SENSE AND RESPOND LOGISTICS:
THE FUNDAMENTALS OF DEMAND NETWORKS

CAPT Linda Lewandowski, US Navy
Office of the Secretary of Defense, Office of Force Transformation

Jeffrey R. Cares
Alidade Incorporated

ABSTRACT

Prevailing wisdom from the Industrial Age holds that the best way to provide logistics to a force is with a highly optimized supply chain. Emerging logistics concepts suggest that application of Information Technology (IT) might enable supply chains to reach unprecedented levels of optimality. At the same time, however, Information Age warfighting concepts suggest fluid, self-organizing military forces. This paper describes a logistics concept that relies on IT-enhanced adaptation and learning, rather than optimization, to transform supply chains into demand networks that more effectively support combat operations. The resulting concept, "Sense and Respond Logistics," is developed in detail using plain language. An appendix of technical and scientific underpinnings provides a deeper exploration of the concept's fundamentals.

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I. INTRODUCTION

Throughout the last decade, long-range planners in the defense industry have proposed concepts for Information Age Warfare, under the rubric of Network Centric Warfare, that use information technology to solve long-standing military challenges and effectively address emerging ones. These challenges include destruction of time-critical targets, theater-wide search and surveillance, long-range power projection, and access to contested littoral areas.[1] Many of these concepts are expected to result in fielded forces that are distributed, networked, highly robust and dynamic.

Long-standing practices in logistics and supply chain management, however, work best in environments where there are high levels of stability and predictability. In other words, they are not designed to cope with the quickly evolving and adaptively *ad hoc* behaviors envisioned for future military forces. Indeed, most concepts proposed for Information Age logistics suggest applying Information Technology (IT) only to improve existing processes and do not address the need (particularly at the tactical level) for Information Age logistics processes that are as robust and dynamic as the forces they would serve. This paper introduces the Sense and Respond Logistics concept, a theory of logistics management that, for the purposes of supporting distributed, networked forces in the most challenging operational and tactical environments, values flexibility, adaptation and learning over predictability, precision and optimization.

Concepts for Focused Logistics

Logistics, by definition, is the "process of planning and executing the projection, movement, sustainment, reconstitution and redeployment of operating forces in the execution of national security policy."[2] Even under the most benign conditions, logistics systems are susceptible to poor information or prediction about consumption rates, transport delays or interruptions, high transportation costs, inter-modal bottlenecks, high warehousing costs (including force protection), operational impacts (e.g., Operational Plan changes), poor information or prediction about transfer rates, poor visibility into the flow of critical items and poor management of arrival of sequenced commodities (e.g., those that require other prerequisite or preparatory items). Some of the solutions proposed to address these problems include better information and prediction about consumption rates, faster transport, cheaper transport, more efficient inter-modal transfer, reduced stockpiling, quicker delivery or shuttle platforms, better information and prediction about transfer rates, better visibility into critical items and better understanding of item sequencing.

Some of these solutions require improvements to the physical characteristics of the supply chain elements, yet most would be the result of improvements to the information conditions in a supply chain. The Joint Staff has proposed the application of IT to improve the information conditions in future logistics systems. Joint and Service future logistics concepts are centered on the idea of "Focused Logistics," which has been defined as the "fusion of logistics information and transportation technologies for rapid crisis response, deployment and sustainment, the ability to trace and shift units, equipment and supplies even while en route, and delivery of tailored logistics packages and sustainment directly to the warfighter." Focused Logistics is concerned with Joint deployment and rapid distribution of logistics, with an increased emphasis on movement velocity, time-definite delivery, reduced footprint, streamlined processes and centrally managed and fused information. Suggesting that a supply chain might trade inventory for speed aided by information, focused logistics concepts expect that an agile infrastructure, reliable information and accelerated cycle times will create "Lean Logistics," "Precision Logistics," or systems that rely mainly on "Velocity Management." Such systems are normally scoped for the theater level of war, advertising an ability to provide a CINC with the capacity to centrally synchronize, prioritize, integrate and coordinate all supply chain efforts in theater. These concepts clearly state that they place a high premium on optimizing the supply chain, and that the best use of IT is to dramatically improve optimization.[3]

Sense and Respond Logistics

The extent to which a supply chain can be optimized, however, depends on the complexity and predictability of the operations serviced by the supply chain. In some parts of a Joint force, operations might be quite "simple" (such as operational level of war OUTCONUS force buildup operations in a protected rear area).[*] For these parts of an operation, a simple, highly optimized supply chain (such as that envisioned by Focused Logistics) will perform best. As operations become more "complex," however, so must the supply chain. This case will be made in Sections II, III and IV.

Prototypical Industrial Age Warfare is characterized by limited communications, massed forces, centralized command, control and decision making, and information that is difficult to obtain and hard to share. The introduction of IT into military force structures is serving to change some important facets of warfare, and the new prototype is characterized by physical dispersion, distributed information, and decentralized cognition. These new characteristics can increase ambiguity and uncertainty of important facets of a future military force:

- ambiguity and uncertainty of purpose, because units are not compelled to act in tight formations or groups
- ambiguity and uncertainty of boundaries, because IT applications and networking can create connections and associations between elements of a force that heretofore might never have interacted
- ambiguity and uncertainty about the essential structure of an organization, as teams and elements task organize themselves to adjust to unfolding opportunity and risk
- ambiguity and uncertainty about what to measure and assess, as the purposeful, collective behavior of a networked force can be more important than, say, the location and movements of individual elements.

