are likely to persist in Edge organizations. But they will likely be complemented by what Mintzberg calls “market” groupings, which focus more on ends of achieving objectives than on means of producing outputs. This is consistent with the military notion *effects-based operations* (see [24, 56]). Some limited action planning will likely comprise C2 in Edge organizations as well, but not to the same extent as in the Hierarchy. And some aspects of Edge organizations will clearly remain centralized too. But selective decentralization also provides a contrast with the centralized nature of the Hierarchy organization. This follows from the autonomy and self-synchronization of modular Edge forces.

In sum, looking at the table entries, the Edge organization reflects aspects of Adhocracy, Simple Structure and Professional Bureaucracy. It represents a contrast with the Hierarchy, which we classify clearly above as a Machine Bureaucracy. But it does not correspond as cleanly with any single archetype. Staying focused on our JTF unit of analysis, and looking to non-military examples of Edge organizations (e.g., university research, open-source software development, soccer teams), we consider the Adhocracy and Professional Bureaucracy to reflect this organizational form best. Hence we label it “Professional Adhocracy” in the table. Clearly this classification involves considerable judgment and interpretation on our part. And the Reader is invited to develop alternate classifications. But the classifications reported here are rooted theoretically and appear to be consistent with current conceptualizations of Edge organizations—at least within the levels of residual ambiguity inherent in such, natural language conceptualizations.

Edge Propositions and Hypotheses

Here we revisit and recapitulate key propositions of current Edge "theory" that can be used to develop a set of hypotheses for testing in this study. This sets the stage for computational experimentation. The key Edge propositions derive principally from [1], as supplemented by [20, 38, 44, 46]. To supplement our theoretically rooted discussion above, this informs our model development with cognizance of military operations.

The seminal Edge publication [1] articulates both a vision of and rationale for the Edge organization and its putative performance advantages over the Hierarchy organization. Drawing from this book, we look to identify a set of essential properties pertaining to Edge organizations. The quotations below (pp. 170 – 180) help toward this end:

> *Power to the edge* is the principle that needs to be applied to enable NCW [network-centric warfare] to reach its full potential. … Edge organizations are characterized by the widespread sharing of information and the predominance of peer-to-peer relationships. … Edge organizations are organizations where everyone is empowered by information and has the freedom to do what makes sense. … The goal is not to be able to perform well in a particular mission in a particular situation, but to create an organization that is agile.

Four points appear key here. First, *edge* represents an organizing principle. This puts *edge* on par with other organizing principles such as *division of labor, coordination, information location* and *information processing* (e.g., see [19, 41, 58, 57, 62]). Second, decentralized information sharing is stressed. This suggests that the topology for information flows is important to the kinds of power flows stressed for Edge organizations. Third, pervasive individual control over decisions and actions is noted. Some kind of "invisible hand" that enables markets may be essential to the Edge organization. Fourth, *agility* is noted as a fundamental goal of the Edge organization. This suggests that some tradeoffs may be required between performance measures such as *cost* and *risk* [46], *flexibility* and *control* [44], and others (e.g., *speed, variety, resilience* and *efficiency*).

Further, we find many examples from current Edge "theory" that characterize a sharp Edge-Hierarchy contrast. For instance, "[given] asymmetries of the 21st century security environment, … decrease in the size and cost of weapons of mass destruction and disruption, … [and increasing] complexity of military operations" [p. 1], "our legacy force structure and concepts of operation are not well suited for the tasks at hand" [p. 2]. The notion that an organization can be suited relatively better or worse for some particular mission-environmental context reflects the long-standing thrust of Contingency Theory [6, 19, 32, 58]. A similarly consistent statement follows: "there was not … a single 'best' approach to (or philosophy of) command and control" [1, p. 18]. A key objective of this present research centers on determining what mission-environmental factors contribute to relatively better versus worse comparative performance of Edge and Hierarchy organizations. One proposition that appears early follows.

Proposition 1. "Power to the Edge is the correct response to the increased uncertainty, volatility, and complexity associated with [21st century] military operations" [p. 6].

Another proposition attempts to prescribe how C2 should approach 21st century warfare.

Proposition 2. "The correct C2 approach depends on [five] factors": 1) shift from static/trench to mobile/maneuver warfare; 2) shift from cyclic to continuous communications; 3) volume and quality of information; 4) professional competence; and 5) creativity and initiative [p. 19].

A third indicates that robust networking is key.

Proposition 3. “Given a robustly networked force, any one of the six effective command and control philosophies proven useful in the Industrial Age is possible” [p. 32].

However, Industrial Age organizing principles and processes are characterized as breaking down in the face of 21st century warfare.

> The 21st century national security environment is qualitatively different from the security environment that nations faced in the Industrial Age. Militaries now need to respond to a wider range of potential threats, many that are difficult to assess and many that cannot be responded to with conventional military tactics and capabilities. Expectations regarding casualties and collateral damage have made it more important to deploy with greater information quality and precision. Many operations require that militaries work together with a variety of civil and nongovernmental partners. The net result is that military planners are faced with more uncertainty with regard to what they need to be prepared to do, a more complex set of tasks to accomplish, and less room for error [p. 53].

Further, knowledge and information play key roles in the Edge organization: “This increased access to information provides an opportunity to rethink the ways that we organize, manage and control” [p. 71]; “we can … move away from a *push* approach to information dissemination to a *post and smart-pull* approach” [p. 82]; and “groups that have worked together over time and across situations prove to be much faster without having to sacrifice decision quality” [p. 92 – 93]. We synthesize these descriptions into a proposition reflecting knowledge and information.

Proposition 4. People who work together, over time, and learn to operate in a “post and smart-pull” environment, will outperform similarly organized and capable people who do not.

The quality *agility* is stressed repeatedly across different conceptualizations of the Edge organization and 21st century warfare environment (cf. [1, 6]). Agile organizations “are the result of an organizational structure, command and control approach, concepts of operation, supporting systems, and personnel that have a synergistic mix of the right characteristics” [p.123]. This characterization is useful for conceptualizing how to assess the comparative performance of Edge and Hierarchy organizations. In particular, six attributes of *agility* are noted: *robustness, resilience, responsiveness, flexibility, innovation,* and *adaptation* [p. 128]. The agility characteristic of organizations also leads to a performance-oriented, contingency-theoretic proposition.

Proposition 5. “The more uncertain and dynamic an adversary and/or the environment are, the more valuable agility becomes” [p. 124].

Further, in characterizing the Edge organization, we find several useful examples to guide our model development and parameterization. For instance:

> In the future, platforms will evolve from being networked entities to being nodes in the network … in the process, the very notion of the platform will evaporate … satisfied by a new approach as a result of a series of transformations consisting of ever larger numbers of smaller, dumber, and cheaper components … dynamically reconfigurable packs, swarms, or other organizations of highly specialized components that work together … less mechanical and more organic, less engineered and more ‘grown’ [p. 169].

Also, we learn that in a hierarchical organization, “those at the top are at the center and those at the bottom are at the edge” [p. 174]. And, “Edge organizations are characterized by the widespread sharing of information and the predominance of peer-to-peer relationships” [p. 176]. Plus, “the need for the communications and translation functions performed by the middle is greatly diminished … with disappearance of stovepipes and the demise of the middle” [p. 177]. Moreover, “Edge organizations are organizations where everyone is empowered by information and has the freedom to do what makes sense" [p. 177]. Finally, "the concept of *power to the edge* therefore is about the empowerment of the edge of an organization" [p. 213]. An important proposition emerges also from this characterization of the Edge organization.

Proposition 6. "An organization's power can be increased without significant resource expenditures" [p. 172].

This proposition suggests that Edge organizations may prove to be more effective than Hierarchy organizations—in some mission-environmental contexts—without sacrificing efficiency.

Each of these characterizations provides guidance, which is informed by operational military C2 understanding, for developing computational models to characterize Edge and Hierarchy organizations. Such guidance supplements our theoretically grounded discussion above and helps us to focus specifically on the Edge conceptualizations and performance claims. Each of these propositions provides a claim that can be operationalized and tested computationally through our dynamic models. The fundamental claim addressed through this study follows.

> If *power to the edge* organizations are … more powerful than current military hierarchies … then they must be able to accomplish more, in less time, under more adverse conditions, and at lower cost than Industrial Age organizations [p. 214].

This leads to our fundamental proposition.

Proposition 0. Edge organizations can outperform Hierarchy organizations in demanding mission-environmental contexts.

Tools and Design for Computational Experimentation

In this section, we provide a brief overview of the tools used to represent computationally and to assess experimentally the comparative performance of Edge and Hierarchy organizations. Much has been written elsewhere about the computational tools. The interested Reader is directed to the corresponding citations and references below for additional information. We also describe, in considerable detail, the experimental design used to specify and test Hierarchy and Edge organizations computationally. Two appendices are included as well to supplement this detailed description and to provide the interested Reader with sufficient information to replicate our models and findings. The goal is to enhance research reliability via such replication.

Computational Tools

Here we draw from [47] to describe the computational methods and tools used for modeling the Hierarchy and Edge organizations. The Virtual Design Team (VDT) Research Program [60] reflects the planned accumulation of collaborative research over two decades to develop rich, theory-based models of organizational processes. Using an agent-based representation [14, 31], micro-level organizational behaviors have been researched and formalized to reflect well-accepted organization theory [33]. Extensive empirical validation projects (e.g., [11, 59]) have demonstrated representational fidelity and have shown how the qualitative and quantitative behaviors of VDT computational models correspond closely with a diversity of enterprise processes in practice.

The VDT modeling environment has been developed directly from Galbraith's [19] information processing view of organizations. This information processing view has two key implications [28]. The first is ontological: we model knowledge work through interactions of *tasks* to be performed, *actors* communicating with one another and performing tasks, and an *organization structure* that defines actors' roles and that constrains their behaviors. In essence this amounts to overlaying the task structure on the organization structure and to developing computational agents with various capabilities to emulate the dynamic behaviors of organizational actors performing work. We model the organization structure as a network of reporting relations, which can capture micro-behaviors such as managerial attention, span of control and empowerment. We represent the task structure as a separate network of activities, which can capture organizational attributes such as expected duration, complexity and required skills. Within the organization structure, we model further various *roles* (e.g., marketing analyst, design engineer, manager), which can capture organizational attributes such as skills possessed, level of experience and task familiarity. Within the task structure, we model further various sequencing constraints, interdependencies and quality/rework loops, which can capture considerable variety in terms of how knowledge work is organized and performed.

Table 3 Representations of Hierarchy & Edge Organizations

Structural Factor	**Hierarchy**	**Edge**
Organization Structure	- High *centralization* - High *formalization* - Low *matrix strength* - 3-level hierarchy - Command (PM): 3 FTE - Coordination (SL): 200 FTE - Operations (ST): 40,000 FTE - 4, large units - Med *skill level*	- Low *centralization* - Low *formalization* - High *matrix strength* - 1-level meritocracy - Command (PM): 0 FTE - Coordination (SL): 0 FTE - Operations (ST): 40,000 FTE - 16, smaller units - Med *skill level*
Communication Structure	- Vertical channels - “Wheel” structure - Few communication links - *Information exchange* (0.1) - Push communications - Low *application experience* - Meetings (2 hr/day, 10%)	- Horizontal network - “Circle” structure - Many communication links - *Information exchange* (0.9) - Post & smart pull - Med *application experience* - P2P communications
Work Structure	- 4 operational tasks - Sequential execution (2-Ph) - Sequential interdependence - *FEP* (0.1) - *PEP* (0.1) - Leader demands extra - *Work duration* (3 months) - Loose coupling - *Rework strength* (0.3) - Command & staff rework	- 16 operational subtasks - Concurrent execution - Reciprocal interdependence - *FEP* (0.2) - *PEP* (0.2) - Leader demands emergent - *Work duration* (0) - Tight coupling - *Rework strength* (0.1) - No Command or staff

Also, each actor within the intertwined organization and task structures has a queue of information tasks to be performed (e.g., assigned work activities, messages from other actors, meetings to attend) and a queue of information outputs (e.g., completed work products, communications to other actors, requests for assistance). Each actor also processes such tasks according to how well the actor’s skill set matches those required for a given activity, the relative priority of the task, the actor’s work backlog (i.e., queue length), as well as how many interruptions divert the actor’s attention from the task at hand. Collective task performance is constrained further by the number of individual actors assigned to each task, the magnitude of the task, and both scheduled (e.g., work breaks, ends of shifts, weekends and holidays) and unscheduled (e.g., awaiting managerial decisions, awaiting work or information inputs from others, performing rework) downtime.

The second implication is computational: both primary work (e.g., planning, design, operations) and coordination work (e.g., group tasks, meetings, joint problem solving) are modeled in terms of *work volume.* This construct is used to represent a unit of work (e.g., associated with a task, a meeting, a communication) within the task structure. In addition to symbolic execution of VDT models (e.g., qualitatively assessing skill mismatches, task-concurrency difficulties, decentralization effects) through micro-behaviors derived from Organization Theory, the discrete-event simulation engine enables (virtual) process performance to be assessed quantitatively (e.g., projecting task duration, cost, rework, process quality). Current VDT technological work and research vectors are described in parallel with this present study [52].

Experimental Design

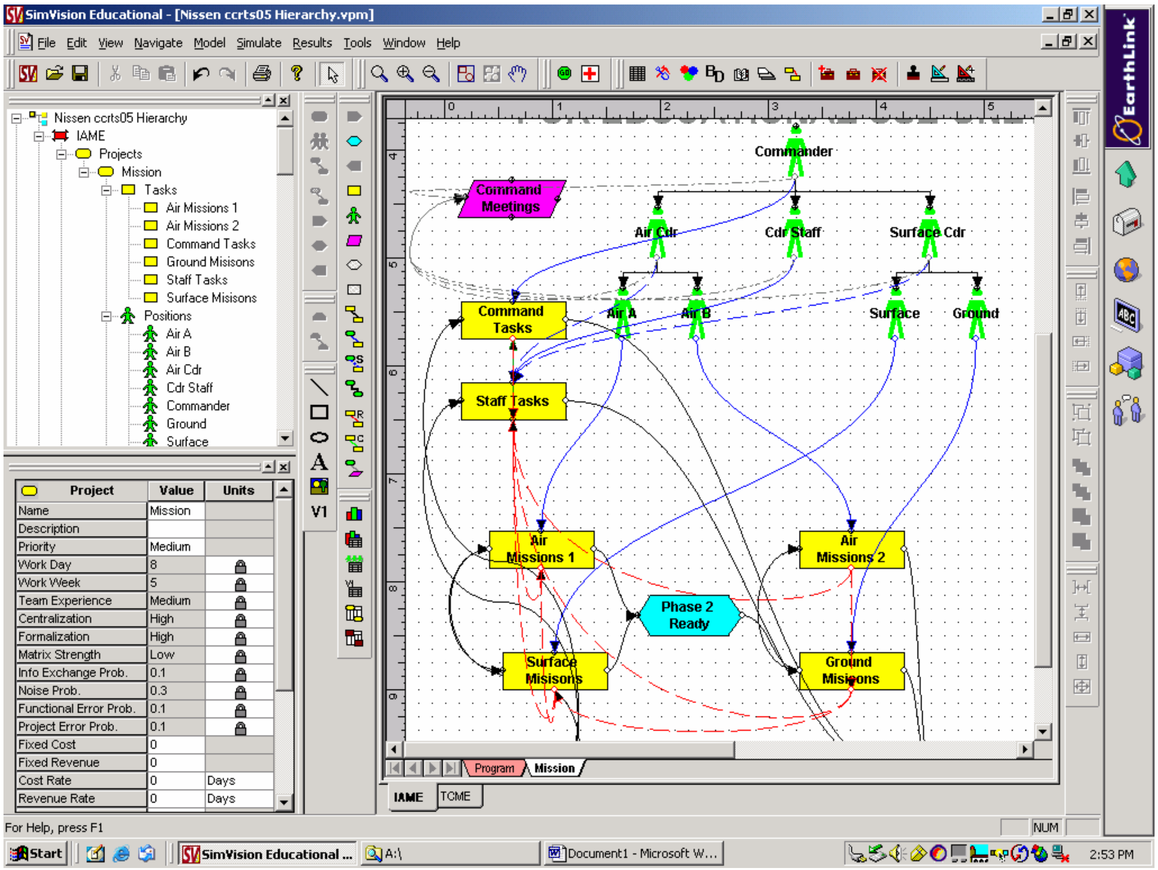

Figure 2 Hierarchy Organization – Industrial Age Mission & Environment

Here we summarize how the VDT modeling environment is used to represent the Hierarchy and Edge organizations. And we detail the experimental manipulations formulated to test the comparative performance of these competing organizational forms. Beginning with the representation, a commercial version of the VDT modeling environment, called SimVision [55], is used for modeling and experimentation here. Using our characterization above for the archetypes *Machine Bureaucracy* and *Professional Adhocracy*, we parameterize the Hierarchy and Edge organizations, respectively, according to both the mapping in Table 2 and to characterizations of Industrial Age and 21st Century mission-environmental contexts. Table 3 summarizes the three structural factors (Column 1) and parameter settings for the Hierarchy (Column 2) and Edge (Column 3) organizations. In Appendices A and B, we include detailed discussion of both organizations, addressing each structural factor and model parameter setting in turn. To preserve continuity for the non-modeler, the discussion here remains at a relatively high level. Definitions of modeling concepts, terms and variables are included in Appendix C for reference.

Figure 2 depicts a SimVision screenshot for the Hierarchy organization. Mission tasks are represented by rectangular boxes. The same four mission tasks are used in representing both the Hierarchy and Edge computational models: 1) suppression of enemy air defenses (SEAD) (labeled “Air Missions 1”), 2) Amphibious Assault (labeled “Surface Missions”), 3) Ground

Invasion (labeled “Ground Missions”), and 4) close air support (CAS) (labeled “Air Missions 2”). Task sequencing in the figure is represented by dark precedence links between tasks. Following current doctrine, the Hierarchy organization plans and executes its operational tasks in two, sequential phases of two tasks each, with a milestone symbol (labeled “Phase 2 Ready”) separating the two. Dashed lines between tasks represent rework links. Rework is required to correct mistakes made in one particular mission task (e.g., SEAD) that impact the performance of another (e.g., CAS). No communication links are included in this model of the Hierarchy, because task interdependence is predominately pooled and sequential [58].