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[*] This is not meant to imply that these logistics operations are somehow trivial or easy. A technical discussion of this use of the terms "simple" and "complex" will be provided in later sections.

The Sense and Respond Logistics concept is being developed to cope with these ambiguities. The concept relies on adaptation, flexibility, agility and responsiveness, all within a "learning," networked context, not a reactive or predictive, optimized model of the supply chain. As such, Sense and Respond Logistics operations are most appropriate for regimes of higher complexity, such as those at the tactical level. Sense and Respond Logistics relies on clever commanders using and sharing local information to improve logistics support rather than centrally collecting information, controlling processes and dictating local decisions from a remote perspective. Sense and Respond Logistics aims to reduce ambiguity: of purpose by translating global governing principles into local rule sets; about boundaries by placing local coordination of modular units at a premium; about essential structure by clearly articulating roles and responsibilities rather than directing behavior and about what to measure by providing a deeper understanding of battle force dynamics.

Sense and Respond Logistics achieves these aims by enabling self-synchronization via local coordination through IT systems, encouraging interaction, connection and recombination at the lowest echelon possible so that innovative teams can emerge to meet local challenges, closing feedback loops so that all levels and perspectives in the force can learn from each other, and by vigorous education and training in the most complex and challenging extremes of the operational spectrum.[4]

Sense-and-respond logistics aims to enable flexibility, rather than focusing on a single 'optimal' process. Sense and Respond Logistics is a concept to create a level of complexity in logistics that matches the complexity in operations. Enabled by IT, Sense and Respond Logistics is not just an Information Age concept because Information Technology is used – it is an Information Age concept because it exploits the advantage from Information Age models of decentralization, adaptation and self-synchronization to solve challenging logistics problems. Sense and Respond Logistics transform highly optimized supply chains to dynamically adaptive demand networks that more closely conform to unfolding battlefield conditions while remaining intimately connected to commander's intent, thereby enabling more fluid operations and creating an ability to seize local opportunities as they develop.

The following sections describe the basic scientific and technical mechanisms that make Sense and Respond Logistics an attractive concept. Section II explores the relationship between the complexity of a system and the most effective type of control that the system admits. Section III discussed recent advances in Network Theory, including implications for networked, distributed systems. Section IV describes a method of observing and controlling complex systems. The conclusion describes how these underpinnings can be applied in practice to detailed development and experimentation. An appendix is provided for those who prefer a more formal treatment of the science and mathematics behind the concept.

II. OPTIMIZATION, CONTROL, COMPLEXITY AND SCALE

Optimization in the real world is closely allied with control – managers, for example, seek to optimize a system mainly to influence or control the things they manage. Indeed, when a system is deemed "optimized," modern managers assume all events and processes are in a sweet spot of productivity, efficiency and profitability. In other words, "things are under control." If the system becomes less than optimal, experts are called in to help regain control by dissecting events and processes to look for even greater degrees of effectiveness.[5] This section discusses three main points. First, this type of optimization is best applied to very stable systems, usually those that are very tightly controlled or highly engineered, i.e., "simple" systems. Second, that many systems are much more robust and dynamic, possessing a range of complex behaviors. Third, that the match between optimization and simplicity is a general property of control: the best control mechanism is one that matches the complexity of the controlled system. These three closely related ideas are indeed new perspectives for control of complex logistics processes.

Optimization

Whether or not supply chain can be optimized depends not on the system itself, but on the stability and predictability of the system, other systems and the environment with which it interacts. Paradoxically, is stability and predictability of a system decrease too much efficiency can actually impair the ability of a system to function properly. To see how this might happen even in a very simple, linear system, consider the idea of "make-span" in production line fabrication. A piece of metal that proceeds through a milling process consisting of several machining steps, is the object of a process that literally "spans the making" of the piece. If a certain amount of time is required on each machine, then the total milling time plus all the transfer and set up time equals the make-span. If there is sufficient transfer time, then the entire process can tolerate the failure of one step, and, for example, work-arounds can be employed.[6] As the transfer time is shortened, however, the probability that the entire process fails can increase dramatically. This is shown graphically in Figure 1.

The parallel with supply chains is direct: *if too much slack is removed from a supply chain, the entire chain becomes much less tolerant of change, and the logistics operations can fail catastrophically.* Of course, supply chain operations are much more complex than the finely engineered process of production line fabrication. Furthermore, logistics operations are not just inherently complex, but they incur additional complexity and uncertainty because they are inextricably connected to combat operations themselves. Moreover, Information Age warfighting concepts suggest that fluid, self-organizing military forces will be the norm, at least at the tactical level. Indeed, it has been proposed that the primary source of advantage in distributed, networked forces arises from networked effects that are distributed in many dimensions throughout a force and can be summoned for use in the manner of advantage chosen by clever commanders based on evolving conditions.[7]

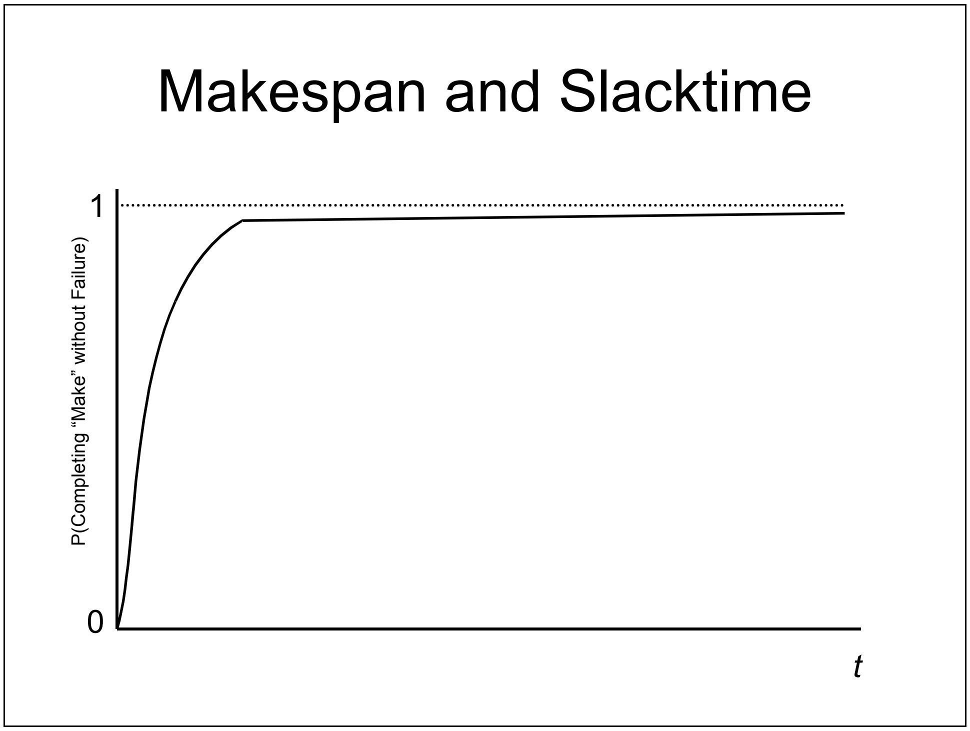

Figure 1

Complexity and Scale

The complementary concepts of complexity and scale help bring the relationship of optimization to control into tighter focus. If one technically defines *complexity* as the number of ways a system can be described, then it is helpful to think of the *scale* at which useful descriptions can be found.[8] To illustrate, at the three-star level, a large amphibious landing might be described in terms of, say, ships, objectives, Marine Expeditionary Units (MEUs) and the total number aircraft sorties. From the perspective of the amphibious ship captain or the MEU commanding officer there is much more detail, including transit lanes, synchronized waves, landing zones, and flight schedules. In addition, there are some issues from the higher scale that are not relevant or useful (perhaps not even observable) at this scale. From the individual Marine's viewpoint, there may a host of detail that changes rapidly from one moment to the next, particularly while attempting to cross a hostile beach under fire or while egressing a transport helicopter in a contested landing zone.

This continuum from a coarse description at a high scale to a more detailed, yet still aggregated, description at medium scales to a great deal of rapidly changing detail at the finest scales is a property of most complex systems. In other words, in the most complex parts of a system, fine scale descriptions tend to be more informative. In less complex parts of a system, coarse, simple, high scale descriptions are sufficient. A graph showing the continuum of complexity and scale for littoral operations such as this notional amphibious operation is shown in Figure 2. It has a curve typical of systems with a great deal of complexity in one part, moderate complexity in another yet relatively simple in yet another part.[9] The curve is "scale free": there is no single scale at which the all the important system behaviors can be described. Systems exhibiting such a complexity-scale profile are called scale free systems. These systems require "multi-scale representation" to show behaviors and structure at the scale at which they are most informatively displayed.[10]

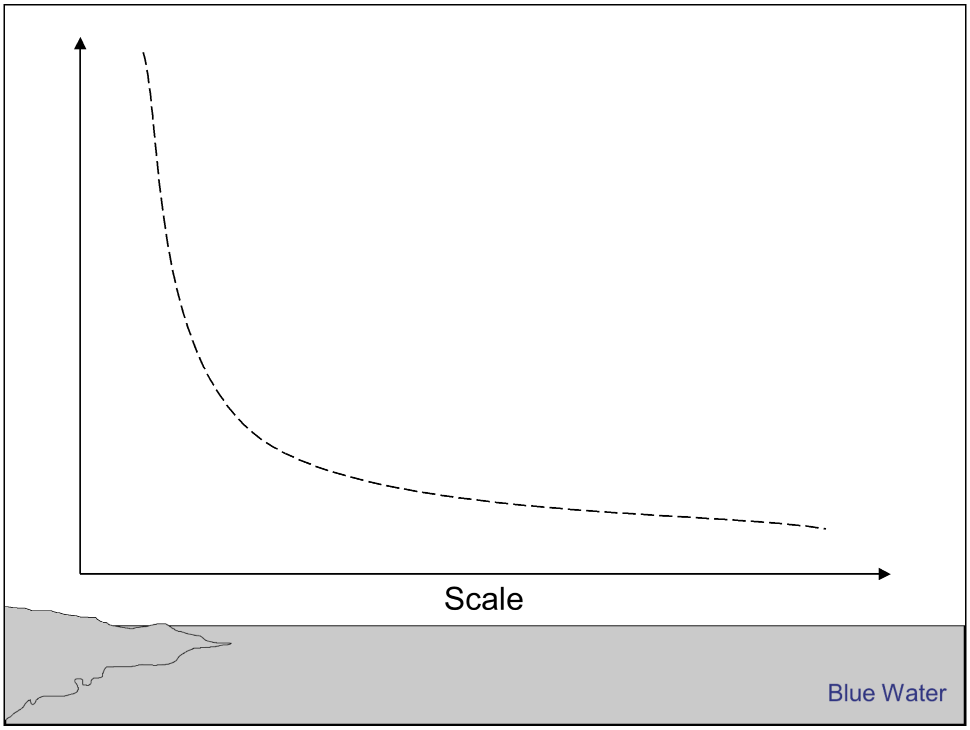

Figure 2

"No Free Lunch" Theorem For Control

In the fields of Mathematics and Computer Science, optimization is a quantitative, analytical process for finding solutions to very hard problems in the shortest time possible. Researchers have recently derived what they call the "No Free Lunch (NFL) Theorem" of optimization, which says there are no universally best optimization routines. This theorem proves that all algorithms perform well on one type of problem at the expense of performance on other types of problems. The reason for is this that the success of an optimization routine depends on the extent to which the structure of the algorithm matches the structure of the problem.[11] Another way to say this is that the scale of the routine that performs best is the same as the scale of the problem. Therefore, there exist no universally efficient problem solving routines for scale free complex problems, only routines that might work best on different parts of a problem. A collection of these routines would exhibit the same scale free properties as the problem itself.