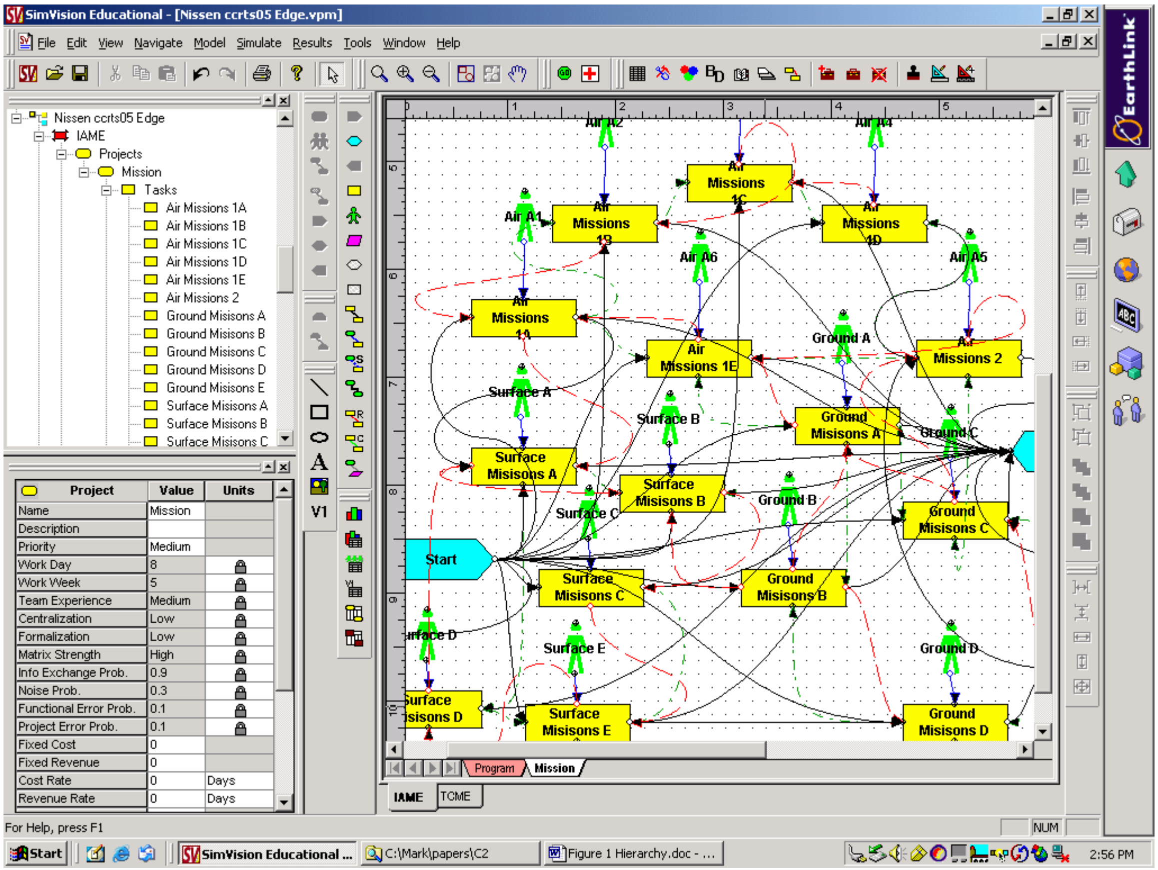

Figure 3 Edge Organization – Industrial Age Mission & Environment

Actors are represented by person icons (e.g., labeled “Commander”). Notice the three-level hierarchy among the actors at the top of the screenshot. This depicts Command, Coordination and Operations levels in the JTF Hierarchy. Correspondence to the Strategic Apex, Middle Line (and staff functions) and Operating Core, respectively, should be clear. Links between actors and tasks represent job responsibilities. Operations level actors (e.g., labeled “Air A,” “Surface,” “Ground”) are responsible directly for the four mission tasks. The Command (e.g., labeled “Commander”) and Coordination (e.g., labeled “Air Cdr,” “Cdr Staff”) level actors are responsible only indirectly for such mission tasks. But they have their own work tasks (labeled “Command Tasks” and “Staff Tasks” in the figure). These are unique to the Hierarchy model. Notice also the trapezoidal shape labeled “Command Meetings.” These represent daily, face-to-face meetings and are unique also to the Hierarchy model. Again, considerable, additional modeling detail is presented in Appendix A.

Figure 3 depicts a SimVision screenshot for the Edge organization. The same representational scheme described above in terms of Figure 2 applies here. But notice the dramatic difference from the Hierarchy screenshot above. Here, many mission tasks are scattered all over, performed concurrently, and interconnected richly with both rework and communication links. Remember, the mission tasks are the same here as for the Hierarchy above. The difference is, the Edge organization undertakes most parts of all four missions concurrently—with only a small number of sequentially dependent tasks—composing itself from 16 smaller units to accomplish different parts when and as appropriate. Also, no organizational hierarchy is present. Nor is there a separate set of Command and Staff tasks or daily Command briefings. Because of empowerment in the Edge organization, leader demands—although still present—are embedded within coordination requirements of the many different actors. And the leaders themselves emerge, informally and implicitly, during mission execution. Edge units are also coupled tightly together, exhibiting reciprocal interdependence [58]. Diverse units are responsible for various mission tasks and coordinate with one another via mutual adjustment. As with the Hierarchy above, considerable, additional modeling detail is presented in Appendix B.

Experimental manipulations. Experimental manipulations are used to characterize different mission-environmental, infrastructural, and knowledge contexts in which the Hierarchy and Edge organizations represented above are required to perform and operate. Three such manipulations are listed in Table 4. Using our computational modeling tools, each manipulation can be conducted independently to isolate separate effects, or they can be conducted collectively to emulate cumulative effects. We also label two alternate scenarios corresponding to each context: "Industrial Age" and "21st Century." Entries in the table below summarize how each of the three experimental manipulations is specified, across the two alternate scenarios, for two contrasting organizational forms. In design terms, this represents a *full factorial, 3 x 2 x 2 experiment*. As above, definitions of modeling concepts, terms and variables are included in Appendix C for reference.

Table 4 Manipulations of Experimental Factors

Manipulation	**Industrial Age**	**21st Century**
Mission & Environmental Context (P1, 5)	- Medium complexity - Med *requirement complexity* - Med *solution complexity* - Med *uncertainty* - Conventional tasks - Same *FEP* - Same *PEP*	- High complexity - High *requirement complexity* - High *solution complexity* - High *uncertainty* - Challenging tasks - Higher *FEP* - Higher *PEP*
Network Architecture (P2, 3)	- Stovepiped - Hierarchy settings - Low bandwidth - *Noise* (0.3)	- Networked - Edge settings - High bandwidth - *Noise* (0.01)
Professional Competency (P2, 4)	- Cumulative learning - Higher *application experience* - Personnel rotation - Lower *skill level* - Low *team experience*	- Marginal learning - Lower *application experience* - Personnel rotation - Higher *skill level* - High *team experience*

The first manipulation is labeled "Mission & Environmental Context" and derives principally from Propositions 1 and 5 above. Following [8] in part, we depict this context as one of "medium complexity" for the Industrial Age scenario. Clearly *complexity* is relative. Even a "medium" complexity military operation such as characteristic of Hierarchy and Edge organizations would be considered "very complex" with respect to most organizations in the world. But within our experimental design, use the level *medium* here principally for contrast with the alternate, 21st Century scenario[i]. We specify medium complexity via two model parameters: *requirement complexity* and *solution complexity*. The same holds for *uncertainty*, which we specify here as "medium" in like manner. We label the difficulty of tasks in the Industrial Age scenario "conventional," which depicts a set of relatively routine and analyzable problems [50] to be solved. In the 21st Century scenario, however, tasks are envisioned to be much more challenging. Hence we use higher levels for error parameters (i.e., *FEP, PEP*; see Appendices).

The second manipulation is labeled "Network Architecture" and derives principally from Propositions 2 and 3. Following [1, 20, 38] here, as well as [8, 46], we characterize the Industrial Age scenario one of a "stovepiped" architecture, in which networks, processes and cultural norms support principally vertical communication within functional "silos" or "chimneys." This is reinforced by our characterization of the *Machine Bureaucracy* organization structure above. Where the Hierarchy organization is run in this scenario, we make no adjustments to the organization structure parameters (e.g., *centralization, formalization* and *matrix strength*) described above. But when the Edge organization is run in this Industrial Age scenario, we modify the appropriate structure factors to make it behave in a more centralized and formal manner. The Industrial Age network architecture is characterized also in terms of "low bandwidth." Again as above, *bandwidth* is relative. But many military combatants in the air, at sea and on the ground have much poorer bandwidth than most land-based organizations do. Following [8] in part, we specify this situation using *noise* and include a relatively high level (0.3) in the Industrial Age scenario. The levels summarized in Table 4 for the 21st Century scenario reflect consistently a more robust and capable network architecture.

The third manipulation is labeled "Professional Competency" and derives principally from Propositions 2 and 4. Professional competency pertains to how knowledgeable people, groups and organizations are with respect to their organizations, missions and environments. In the Industrial Age scenario, people, teams and organizations are able to develop extreme degrees of proficiency with the specific, limited set of missions and environments that they plan, generally well in advance, to encounter. Education and training are extensive. And the Military has accumulated and documented vast amounts of doctrine to formalize organizational learning along these lines. We represent this with higher values for the parameter *application experience*. Conversely, people in Industrial Age military organizations change jobs frequently (e.g., every 2 – 3 years). This makes it difficult for individuals to develop high skills specific to any particular job. We specify this effect through lower values for the parameter *skill level*. This frequent job rotation makes it difficult also for teams to develop long-term, cohesive bonds—which affect trust—and the kind of deep familiarity and understanding that comes only through tacit learning over extended periods of time (see [45]). We specify this effect through low *team experience*.