The same logic can be applied to control of scale free complex systems. If a system includes parts with different degrees of complexity, then local behaviors occur at scales and complexities substantially different than global behaviors. The globally optimized control process cannot control local behaviors. Treating the consumptive behavior of a force as a "problem" to be solved by logistics, one can propose a similar "No Free Lunch Theorem for Logistics": the best logistics system is one in which the complexity of the logistics process most closely matches the complexity of operations.

Making the Connections

To summarize, optimized chains can be brittle in the face of dramatic external changes while complex systems and processes are sensitive to the scale at which they are observed, manipulated or controlled. A general theorem for control systems states that a control process or algorithm must be appropriately matched to the system to which it is applied. If combat processes are complex (a fundamental assumption of this concept), then the process for controlling the logistics function of the process must account for these facts. The following sections explore these ideas more fully.

III. CHAINS, NETWORKS AND PROFILES

The previous section presented two conclusions: first, that highly optimized chains are brittle and susceptible to catastrophic failure under dynamic conditions and second, that for sufficiently complex systems, scale free control systems outperform control systems with limited scale. What logistics structure, then, should be used to overcome the brittleness and scale of a chain? The answer to this question lies in a formal examination of the larger class of structures of which a chain is only one type: networks.

Basic Networks

Many people confuse abstract mathematical networks with IT structures. Understandably, office IT "networks" are often the only networks most of them see in their daily lives. Formally, however, what mathematicians call a network is any collection of arcs and nodes. Mathematical networks are typically used to model flows or analyze dynamics in a networked, distributed system.* A *connected network* is one in which every node is attached to the network by at least one arc. A *minimally connected network* is one in which the nodes are all connected with the minimum number of arcs possible (one less than the number of nodes). When a minimally connected network is laid out so that the collection of arcs and nodes resembles a string of pearls, then this network is called a chain. The features of a chain are that they are brittle, require many "hops" to get from one end of the chain to the other, are not very densely connected (in the jargon of networks, they are not very clustered), they have a simple pattern and require simple control. As stated earlier, a chain has a definitive scale and is not a good structure for a complex logistics system.

At the other extreme is another kind of network, the maximally connected network. In this network, each node is directly connected to all other nodes. Maximally connected networks have more arcs and more possible subnets than any other type of connected

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* The ideas described here are presented in mathematical detail in the appendix.

network and are therefore the most expensive and complex of all connected networks. However, they are robust (because of their extreme redundancy, snipping arcs will not cause catastrophic failure), require only one hop to get to any other location in the network, are very clustered, have a simple pattern and are scaled. Because they have a definitive scale and because the number of subnets grows at a phenomenal rate, these networks are not good candidates for a logistics structure that is useful in complex environments.

A less extreme network than the chain or the maximally connected network is the "regular" network, also known as a "lattice" or "grid." These networks have a standard number of nodes for each arc. A piece of graph paper with nodes placed at each intersection of a vertical and a horizontal line would create a "regular network of degree four." These networks are robust, require many hops to navigate the grid, are highly clustered, retain a simple pattern and require simple control.[12] These networks are also scaled and are therefore poor candidates for the structure of a logistics system under complex conditions. Other scaled networks, such as the random network (in which arcs and nodes are randomly connected) or the Small World Network (a network with the features of both regular and random networks) are likewise not good candidates.[13]

Scale Free Networks

Recent research into the topology of the internet, collaboration networks of scientists, and the structure of other networked systems has led to the discovery of a new class of networks, scale free networks.[14] Such networks arise because of the popularity or the importance of particular nodes (based, typically, on some value that accrues because of the importance of these nodes to the networks' structure or function), as well as the fact that complex networks usually grow node by node, so that older nodes tend to be more connected than younger nodes (by the simple fact that their older age permits more opportunities). The distribution of arcs among their nodes looks very much like complexity-scale profiles of complex systems; the interplay of complexity and scale in these networks is, in fact, an identical mechanism. They have very few nodes connected to by a large number of arcs (these are the networks' "hubs"), a small number of moderately connected nodes and they have a lot of nodes connected by a very few arcs (the networks' "spokes").[*] These networks are very robust, require only a few hops to get from one place to another in the network, are not very clustered, have complex patterns and require complex control. Best of all, these networks are scale free and hence are very good candidates for a logistics network in complex environments.

Diffusion Profiles

Scale Free Networks (like other complex networks) have an additional property not available to chains that might be exploited by logistics networks. This property is the tendency for these networks to diffuse commodities in a non-linear pattern. While chains typically diffuse at a fixed rate, complex networks reach a "tipping point" where the rate

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[*] Scale free networks are different from other types of hub-spoke networks, such as centralized networks with only one hub that connects all nodes in that the distribution of arcs among the nodes matches the complexity-scale curve found in Figure 2. In other words, the presence of intermediate sized hubs in a key feature of scale free networks. The appendix explains this point mathematically.

of diffusion suddenly increases dramatically until the network begins to reach maximum capacity and the rate begins to slow. This results in an "S" curve.[*] The steepness of the curve and the takeoff point are related to the network structure and are affected by initial values, diffusion rate of a critical mass, and local spreading rates. Scale-Free Networks have some of the steepest curves, and hubs can appear very early in network formation. More interestingly, hubs and patterns can be created, disappear and then reappear by changing only a relatively few arcs.[15] If this property can somehow be plied to advantage in a logistics network, then scale free networks are not only a good structures for logistics networks because they satisfy the No Free Lunch Theorem, but also because they are very adaptive and flexible.

IV. CONTROL IN COMPLEX COMPETITIVE ENVIRONMENTS

If a logistics network is merely to supply forces in peacetime garrison, then one might call the demand-supply interaction a "closed system," meaning that exogenous factors do not greatly impact an observer's ability to monitor the logistics system, decide what to do and then control it. Combat operations (as well as many other real-world non-combat operations), are "open systems" as enemies and adversaries often thwart even the best-designed plans.[16] Even for friendly observers, the control task can become increasingly complex merely by the addition of competition. In such cases, friend and foe are faced with the very difficult challenge of control in complex systems.

Control in Complex Systems

The main problem with control of complex systems in competition arises from the fact that not only are behaviors occurring at many different scales (including time scales), but also that many of the behaviors are the result of actions that one side cannot control: the actions of the adversary.[17] To determine how to control such a system by observation alone requires an ability to discern patterns (signals) in observed behavior (that includes both signal and noise) of the system. Some types of signals are usually evident and known to both sides: information about the basic structure of the environment, the competition, as well as information about the competitors that is not likely to change during the time scale of the competition. After this basic structure (signal) is determined, everything else might appear random (noise). However, within this "apparent noise" are two other types of information: dynamic patterns yet to be discovered and true noise.[18] As more observations are made, the goal is to extract signal out of the apparent noise, combine it with the structural information already known and create a better picture of the competition. This "learning through feedback" is central to the success in controlling complex systems (and one of the hallmarks of a sense and respond concept). [19]

Great difficulty, however, lies in fact that an observer must watch a system for an infinite amount of time to determine which part of a system is structure and which part is pure random noise.[20] Since no one has an infinite amount of time to watch a system (and particularly not during dynamic lethal competition), the control problem can get quite messy. For this reason, it is even more important to interact with the competitive system

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[*] A more complete and formal description of these diffusion patterns is found in the appendix.

at as many scales as possible. This serves to ensure that one observes important behaviors on the scale at which they occur and increases the chances that actions on a particular scale might not be observed by a competitor who is not observing at the right scale. Lastly, controlling one's own system is much easier than trying to control an enemy's system because even in the face of an interrupted plan, friendly operations are still driven by friendly commander's intent. This insight is a crucial advantage in complex control since a great deal of apparent noise will make sense when viewed through the lens of commander's intent. By contrast, trying to control by observation only is one of the most difficult tasks in complex environments.

Advantage in Distributed, Networked Forces

Although rudimentary military networks have existed for many decades, preliminary concepts for advanced networked forces began to emerge in the early 1990s. These concepts mirrored a similar phase of technological innovation in other industries: the initial thrust was in developing systems to help people perform current tasks better. One drawback, however, is that there is an upper limit on improving existing processes with IT networks— the upper performance limit of the process itself. Soon after concepts for networked forces began to circulate in the defense community, concepts for smaller distributed forces began to emerge. The basic assumption: distributing a networked military force creates more options for a commander, increases the surveillance burden of an adversary, and allows fires to be massed while forces remain dispersed. Without proper networking, however, distributed forces are at risk. There is, therefore, great advantage to both networking and distributing. Military applications have a unique characteristic that profoundly capitalizes on distributed, networked effects: advantage can emerge from a broad pool of inputs and manifest itself in a multitude of ways, each of which will not likely be evident to an opponent until advantage is ready to be applied.[21] The methods of sense-making and control in complex systems will therefore continue to grow in importance as concepts for future distributed, networked forces mature.