The levels summarized in Table 4 for the 21st Century scenario reflect a mix of effects with respect to those specified for its Industrial Age counterpart. Because the organization as a whole stresses *agility* over efficacy or efficiency [1, p. 180], it must prepare for a much wider variety of diverse missions and environments than its counterparts do. This offsets in part the kind of cumulative learning noted above and renders the organization in a situation requiring rapid learning on the margin for each, distinct mission. We specify this effect by lowering *application experience* by one level. Conversely, agility calls for relatively small, experienced, cohesive units that can self-organize into larger compositions of units and can self-synchronize their operations dynamically. Our interpretation of this is that less personnel rotation across units will become the norm (e.g., as it is in many knowledge organizations such as universities). As above, we specify this effect by raising *skill level* by one level and by parameterizing *team experience* at "high."

Results

In this section, we include a sample of preliminary, experimental results produced using the computational models and experimental design outlined in the study. Such results represent only a sample, because we have not yet conducted the full-factorial, 3 x 2 x 2 experiment outlined above. Our primary purpose in this article is to specify computational models of Hierarchy and Edge organizations. Conducting the experiment represents our next step in terms of imminent future research[ii]. Nonetheless, we include some preliminary results to illustrate the use and utility of computational experimentation. Specifically, here we evaluate emulated organizational performance via simple, 2 x 2 experimental design: both Hierarchy and Edge organizations are assessed in both Industrial Age and 21st Century mission-environmental contexts. Notice this represents the top row of Table 4 above. Preliminary results are summarized in Table 5. We address the two mission-environmental scenarios in turn.

Table 5 Preliminary Experimental Results

Measure	Hierarchy Organization: Industrial Age (HOIA)	Edge Organization: Industrial Age (EOIA)	Hierarchy Organization: 21st Century (HOTC)	Edge Organization: 21st Century (EOTC)
Duration	227 days	223 days	314 days	235 days
Cost	$12B	$9B	$16B	$10B
Project Risk	0.36	0.78	0.36	0.78
Max Backlog	24 days (Commander)	14 days (Ground A)	27 days (Commander)	16 days (Ground A)
Work Volume	830K days	819K days	830K days	819K days
Rework Volume	131K days	113K days	422K days	166K days
Coordination Volume	15K days	186K days	40K days	227K days
Decision Wait Volume	62K days	0K days	184K days	0K days

Industrial Age Mission-Environmental Scenario

Column 1 of the table includes eight measures used here to summarize and report the results. Column 2 includes values for the Hierarchy Organization in the Industrial Age (HOIA) scenario. This can be considered as a baseline for comparison with the other organization-scenario results. The other three columns pertain to results from the remaining cells of our 2 x 2 experimental design. In the first two rows, the measures *duration* and *cost* quantify, respectively, the length of time (expressed here in days of calendar time) and cost (expressed here in billions of dollars[iii]) required for performance of a mission. For instance, in the case of the baseline (HOIA) scenario, simulated duration and cost are 227 days and $12B, respectively.

Project risk is a measure of project-level tasks left incomplete at the end of a mission. Clearly some tasks are more important than others are, and it is unnecessary often to complete 100% of all assigned tasks. But the more tasks that remain incomplete, the higher the risk of missing an important one and jeopardizing mission success. Hence this measure provides a gauge of mission risk. It is expressed as the fraction of total effort (e.g., work, cost) that would have to be expended, *in addition to the time and cost incurred for mission performance*, to perform the remaining work and coordination tasks that were left incomplete at the end of a mission. For instance, the first scenario value of 0.36 indicates that an additional 36% of time and cost would be required to complete all of the tasks left undone at the end of the mission.

Maximum backlog represents the magnitude of assigned work that accumulates over time in the in-box or queue of a particular actor in the model. It is a measure (expressed here in work days) of how far behind the actor is at the peak. The further behind one gets (i.e., larger work backlog), the more difficult it is for the actor to attend to even very important tasks at hand, to coordinate with others, and to make decisions that are important to guide other actors' work tasks. In this scenario, the Commander actor accumulates progressively greater backlog over time and experiences a peak value of 24 days in Month 4. This phenomenon is characteristic of centralized organization and decision making.

Work volume is described above as a construct used to measure the magnitude of work tasks performed by each actor. The values reported in the table (expressed here in thousands of work days) reflect accumulated totals of all tasks performed by all actors. The value for our scenario is 830K days. Notice this value is much higher than the 227 days duration reported above. Because multiple actors perform their tasks concurrently, many thousands of days of work volume can be accomplished on each calendar day. Consider, for instance, if 1000 people work for one day to complete a mission component. The elapsed calendar time (i.e., 1 day) would be reported by the measure *duration*, and the magnitude of effort (i.e., 1000 work days or 1K day) would be reported by the measure *work volume*.

The other three "volume" measures—*rework, coordination* and *decision wait*—are expressed in the same units. Rework measures the magnitude of effort expended on fixing mistakes. The value for our scenario is 131K days; that is, in addition to the 830K days of direct work reported above, actors in this scenario expend the equivalent of another 131K days of effort on rework. Coordination measures the magnitude of effort expended on communicating and coordinating between actors. The value for our scenario is 15K days; that is, in addition to the 830K days of direct work reported above, actors in this scenario expend the equivalent of another 15K days of effort on coordination. Decision wait measures the magnitude of time spent by actors waiting for decisions to be made. The value for our scenario is 62K days; that is, in addition to the 830K days of direct work reported above, actors in this scenario expend the equivalent of another 62K days waiting for decisions to be made. These values are all reflective of a Hierarchy performing in mission-environmental conditions that are characteristic of the Industrial Age Military.

In terms of comparison, notice the Edge organization performs the same mission tasks, in this same Industrial Age scenario (EOIA), in almost the identical length of time (i.e., 223 days). Indeed, the two duration values are statistically indistinguishable from one another. Hence in this scenario, the Hierarchy and Edge organizations perform their missions equally quickly. But the Edge organization performs its mission tasks for three-fourths the cost (i.e., $9B) incurred by the Hierarchy. The lower cost reflects in part the absence of Command Headquarters and staff functions. The lower volume of rework for the Edge (i.e., 113 vs. 131K days) contributes in part also to the lower cost, as the Edge organization invests less time and effort in reworking mistakes than the Hierarchy does.

Alternatively, notice the Edge experiences over twice the project risk of the Hierarchy (i.e., 0.78 vs. 0.36). Recall this measures the magnitude of tasks that are left incomplete at the end of a mission. When compared with the Hierarchy, the Edge organization—relying on concurrent and decentralized mission execution—leaves more incomplete tasks left to be done and hence experiences greater risk to mission success. Here the results point to the Edge concept representing a metaphorical two-edge sword: missions are accomplished more cheaply but with greater risk. Such tension between cost and risk is consistent with previous empirical results (e.g., see [46]). The leader or manager must decide for him or herself what kinds of tradeoffs between these competing performance measures are appropriate.

The maximum backlog of the Edge organization (i.e., 14 days for the Ground A units) is nearly half that experienced by the Hierarchy Commander (i.e., 24 days). This reflects the relatively autonomous and distributed, self-organizing and self-synchronizing nature of Edge organizations. But still, interdependencies between different units and mission tasks require coordination, information seeking and decision making, which can cause work to back up in any organization. Notice the work volume is a bit smaller for the Edge organization than for the Hierarchy (i.e., 819 vs. 830K days). The volume of mission tasks (i.e., performed by the Operating Core) is the same for both organizations. The difference reflects principally that of Command Headquarters and staff functions in the Hierarchy.

In contrast with the lower rework volume discussed above, the coordination volume for the Edge organization is an order of magnitude greater than for the Hierarchy (i.e., 186 vs. 15K days). This reflects the tremendous time and energy required to coordinate and control distributed, decentralized, concurrent, reciprocally interdependent work activities. Finally, notice the Edge organization experiences zero decision wait volume. Actors in the Edge organization do not wait around for Commanders and others to make decisions. Rather, they do the best that they can with the knowledge and skills that they possess or can acquire quickly. This contributes in part to the somewhat faster mission execution speed and considerably lower execution cost. But it is offset in part by higher mission risk and order-of-magnitude greater coordination effort.

In all, comparing emulated performance of the Hierarchy and Edge organizations across this set of eight measures, one cannot say definitively that one organizational form or the other is "better." *Better* is in the eye of the beholder (i.e., is constructed socially) and depends upon what performance factors are considered to be important by Stakeholders who matter. For instance, if mission cost (e.g., consider factors such as *budget deficits, weapon system recapitalization,* and *Social Security funding needs)* is paramount, then one would consider the Edge organization to represent a superior choice in this Industrial Age scenario. Alternatively, if mission risk (e.g., consider factors such as *collateral damage, casualties,* and *political embarrassment*) is key, then one would consider the Hierarchy to represent a more conservative choice. Again, both organizational forms have their relative advantages and disadvantages, and both perform the same Industrial Age missions at equivalent speeds. The choice is dependent upon Stakeholders' relative utilities and preferences.

21st Century Mission-Environmental Scenario

Quite unlike the results reported and discussed above for the Industrial Age mission-environmental scenario, in this 21st Century emulation of comparative organizational performance, the Edge organization completes its mission tasks roughly a third faster (e.g., 235 vs. 314 days) and much less expensively (e.g., $10 vs. 16B) than the Hierarchy does. Indeed, notice the Edge organization performs it missions in this demanding, 21st Century scenario almost as fast as the Hierarchy does in the comparatively simple, Industrial Age context (i.e., 235 vs. 227 days).