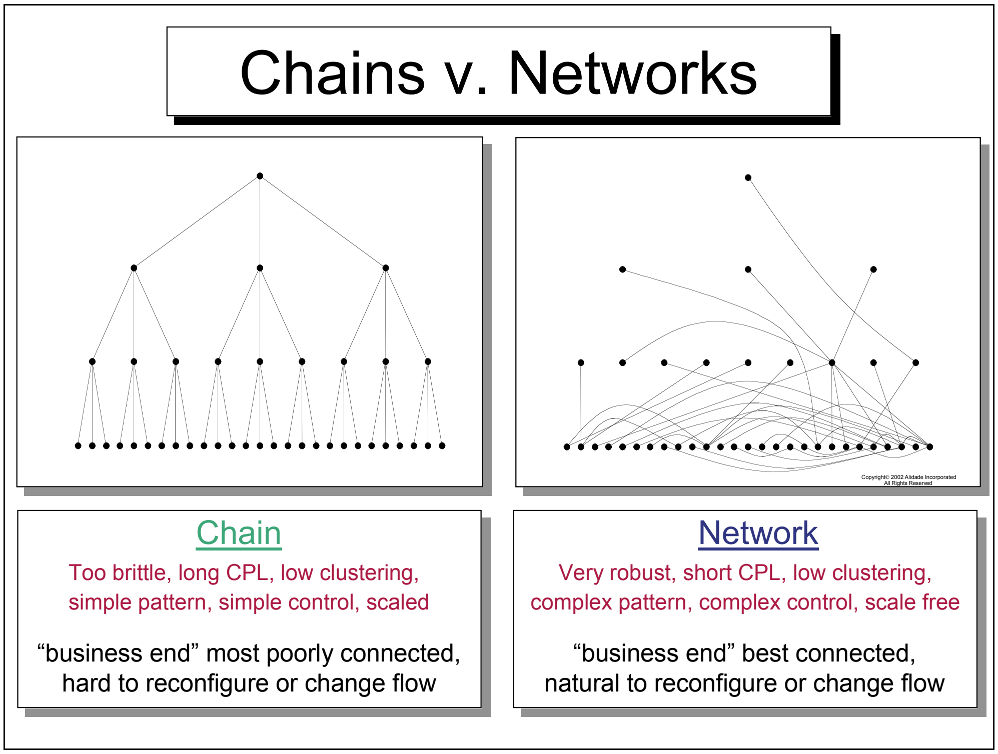
V. SENSE AND RESPOND LOGISTICS

The last three sections laid down the scientific and technical fundamentals of Sense and Respond Logistics. The concept itself can now be more formally presented.

Chains v. Networks

Figure 2 underscores the difference between supply chains and networks. The left is a prototypical, hierarchical supply chain. As discussed in Section III, this chain is brittle and requires quite a bit of re-routing/retrograding to move commodities from one side of the chain to the other. In addition, although its simple pattern suggests simple control, an enemy likewise has a simple task to understand and influence this network. Since it is not a scale free network, it will not easily respond to changes in a complex environment. Since it is not a complex network, it cannot exploit the S-curve effect of nimble reconfiguration. In addition, notice a particular feature of using such chains for logistics: the most important nodes – the one's in contact with the enemy – are the least connected.

Contrast this with the network on the right, a scale free network. This network is very robust and has a short “characteristic path length” (CPL, the average distance from one side of the network to another). It is scale free, which means it can quite naturally adapt to changes in the competitive environment, and although its complex pattern requires complex control, the network is nonetheless more protected against efforts by an enemy to understand the intent behind its operations. Finally, note how the most important nodes in the network – those in contact with the enemy, are very well connected.



Chains v. Networks

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Chain

Too brittle, long CPL, low clustering, simple pattern, simple control, scaled

“business end” most poorly connected, hard to reconfigure or change flow

Network

Very robust, short CPL, low clustering, complex pattern, complex control, scale free

“business end” best connected, natural to reconfigure or change flow

Figure 2.

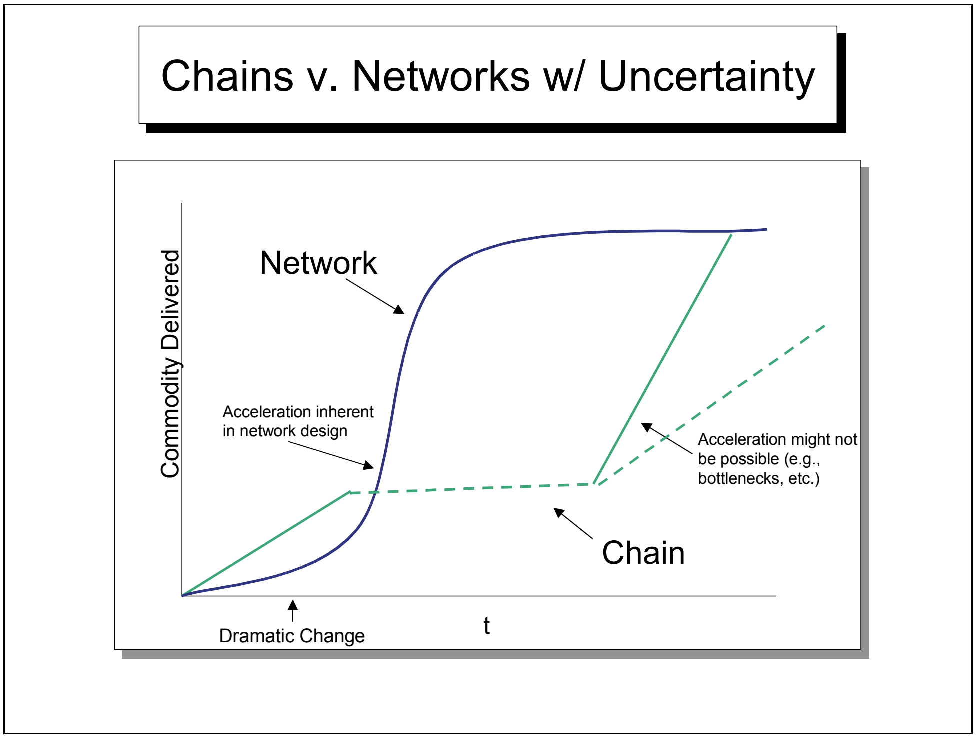

Figure 3.

Figure 3 shows another important difference between chains and networks. It shows a graph of the accumulation of commodities over time. While both the network and the chain appear to do well initially, the performance of each type of logistics system begins to diverge if operations experience dramatic a change. In a supply chain, commodities, by design, accrue roughly linearly, limited by the throughput capacity of nodes. A dramatic change will require a substantial shift in flow, to possible include retrograde and re-shipment down alternative paths. This can effectively cause the rate of throughput to plummet, as represented by the nearly horizontal dashed line. Once the system is reconfigured, the supply chain can then attempt to accelerate delivery to demand centers in response to the external stimulus. Unfortunately, because few alternate paths exist, this acceleration might be hampered by the original throughput of the system. By contrast, the S-shaped curve of the network takes a shape (and delivery rates) opposite to the supply chain. By exploiting the ability to rapid move hub and spokes through re-connection of relatively few nodes, the network can deliver supplies at a very rapid rate when they are needed most.

Supply v. Demand

It is telling to note the prominence that the word "supply" has in the contemporary logistics community. The Defense Department has supply centers, units have supply officers and the Navy even has a Supply Corps. This focus on supply rather than demand is a perspective rooted firmly in Industrial Age logistics when the gap between consumption and re-supply could be many days, weeks or months, but never near-real time. The "supply system" focused on decreasing time or cost of delivery, and optimized supply chains became the standard. With the advent of advanced IT, companies like WalMart turned the supply chain into a high art, using the new technology to refine the chain via dis-intermediation (removing levels of hierarchy by rapidly informing suppliers of purchases right at the check-out lane) or via better prediction (gathering scads of data from hundred of stores and millions of customers). As profitable and beneficial as such a system is, it is still a chain; as illustrated by the makespan case, this chain still has an upper limit of efficiency. This system would function poorly under the type of uncertainty, complexity and scales inherent in military operations.

By contrast, "demand" is a much better term for Sense and Respond Logistics than "supply." Demand is the true control signal in the logisitics system, containing more information about local operational conditions than a classic aggregation of supply chits ever can. Demand for the tools of battle is intimately related to unfolding battlefield operations, including the uncertainties of combat, and is also quite closely tied to commander's intent. Legacy (classic?) supply processes require great predictability, depend on the statistics of stability for efficiency and remain a lagging response to dramatic changes in battle conditions. Demand signals provide the best insight into required control methods for complex systems and allow Sense and Respond Logistics to adapt by learned response rather than planned reaction. Further, supply is a proxy for the demand signal; focusing on demand simplifies the process of assessing own-force operational patterns yet preserves an adversary's difficulty of control by observation.[this last clause needs to change some, but I don't know how yet]

VI. CONCLUSION

By turning supply chains into demand networks, Sense and Respond Logistics can provide a transformational capability to combat support. Units will no longer be at the far end of a delivery system – those in the main effort will become hubs for logistics support and the system itself can quickly configure to create, remove or reconstitute these hubs as situations warrant. Scale-free units of issue (another word for modularity) will be at a premium in Sense and Respond Logistics, as adaptive Unit-to-Unit (U2U) resupply becomes the norm, not the exception. The demand networks of Sense and Respond Logistics will more closely tie logistics to operations through commander's intent (perhaps even turn enemy units into receptor hubs for ourcombat power) while obscuring friendly strategies in a distributed logistics train and operating without a centralized dump. More importantly, Sense and Respond Logistics will be a true Information Age capability as adaptive learning, networked advantages and distributed decision making replace reactive planning, mass and centralized control. [maybe consider deleting or modifying reference ot U2U and modularity, since this is the first time they are mentioned.]

APPENDIX

SCIENTIFIC AND TECHNICAL FUNDAMENTALS

Introduction

- Logistics/Supply Chain Theory
- Adaptive Enterprise/S&R Concept
- Network Flows and Graphs
  - Scale Free Networks (c. 1999-2002+)
- Multi-scale Representations
- Diffusion of Innovations
- Social Network Analysis
- Complex Control Theory
- Physics of Information

Network Theory

21 July, 1999

Title: Network Fundamentals
Author: LCDR Jeffrey R. Cares, USN

ABSTRACT

This paper discusses the fundamentals of arranging objects in a network. Basic network arrangements are discussed and different network statistics are examined. A particular type of network, the "Small World," is offered as an example of networks with desirable characteristics. Collective choice schemes are explored. The paper concludes that warfare networks must have operationally derived structure to be useful in combat.

I. Introduction

Contemporary military strategists predict that improvements in information technology will provide a revolutionary advance in warfare capability. A new method of combat, Network Centric Warfare (NCW), has emerged as an operational concept that capitalizes on this advance. Central to the concept of NCW is the notion that combat objects are arranged in networks.[*] In general, however, a discussion of the behavior of networks is absent from the literature of this emerging revolution. This paper discusses the behavior of ob $\sum_{i}^{n-1} i$ in a network, the character of their interactions and the extent of their connectivity. cifically, this paper concludes that the key characteristics of a warfare network are the organizing principles that underlie its behavior.

II. Theory

a. Networks

What is commonly called a *network* is actually a *graph*. A graph is a simple collection of *arcs* and *nodes*. When values are assigned to the arcs and nodes, a system with its own logic is created and this system is properly called a *network*. Networks are typically used to mathematically model flows, analyze network circulation or evaluate costs in a dynamic, distributed system. Since the calculation of flows is beyond the scope of this paper, the remainder of the discussion and related figures do not include arc and node values. The complexity avoided by this simplification is significant.

III. Discussion

a. Minimally Connected Networks

A *connected network* is one in which every node, n, is attached to the network by at least one arc. A *minimally connected network* is one in which the nodes are all connected with the minimum number of arcs possible, i.e., $n - 1$ arcs. Figure 1 shows a minimally connected network with 16 nodes and 15 arcs. A minimally connected network contains different sub-networks. The number of subnets in Figure 1 is 120.