Further, the Edge organization's performance does not degrade nearly as severely across scenarios. The Hierarchy performs much worse in this 21st Century scenario than it does in the Industrial Age mission-environmental context (e.g., 314 vs. 227 days, $16 vs. $12B). In contrast, the Edge organization's performance degrades only by 5 – 10%. It is important to remember, the magnitude of operations-level work to be performed (e.g., as measured by *work volume* of the operating core) is the same across scenarios. Only the mission-environmental context changes. Alternatively, the Edge performance results continue to reflect much higher mission risk than those pertaining to the Hierarchy do. Even in the 21st Century scenario, a fundamental tension between cost and risk continues to hold.

Notice how the magnitude of rework, coordination and decision wait time more than double and even triple for the Hierarchy organization across these two scenarios (i.e., 422 vs. 131; 40 vs. 15; 184 vs. 62K days, respectively). This organization has a very difficult time operating in the 21st Century mission-environmental context. The Edge organization experiences sizeable increases in rework and coordination also (i.e., 166 vs. 113; 227 vs. 186K days). But it still experiences zero decision wait time. And the magnitude of increases in such measures grows more slowly in the Edge organization than in the Hierarchy. In mathematical terms, the *first derivative* is positive for both organizational forms (e.g., in terms of *duration, cost, rework* and *coordination*) as mission-environmental demands increase. But the *second derivative* appears to be quite different (e.g., considerably smaller for the Edge than for the Hierarchy) when comparing the alternate and contrasting organizational forms. We do not have enough results to plot or measure such derivatives, or to even determine their signs. But we can observe that the Edge organization appears to be more robust across scenarios. The more demanding that mission-environmental contexts become, the more appropriate the Edge organization may prove to be.

Conclusion

The *Edge* represents a fresh approach to organizational design, moving knowledge and power to the edges of organizations. But this raises issues in terms of comparative performance with respect to alternate organizational designs (esp. military C2). The research described in this article represents the first stage of a multi-disciplinary, multi-year investigation into the design and efficacy of Edge organizations for current and future, military, mission-environmental contexts. Specifically, we employ methods and tools of computational experimentation to compare empirically the performance of current and competing organizational forms. In this closing section, we note multiple contributions to C2 research. We also suggest several insights and results that are amenable to immediate practical application. And we reveal key parts of an exciting agenda for continued research along the lines of this investigation.

Through this research, we illustrate how computational methods are able to mitigate problems experienced with both laboratory (e.g., external validity) and field (e.g., internal validity) research methods. Developing semi-formal, computational models also enables researchers to overcome much of the residual ambiguity inherent in natural language description. By committing to a parameterized, computational representation, researchers are able to be clear about exactly what they mean by terms such as *centralization, uncertainty* and *interdependence*, for instance. Through our discussion above, and the detailed appendices that follow, the Reader should be able to understand exactly how we have developed and specified the models of Hierarchy and Edge organizations discussed in this article[iv]. This contributes to C2 research through theoretical clarity that is uncharacteristic for scholarly discourse in the military domain.

This first study begins by specifying computational models of Hierarchy and Edge organizations in the C2 domain. Rooted firmly in Organization Theory, yet cognizant of military operations, in this article we report the bases and results of such specification in considerable detail. Drawing from Organization Studies, we survey a large variety of organizational forms and illustrate the power of abstraction through organizational archetypes. And through our two-step approach to model development, we draw strongly from the literature to indicate the organizational archetypes that fit most closely the current conceptualizations of contemporary military C2 and Edge organizations. This contributes to C2 research by rooting such conceptualizations firmly in the literature. We contribute also to Organization Theory by articulating the “new” form *Edge* in a manner that is rooted firmly in the knowledge accumulated through its scholarly literature.

Further, we design an experiment with three, orthogonal manipulations—mission-environmental context, network architecture and professional competency—to compare explicitly the performance of two, competing, organizational forms—Hierarchy and Edge—across two, contrasting, mission-environmental scenarios—Industrial Age and 21st Century. The full-factorial, 3 x 2 x 2 experimental design leverages our theoretically rooted organizational characterizations from above by identifying a set of essential properties pertaining to Edge organizations and by defining key propositions for their performance in the kind of 21st Century, mission-environmental context forecast for their efficacy. As with our commitment above to semi-formal, computational modeling, we also reduce residual ambiguity pertaining to how the future C2 mission-environmental context is characterized. This contributes to C2 research by extending and refining current Edge conceptualizations and “theory,” respectively.

Preliminary, experimental results reveal insightful dynamic patterns and differential performance capabilities of Hierarchy and Edge C2 organizations. We illustrate how Hierarchy and Edge organizational forms manifest qualitatively different behaviors when performing a common set of mission tasks in the military C2 domain. In the context of an Industrial Age mission and environment, Hierarchy and Edge organizations perform equivalently in terms of mission speed. But results reveal what appears to be a fundamental tension between mission cost and risk. We also illustrate fundamental differences between dynamic behaviors of these alternate and competing organizational forms, through performance measures such as *rework, coordination, backlog* and *decision wait time*. Together, these empirical measures, results and insights contribute to C2 research by illustrating the use and utility of computational experimentation and by quantifying empirical results of Hierarchy and Edge organizations performing head-to-head on contemporary C2 missions.

Additionally, by comparing both Hierarchy and Edge organizations across contrasting mission-environmental scenarios, we elucidate how the Edge organization—as we have specified it here—appears to be more robust to increases in the demands, uncertainties and dynamics of different contextual scenarios. Here we contribute to C2 research in a major way: developing new contingency theory in this domain that both describes and explains—empirically—the organizational characteristics and behaviors contributing to *fit* with diverse mission-environmental contexts. This serves to add new theory that can be applied immediately and directly to practical problems in military C2. We contribute further by illuminating how one organizational form is not inherently or fundamentally “better” than another across all scenarios and in all circumstances. Hence the choice of one organizational form versus another depends most fundamentally upon which performance factors are considered to be most important by Stakeholders who matter. This serves to temper some of the hyperbole surrounding the Edge organizational form at present.

Nonetheless, the research described in this article represents just one, small step toward developing and accumulating new knowledge and applying it to improve organizational performance. Yet it represents an important step that opens up a rich array of future research. For instance, our imminent studies will focus on model validation in the field and on conducting computational experiments according to the full-factorial design described above. As other instances, in parallel with the present hypothesis-testing research, we are engaged also in theory-building work in areas such as knowledge inventory measurement and optimization [35], intercultural organizational interactions and trust effects [21]. Additionally, we continue to develop and enhance the computational toolset to incorporate such theoretical developments [52]. And we employ other, existing computational tools such as a scholarship-based expert system to induce requirements and to delineate transformation pathways for Edge organizations [44]. We engage richly in fieldwork as well, both to develop new theory through ethnographic research and to apply, test and validate our models through examination of operational organizations in their real-world environments. Because *edge* is defined by where organizations interact directly with their environments, for us to conduct cutting-edge research, the edge is where we need to be and where we intend to stay.

Of course every study has limitations. Ours is clearly no exception. Computational experimentation is suited well to complement, not to replace, other research methods [46]. Plus, several aspects of our model conceptualization, specification and parameterization include admittedly substantial interpretation and judgment. And we have yet to take these computational models out into the field for calibration. But we employ demonstrated methods and validated tools. And we are committed to empirical validation in the field. Moreover, we encourage replication of our models and results to enhance reliability.

Finally, even a first study such as this, offering only a sample of preliminary results, contributes to C2 research and provides new, valuable, immediately applicable insight. And we look forward to continuing our contributions to C2 knowledge through research. Moreover, as academic researchers in this military domain, we are committed to education and practical application as well as to theory development. In addition to conference presentation and journal publication, we hope to formalize new knowledge developed through Edge research into novel university and professional courses that can bring our contingency-theoretic results and insights down to the deck plate level—or in Edge parlance, to where and when it is needed most: at the *edge.*

References

[1] Alberts, D.S. and Hayes, R.E., *Power to the Edge* CCRP (2003).

[2] Badaracco, J.L., Jr., *The Knowledge Link: How Firms Compete through Strategic Alliances* Boston, MA: Harvard Business School Press (1991).

[3] Box, G.E.P., Hunter, W.G. and Hunter, J.S., *Statistics for Experimenters: an Introduction to Design, Data Analysis and Model Building* New York, NY: Wiley (1978).

[4] Brown, S.L. and Eisenhardt, K.M., *Competing on the Edge: Strategy as Structured Chaos* Boston, MA: Harvard Business School Press (1998).

[5] Burris, B.H., *Technocracy at Work* Albany, NY: State University of New York Press (1993).

[6] Burton, R.M. and Obel, B., *Strategic Organizational Diagnosis and Design: Developing Theory for Application* (Second Edition) Boston, MA: Kluwer (1998).

[7] Campbell, D.T. and Stanley, J.C. *Experimental and Quasi-Experimental Designs for Research.* Chicago, IL: Rand McNally (1973).

[8] Carroll, T. and Burton. R.M., "Organizations and Complexity: Searching for the Edge of Chaos," *Computational & Mathematical Organization Theory* 6:4 (2000), pp. 319-337.

[9] Chandler, A.D., Jr., *Strategy and Structure: Chapters in the History of the American Industrial Enterprise* Cambridge, MA: MIT Press (1962).

[10] Cheng, C.H.F., and Levitt, R.E., "Contextually changing behavior in medical organizations," Proceedings of the 2001 Annual Symposium of the American Medical Informatics Association, Washington, DC (Nov 3-7, 2001).

[11] Christiansen, T.R., *Modeling Efficiency and Effectiveness of Coordination in Engineering Design Teams* doctoral dissertation, Department of Civil and Environmental Engineering, Stanford University (1993).

[12] Ciborra, C.U., "The Platform Organization: Recombining Strategies, Structures, and Surprises," *Organization Science* 7:2 (1996), pp. 103-118.

[13] Cloke, K. and Goldsmith, J., *The End of Management and the Rise of Organizational Democracy* San Francisco, CA: Jossey-Bass (2002).

[14] Cohen, G.P., *The Virtual Design Team: An Object-Oriented Model of Information Sharing in Project Teams* doctoral dissertation, Department of Civil Engineering, Stanford University (1992).

[15] Constantin, E., Papapanagiotou, N. and Singh, S., "Analysis of DDD and VDT Simulation Techniques to Determine feasibility of Using VDT Simulation to Validate DDD Models," MBA application project, Graduate School of Business & Public Policy, Naval Postgraduate School (June 2004).

[16] Cook, T.D. and Campbell, D.T., *Quasi-Experimentation: Design and Analysis Issues for Field Settings* Boston, MA: Houghton Mifflin (1979).

[17] Davidow, W.H. and Malone, M.S., *The Virtual Corporation* New York, NY: Harper Business (1992).

[18] Fyall, M., "When Project Information Flow Becomes Turbulent: Toward an Organizational Reynolds Number," CIFE Technical Report #138, Stanford University (2002).

[19] Galbraith, J.R., *Organization Design*, Addison-Wesley, Reading, Massachusetts (1977).

[20] Garstka, J. and Alberts, D., "Network Centric Operations Conceptual Framework Version 2.0," U.S. Office of Force Transformation and Office of the Assistant Secretary of Defense for Networks and Information Integration (2004).

[21] Gavrieli, D.A. and Scott, W.R., "Exploring and Exploiting Intercultural Knowledge Flows in Edge Organizations: Trust as an Enabler," *Proceedings* International Command and Control Research and Technology Symposium, McLean, VA (June 2005).

[22] Handy, C., *The Age of Unreason* Boston, MA: Harvard Business School Press (1990).

[23] Hansen-Bauer, J. and Snow, C., "Responding to Hypercompetition: The Structure and Processes of a Regional Learning Network Organization," *Organization Science* 7:4 (1996), pp. 413-427.

[24] Hayes, R.E., and Iwanski, S., "Analyzing Effects Based Operations (EBO) Workshop Summary," *PHALANX* 35:1 Military Operations Research Society (March 2002).

[25] Heckscher, C., “Defining the Post-Bureaucratic Type,” in: C. Heckscher and A. Donnellon (Eds.), *The Post-Bureaucratic Organization: New Perspectives on Organizational Change* Thousand Oaks, CA: Sage (1994).

[26] Hedlund, G., “The Hypermodern MNC—A Heterarchy?” *Human Resource Management* 25:1 (1986), pp. 9-35.

[27] Jaffe, G., “New Factor in Iraq: Irregular Brigades Fill Security Void,” *Wall Street Journal* 245:33 (16 February 2005).

[28] Jin, Y. and Levitt, R.E., “The Virtual Design Team: A Computational Model of Project Organizations,” *Computational and Mathematical Organization Theory* 2:3 (1996), pp. 171-195.

[29] Johnson, R.A. and Wichern, D.W., *Applied Multivariate Statistical Analysis* (Third Edition) Englewood Cliffs, NJ: Prentice Hall (1992).

[30] Keen, P.G.W., “Telecommunications and Organizational Choice,” in: J. Fulk and C. Stenfield (Eds.), *Organizations and Communication Technology* Newbury Park, CA: Sage (1990).

[31] Kunz, J.C., Levitt, R.E. and Jin, Y., “The Virtual Design Team: A Computational Simulation Model of Project Organizations,” *Communications of the Association for Computing Machinery* 41:11 (1998), pp. 84-92.

[32] Lawrence, P.R. and Lorsch, J.W., *Organization and Environment: Managing Differentiation and Integration* Boston: Division of Research, Harvard Business School Press (1967).

[33] Levitt, R.E., Thomsen, J., Christiansen, T.R., Kunz, J.C., Jin, Y. and Nass, C., “Simulating Project Work Processes and Organizations: Toward a Micro-Contingency Theory of Organizational Design,” *Management Science* 45:11 (1999), pp. 1479-1495.

[34] Liebeskind, J.P., Oliver, A., Zucker, L and Brewer, M., “Using Social Networks to Gain Competitive Advantage: Sourcing Scientific Knowledge in New Biotechnology Firms,” *Organization Science* 7:4 (1996), pp. 428-443.

[35] MacKinnon, D.J., Levitt, R.E. and Nissen, M.E., “Knowledge as Inventory: Near-Optimizing Knowledge and Power Flows in Edge Organizations (Phase One),” *Proceedings* International Command and Control Research and Technology Symposium, McLean, VA (June 2005).

[36] Malone, T.W., *The Future of Work: How the New Order of Business Will Shape Your Organization, Your Management Style, and Your Life* Boston, MA: Harvard Business School Press (2004).

[37] Malone, T.W., Yates, J., and Benjamin, R.I., “Electronic Markets and Electronic Hierarchies,” *Communications of the ACM* 30 (1987), pp. 484-496.

[38] Maxwell, D., “SAS-050 Conceptual Model Version 1.0,” NATO C2 conceptual model and associated software (2004).

[39] McKelvey, B., *Organizational Systematics: Taxonomy, Evoluation, Classification* Berkeley, CA: University of California Press (1982).

[40] Miles, R.E. and Snow, C.C., *Organizational Strategy, Structure, and Process* New York: McGraw-Hill (1978).

[41] Mintzberg, H., *The Structuring of Organizations* Englewood Cliffs, NJ: Prentice-Hall (1979).

[42] Monge, P.R. and Fulk, J., “Global Network Organizations,” paper presented to International Communication Association, Albuquerque, NM (1995); cited in Fulk, J. and DeSanctis, G., “Electronic Communication and Changing Organizational Forms,” *Organization Science* 6:4 (1995), pp. 337-349.

[43] Nissen, M.E., "Understanding 'Understanding' Flow for Network-Centric Warfare: Military Knowledge-Flow Mechanics," NPS Technical Report NPS-GSBPP-02-001 (2002).

[44] Nissen, M.E., “A Computational Approach to Diagnosing Misfits, Inducing Requirements, and Delineating Transformations for Edge Organizations,” *Proceedings* International Command and Control Research and Technology Symposium, McLean, VA (June 2005).

[45] Nissen, M.E., *Harnessing Knowledge Dynamics: Principled Organizational Knowing & Learning* Hershey, PA: Idea Group Publishing (forthcoming 2005).

[46] Nissen, M.E. and Buettner, R.R., “Computational Experimentation with the Virtual Design Team: Bridging the Chasm between Laboratory and Field Research in C2,” *Proceedings* Command and Control Research and Technology Symposium, San Diego, CA (June 2004).

[47] Nissen, M.E. and Levitt, R.E., "Agent-Based Modeling of Knowledge Dynamics," *Knowledge Management Research & Practice* 2:3 (2004), pp. 169-183.

[48] Nogueira, J.C., *A Formal Model for Risk Assessment in Software Projects* doctoral dissertation, Department of Computer Science, Naval Postgraduate School (2000).

[49] Ouchi, W.G., *Theory Z* Reading, MA: Addison-Wesley (1981).

[50] Perrow, C., “A Framework for Comparative Analysis of Organizations,” *American Sociological Review* 32 (1967), pp. 194-208.

[51] Piore, M.J., “Corporate Reform in American Manufacturing and the Challenge to Economic Theory,” in: T. Allen and M. Scott-Morton (Eds.), *Information Technology and the Corporation of the 1990s: Research Studies* New York: Oxford University Press (1994).

[52] Ramsey, M.S and Levitt, R.E., “POW-ER: a Computational Framework for Experimentation with Edge Organizations,” *Proceedings* International Command and Control Research and Technology Symposium, McLean, VA (June 2005).

[53] Scott, W.R., *Organizations: Rational, Natural, and Open Systems* (Fifth Edition) Upper Saddle River, NJ: Prentice-Hall (2003).

[54] Senge, P., *The Fifth Discipline: The Art and Practice of the Learning Organization* New York, NY: Doubleday (1990).

[55] SimVision, Online Help and Tutorial, Version 3.11 (2005).

[56] Smith, E., *Effects Based Operations: Applying Network Centric Warfare in Peace, Crisis, and War* Washington, DC: CCRP Publication Series (2003).

[57] Stinchcombe, A.L., *Information and Organizations* Berkeley, CA: University of California Press (1990).

[58] Thompson, J. D., *Organizations in Action: Social Science Bases in Administrative Theory*, McGraw-Hill, New York (1967).

[59] Thomsen, J., *The Virtual Team Alliance (VTA): Modeling the Effects of Goal Incongruency in Semi-Routine, Fast-Paced Project Organizations* doctoral dissertation, Department of Civil and Environmental Engineering, Stanford University (1998).

[60] VDT. The Virtual Design Team Research Group website; URL: http://www.stanford.edu/group/CIFE/VDT/ (2005).

[61] Volberda, H.W., "Toward the Flexible Form: How to Remain Vital in Hypercompetitive Environments," *Organization Science* 7:4 (1996), pp. 359-374.

[62] Weber, M., *The Theory of Social and Economic Organization* (1947 translation), A. Henderson and T. Parsons (Eds.), Glencoe, IL: Free Press (first published in 1924); cited in Scott, W.R., *Organizations: Rational, Natural, and Open Systems* (Fifth Edition) Upper Saddle River, NJ: Prentice-Hall (2003).

[63] Williamson, O.E., *Markets and Hierarchies: Analysis and Antitrust Implications* New York, NY: Free Press (1975).

Appendix A – Hierarchy Organization Model

This appendix provides additional detail pertaining to specification of the Hierarchy organization model. Recall Table 3 above summarizes the three design factors (Column 1) and parameter settings for the Hierarchy (Column 2) and Edge (Column) organizations. We reproduce the Hierarchy portion of this summary as Table 6 below for reference and organize the discussion in terms of the three design factors.

Table 6 Representation of the Hierarchy Organization

Design Factor	Hierarchy
Organization Structure	- High *centralization* - High *formalization* - Low *matrix strength* - 3-level hierarchy - Command (PM): 3 FTE - Coordination (SL): 200 FTE - Operations (ST): 40,000 FTE - 4, large units - Med *skill level*
Communication Structure	- Vertical channels - “Wheel” structure - Few communication links - *Information exchange* (0.1) - Push communications - Low *application experience* - Meetings (2 hr/day, 10%)
Work Structure	- 4 operational tasks - Sequential execution (2-Ph) - Sequential interdependence - *FEP* (0.1) - *PEP* (0.1) - Leader demands extra - *Work duration* (3 months) - Loose coupling - *Rework strength* (0.3) - Command & staff rework

Organization structure. We begin with organization structure factors from Table 2 such as *coordination, specialization, formalization, grouping,* and *decentralization*. For the Hierarchy, *centralization* and *formalization* are set to “high” levels, and *matrix strength* is set to “low.” These three parameters combine to form a suite of variables that have been used in prior work to characterize bureaucratic C2 organizations [Nissen & Buettner]. We include also a three-level managerial hierarchy to depict explicitly command (3 full-time equivalents (FTEs) to reflect a coalition type environment; this corresponds to the Strategic Apex), coordination (200 FTEs including both line and staff; this corresponds to the Middle Line and both Technical and Support Staffs), and operations (40,000[v] FTEs; this corresponds to the Operating Core) levels of the C2 organization. Multiple, additional levels within each of these are represented implicitly as well, as the actors at each level are specified as collectivities; that is, each “actor” represents a collection of people. Collectivity size increases geometrically with distance from the center (e.g., top of the hierarchy) and toward the edge (i.e., bottom of the hierarchy).

Communication structure. Next we address the communication structure. Drawing from our theoretical characterization summarized in Table 2 above, the "few" versus "many throughout" liaison activities are represented here. For the Hierarchy, communications are principally vertical in nature, following the formal lines of hierarchical organization and authority. This representation is reinforced by the high *centralization* factor noted above in terms of structure. The communications configuration follows approximately the "wheel" structure (e.g., with two, nested "hubs") described in [Carroll & Burton]. We represent this further through inclusion of only *few communication links* in the model. Communication links are depicted by the screenshot in Appendix B as connections between specific tasks (e.g., Command and Staff). Commensurately, we represent the Hierarchy as an organization with low *information exchange* ($p = 0.1$), which affects information processing corresponding to the communications links included. Push, broadcast style information dissemination is characteristic also of the Hierarchy. This complicates the information-processing tasks associated with searching for and learning important knowledge (e.g., learning what is necessary, when it is needed). We represent this with low *application experience*. Finally, many meetings (e.g., 2 hours daily for the Command, Coordination and Staff organizations; 10% allocation except for Command at 100%) are included to represent the manner in which high-level coordination is conducted principally today.

Work structure. In terms of work structure, the representation for the Hierarchy organization is adapted from [Nissen & Buettner]. The work structure specifies principally what tasks need to be accomplished. For purposes of control in this computational experiment, both organizations are required to perform the same four operational tasks: 1) suppression of enemy air defenses (SEAD) Missions, 2) Surface Missions, 3) Ground Missions, and 4) close air support (CAS) Missions.

Following current doctrine, the Hierarchy organization plans and executes its operational tasks in two, sequential phases of two tasks each (i.e., "2-Ph"). The first task of Phase 1, SEAD, follows current doctrine of attacking first enemy defenses and C2 capabilities to enable air superiority and debilitate an adversary's coordination capabilities. Roughly three months of effort are planned for this task, to be accomplished by approximately 500 people. The second involves maritime interdiction, mine-clearing, shore bombardment, and like activities to get invasion forces ashore. Roughly three months of effort are planned for this task also, although it entails a much larger force of approximately 9000 people. This latter, surface mission can begin at the same time as the SEAD. But the two are loosely coupled and relatively independent (i.e., interdependence is *pooled* [Thompson]).

When these first two missions are complete, the campaign reaches a milestone at which Phase 2 is ready to begin. The third task begins Phase 2 and involves ground missions to attack targets, weaken resistance, and capture territory. Roughly three months of effort are planned for this task. It entails a very large force of approximately 27,000 people. The fourth mission, CAS, involves the use of aircraft to support ground forces. Roughly one month of effort is planned for this task, with approximately 500 people assigned. It begins at the same time as the Ground Mission but involves only loose coupling pooled interdependence. In this kind of loosely coupled, nearly independent work structure, we use relatively low values for the two error parameters: *functional error probability (FEP* = 0.1) and *project error probability (PEP* = 0.1).

We also follow [Carroll-Burton] to include level-of-effort tasks that we label "Leader demands" in the table. These represent activities and priorities (e.g., coordinating with Headquarters, staff work, organizational maintenance) beyond the four mission tasks above. Such demands are heavy in the Hierarchy, as even Battle Theater Commanders in a Machine Bureaucracy must spend great time attending to people above, below and lateral to themselves. The command actors have one such leader task, and the staff organizations work jointly on another. The *work duration* used to specify this effort is 3 months for both. Complexity and uncertainty are specified as "medium" for this kind of work.

Finally, loose coupling characterizes the Hierarchy, as *failure dependencies* between different tasks are relatively weak. We specify this using the *rework links* shown in Figure 2, with relatively high *rework strength* (0.3) in the case of the Hierarchy. This reflects the importance of good performance at each stage of a sequentially dependent workflow. Further, in the Hierarchy, we include rework links to the Staff leader demands activity from each of the four mission tasks. This represents the manner in which staff organizations must respond to the progress, exceptions and uncertainties pertaining to the warfare tasks. It represents also how command staffs are stressed by operational activities.

Appendix B – Edge Organization Model

This appendix provides additional detail pertaining to specification of the Hierarchy organization model. Recall Table 3 above summarizes the three design factors (Column 1) and parameter settings for the Hierarchy (Column 2) and Edge (Column) organizations. We reproduce the Edge portion of this summary as Table 7 below for reference and organize the discussion in terms of the three design factors.

Table 7 Representation of the Edge Organization

Design Factor	Edge
Organization Structure	- Low *centralization* - Low *formalization* - High *matrix strength* - 1-level meritocracy - Command (PM): 0 FTE - Coordination (SL): 0 FTE - Operations (ST): 40,000 FTE - 16, smaller units - Med *skill level*
Communication Structure	- Horizontal network - “Circle” structure - Many communication links - *Information exchange* (0.9) - Post & smart pull - Med *application experience* - P2P communications
Work Structure	- 16 operational subtasks - Concurrent execution - Reciprocal interdependence - *FEP* (0.2) - *PEP* (0.2) - Leader demands emergent - *Work duration* (0) - Tight coupling - *Rework strength* (0.1) - No Command or staff

Organization structure. We begin with organization structure factors from Table 2 such as *coordination, specialization, formalization, grouping,* and *decentralization*. In contrast to the Hierarchy above, the Edge organization has opposite settings for these three parameters and only a single-level meritocracy; that is, no one is designated *ex-ante* as being “in charge.” The parameter settings are consistent with our *Professional Adhocracy* characterization of the Edge organization. And the flattened hierarchy and meritocracy depict the kinds of peer-to-peer coordination and emergent leadership characterized in current Edge conceptualizations. The same total number of people is included in the operating core of both the Edge and Hierarchy organizations. But the number of separate units is four times larger in the Edge organization than in the Hierarchy. This represents the theoretical difference in terms of unit size (i.e., large for Machine Bureaucracy, small for Professional Adhocracy). Similarly, we represent *training and indoctrination* the same way for both Hierarchy and Edge organizations: by specifying the same, "medium" skill levels (i.e., adequate for the tasks at hand) for actors.

Communication structure. Next we address the communication structure. Drawing from our theoretical characterization summarized in Table 2 above, the "few" versus "many throughout" liaison activities are represented here. In contrast with the Hierarchy, the Edge organization is represented differently. A horizontal communication network, comprised of lateral communications, is reinforced by the low *centralization* factor noted above in terms of structure. The communications configuration follows approximately the "circle" structure (e.g., 3, interconnected circles for Air, Surface and Ground mission tasks) described in [Carroll & Burton]. This represents an intermediate configuration between centralized communications (e.g., "wheel") and a fully connected network (e.g., where everyone communicates with everyone else). We represent this further through inclusion of *many communication links* in the model. See the screenshot in Appendix C. Commensurately, we represent the Edge as an organization with high *information exchange* (p = 0.9), which affects information processing corresponding to the communications links included. Post-and-smart-pull communication is characteristic also of the Edge. This facilitates the information-processing tasks associated with searching for and learning important knowledge (e.g., learning what is necessary, when it is needed). We represent this with medium *application experience*. Peer-to-peer (P2P) communications, on demand, characterize the Edge approach to coordination without Command-level meetings every day.

Work structure. In terms of work structure, the representation for the Hierarchy organization is adapted from [Nissen & Buettner]. The work structure specifies principally what tasks need to be accomplished. For purposes of control in this computational experiment, both organizations are required to perform the same four operational tasks: 1) suppression of enemy air defenses (SEAD) Missions, 2) Surface Missions, 3) Ground Missions, and 4) close air support (CAS) Missions.

In contrast with the Hierarchy, the work structure for the Edge organization is different entirely. The Edge organization undertakes most parts of all four missions concurrently, composing itself from 16 smaller units to accomplish different parts when and as appropriate. And performance of most mission tasks is concurrent: only a small number of tasks are dependent sequentially (i.e., Air Missions 2 follow Air Missions 1D; Ground Missions E follow Ground Missions D, which follow Surface Missions E; Surface Missions A follow Air Missions 1A; and Air Missions 2 start with Ground Missions E). This difference can be observed by visual comparison of the work structures depicted in Figures 2 and 3. The successor links emphasize the concurrent nature of work tasks and the difference of this arrangement from that described and delineated above for the Hierarchy. The communication links noted above reinforce this difference, as they represent tight coupling and a preponderance of reciprocal task interdependence in the Edge work, which requires coordination via mutual adjustment [Thompson]. This represents a contrast with the preponderance of pooled and sequential interdependence in the Hierarchy, the coordination of which can be accomplished via standardization and planning, respectively. Notice this is consistent with our theoretical characterization [Mintzberg] of coordination differences in Table 2. In this kind of tightly coupled, highly interdependent work structure, we use higher values for the error parameters: (*FEP* = 0.2; *PEP* = 0.2).

In further contrast with the Hierarchy, because of empowerment in the Edge organization, leader demands—although still present—are emergent from within the coordination requirements of the many different actors. Hence no additional task or *work duration* is specified for such activity. However, the model emulates the effects through dynamic communication, coordination and decision making between actors. Additionally, the Edge organization exhibits much tighter coupling between tasks than the Hierarchy does, and it has correspondingly denser failure dependencies. Indeed, a rework link is included between every activity that shares a

communications link. But a lower *rework strength* (0.1) is used to represent the positive effects of coordination via mutual adjustment as opposed to planning and sequential execution.
In final contrast with the Hierarchy, the Edge organization does not have command and staff organizations.

Appendix C – Model Parameter Definitions

In this appendix, we both paraphrase and quote from [SV online help] to include definitions of the model elements and parameters that are discussed above and applicable to the computational experimentation reported in this study.

Activity-See Task.

Actor-See Position.

Application experience-A measure of how familiar the position or person is with similar projects.

Behavior file-A file that specifies the simulator's default behavior, such as how much rework to add to tasks with exceptions.

Centralization-A measure of how centralized the decision-making is in a project. For example, high centralization indicates that most decisions are made and exceptions handled by top managerial positions such as the Project Manager. Low centralization means decisions are made by individual responsible positions.

Communication-The passing of information between positions about tasks.

Communications link-A dashed green link that links two tasks, indicating that the position responsible for the first task must communicate with the other position during or at the completion of the first task.

Coordination-A combination of the information exchange generated by communication and meetings.

Coordination Volume-The predicted time during a project or program that all positions spend at meetings and processing information requests from other positions.

Critical path-The set of tasks in a project that determine the total project duration. Lengthening any of the tasks on the critical path lengthens the project duration.

Decision wait time-The time a position waits for a response from the supervisor about how to handle an exception, plus any time the position waits for exception resolution before making the decision by default. See also Wait Volume.

Exception-A situation detected by the simulator where part of a task requires additional information or a decision, or generates an error that may need correcting.

Exception handling-Involves positions reporting exceptions to supervisors and supervisors making decisions on how to deal with the exceptions.

Failure dependency link-See Rework link.

Formalization-A measure of the formality of communication in an organization. For example, high formalization indicates that most communication occurs in formal meetings.

FRI (Functional Risk Index)-A measure of the likelihood that components produced by a project have defects. Also called CQI, or Component Quality Index.

Full-time equivalent (FTE)-A measure of position or person availability to perform a task. For example, a position with an FTE value of 3 has the equivalent of 3 full-time employees to perform tasks.

Functional exception-An error that causes rework in a task but does not affect any dependent tasks.

Links-A set of color-coded arrows that represent the relationships between shapes.

Matrix Strength-A measure of the level of supervision in a project or program, and a reflection of the structure of the organization. Low matrix strength means that positions are located in skill-based functional departments and supervised directly by functional managers. High matrix strength means positions are co-located with other skill specialists in dedicated project teams and have project supervision from a Project Manager.

Meeting-A gathering of positions to communicate about the project and project tasks.

Meeting Participant link-A dashed grey line that links a position to a meeting, indicating that the position must attend the meeting.

Milestone-A point in a project or program where a major business objective is completed.

Model-A visual representation of a program and its projects.

Noise-The probability that a position is distracted from assigned tasks.

Organization-A group of departments that staff a program or project.

Organization Assignment link-A solid pink line that links an organization to a project within a program.

PM-Project Manager, the position that assumes overall responsibility for a project.

Position-An abstract group representing one or more FTEs (full-time equivalents) that performs work and processes information. In a staffed project, positions represent a person or a group of persons.

PRI (Project Risk Index)-A measure of the likelihood that components produced by a project will not be integrated at the end of the project, or that the integration will have defects. PRI is thus a measure of the success of system integration.

Primary Assignment link-A solid blue line that links a position to a primary task, which is a task that takes priority over any secondary assignments.

Program-A set of related projects that share dependencies and together achieve the client's business objectives. A program also includes the associated responsible organizations, milestones, and relationships between projects.

Project-A project represents work an organization must perform to achieve a major business milestone. The work is represented by tasks, milestones, the positions that perform tasks, meetings, and the dependencies between all these elements. While a model may contain numerous projects, it need only contain one. Each project in a model supports the goal of the program to which the project belongs.

Project exceptions-Errors that might cause rework in a driver task and all its dependent tasks.

Project Exception Rate-The probability that a subtask will fail and generate rework for failure dependent tasks. This probability is generally in the range 0.01 (low) to 0.10 (significant, but common). If the Project Exception Rate is greater than about 0.20, so much rework can be generated that the project may never finish.

Project Successor link-A solid black line that links a project to another project or to a project milestone.

Rework-Redoing all or part of a task. Compare with direct work.

Rework Cost-The predicted cost of rework, or rework volume weighted by average cost per FTE of positions that do rework.

Rework link-A dashed red line that links a task to a dependent task that will need rework if the driver task fails.

Rework Volume-The predicted time needed for all positions on a project to do the required rework.

Scenario-See Case.

Secondary Assignment link-A dashed blue line that links a position to a secondary task, which is a task that can be worked whenever the position is not working on a primary task.

Simulator-Software that simulates the work done by positions as they perform individual project tasks, including both planned direct work and coordination and rework.

Simulation charts-Charts that summarize and provide details of the simulated performance of the program and the individual modeled projects.

Successor link-A solid black line that links milestones and tasks.

Supervision link-A solid black line that links a supervisory position to its supervised position.

Task-Any work that consumes time, can generate communications or exceptions, and is required for project completion.

VFP (Verification Failure Probability)-The probability that an exception will be generated for a task. The VFP is calculated during simulation based on a number of factors, including noise, communication rates, and team experience.

Wait Volume-A measure of the cumulative time spent by positions waiting for decisions to be made in a project.

Work volume-The predicted time that all positions on a project spend doing direct work.

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[i] The static level may not reflect excellent face validity in either representation when examined alone, but the relative effects of the differences—when the two scenarios are examined comparatively—are likely to be preserved faithfully through dynamic behavioral emulation. Here we trade off some static validity to ensure valid dynamic behaviors.

[ii] The reason stems from validation concerns. In addition to the bottom-up, theoretically driven model specification effort that constitutes the focus of this article, we need to also perform some top-down, empirically driven model validation and calibration work in the field. Because C2 represents a relatively new domain for VDT application, such additional effort is important to ensure that dynamic behaviors of our computational models are representative of those exhibited by operational C2 organizations in the field. Nonetheless, as noted above, the VDT modeling environment has undergone extensive field validation in other domains (e.g., power plant construction and offshore drilling, see [Christiansen 1993]; aerospace, see [Thomsen 1998]; software development, see [Nogueira 2000]; healthcare, see [Cheng and Levitt 2001]; others). Hence we feel comfortable presenting these preliminary results to illustrate the use and utility of computational experimentation.

[iii] These are relative values, not absolute cost estimates. They are useful for comparison across scenarios. This reflects the validation of the model to represent the correct directions and relative effects of performance variables across different scenarios. But do these cost figures do not purport to reflect the right orders of magnitude. Additional effort to push beyond model validation (i.e., get the direction and relative effects right) and to calibrate it (i.e., get the absolute values right) represent items on our agenda for future research.

[iv] We will be happy to send copies of the SimVision model files upon request. The Reader must obtain his or her own copy of SimVision or comparable software to run the models.

[v] Because these values are very large with respect to the SimVision software, we reduce proportionately the number of FTEs and the corresponding work volumes for the operations level actors and tasks, respectively. This has negligible effect on the results when compared across cases.