Minimally connected netwo $\sum_{i}^{n-1} i$ ave fewer arcs and fewer subnets than any other connected network and are therefor cheapest and simplest connected networks, but they have less redundancy and commodities take much longer to proliferate among the nodes. A network statistic that measures commodity proliferation is the characteristic path length, L. L is a measure of the average length of a path from any one node to every other node. Minimally connected networks have the largest L of any connected network.

b. Maximally Connected Networks

A *maximally connected network* is one in which every node is directly connected to every other node by one arc, i.e., arcs. Figure 2 shows a maximally connected network with 16 nodes and 120 arcs. A maximally connected network contains $n!$ different sub-networks.[†] The number of subnets in Figure 2 is over 20 trillion.

Maximally connected networks have more arcs and more subnets than any other type of connected network and are therefore the most expensive and complex connected

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[*] Most of the literature of networked warfare employs the metaphor of a communications network. More appropriate metaphors can be found in the more general theory of mathematical networks, or *combinatorics*.

[†] $n! = n(n - 1)(n - 2)(n - 3) \ldots (1)$. $n!$ (spoken, "n factorial") is the highest level of "computational complexity" in network mathematics.

networks. They have more redundancy and commodities are proliferated more quickly to the nodes (that is, they have the shortest characteristic path length, *L*). The biggest drawback of maximally connected networks is that the number of subnets can easily overwhelm attempts to use them efficiently (that is, each flow calculation for the network in Figure 2 requires over 20 trillion calculations).

c. Random Networks

Minimally connected and maximally connected networks represent the extremes of network connectivity. For most warfare network applications, neither of these two extremes are useful. A simple thought experiment demonstrates that even a random arrangement of arcs and noes can result in good connectivity. Imagine that there are 400 buttons and many pieces of string on a table. A button is selected randomly from the table, picked up, tied to a piece of string and placed back on the table. This process is repeated indefinitely.

Figure 3 is a plot of the number of buttons connected to other buttons and the ratio of strings to buttons. The resulting curve shows that as the ratio of strings to buttons approaches 0.5, the connectivity of the buttons dramatically increases. The curve flattens quickly, however, and each additional string adds only marginally fewer buttons to the network. Obviously, a connected network is not guaranteed by this method (the curve is asymptotic to the maximum number of buttons) but the method clearly displays the nature of the transition from an unconnected group of nodes to a highly connected network.

Figure 4 shows such a randomly connected network. The ratio arcs to nodes in this network is 2 (that is, there are 32 arcs, about twice as many as the minimally connected network in Figure 1 yet only about a quarter of the maximally connected network in Figure 2). The characteristic path length of this network is about halfway between the minimally connected network and the maximally connected network. The random network therefore, is more redundant and commodities are proliferated more quickly than the minimally connected network yet the number of arcs and subnets is dramatically lower than the maximally connected network.

Two drawbacks arise from the random connection of arcs and nodes. The first is that the network is irregular in the sense that *L* has a large variation from node to node. The second is that the network is irregular in the sense that there is a large variation in the number of nodes that are immediate neighbors to each other. A measure of this network "clustering" is the clustering coefficient, γ, the ratio of the number of arcs between neighbors to the number of possible arcs between neighbors. Highly clustered networks tend to have pockets of connectivity, which can increase the connectivity and redundancy of the whole network. Irregularity in *L* and γ can cause great unpredictability in networks.

d. Regular Networks

Figure 5 shows a completely regular network using the same ratio of arcs to nodes as the irregular, random network. Although the clustering of this network is much more regular than the random network, the characteristic path length is necessarily increased (although *L* becomes more regular). The number of arcs will have to increase to reduce *L*, yet increasing the number of arcs dramatically increases the number of subnets.

e. Small World Networks

A minor "re-wiring" of the regular network can create a "Small World" network with a high degree of regularity, good clustering and a shorter characteristic path length. In a Small World network, remote clustered groups share members so that the number of "handshakes" connecting all members remains small (just like handshakes in its cultural counterpart). Figure 6 shows how a regular network in Figure 5 can be re-wired to create a Small World network.

IV. Analysis

a. Network Statistics.

Table 1 is a summary of the statistics from the networks described in Section III. These statistics are the number of arcs, the number of nodes, the ratio of arcs to nodes, the characteristic path length *L,* the average number of nodes reached by traversing some number of arcs (or the number of "switches", listed for 1 to 4 arcs) and the clustering coefficient γ.

The minimally connected network has a low ratio of arcs to nodes, yet the characteristic path length is high. This is because the average number of additional nodes reached for each additional arc length traversed increases only by two for each additional arc. *L* = 1 in the maximally connected network, yet the overhead incurred is an order of magnitude more arcs and a factorial number of additional subnets. The minimally connected network has no clustering and the maximally connected network is maximally clustered.

Random connection of arcs and nodes with an arc-node ratio of 2 can connect all nodes in only about 3 switches, *L* is low (1.9) and clustering is also better. Although the random network provides better performance than the minimally connected network and avoids the overhead of a maximally connected network, the network is irregular. One measure of regularity of a system is the standard deviation of the measurements within the system.[*] The standard deviation of γ listed in Table 1 for the random network means that some nodes may have values of γ similar to the minimally connected network. Arranging the same number of arcs and nodes in a more regular network, however, reduces the irregularity γ but *L* gets more irregular. The regular network also has a longer *L* (that is, commodities proliferate much more slowly in the network in Figure 5).

The Small World network uses the same ratio of arcs to nodes in a network that is fairly regular and clustered yet still proliferates commodities quickly. In other words, the Small World network uses as few nodes as possible to perform as well as the random

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[*] The standard deviation of a statistic, *(s.d.)* in Table 1, is the square root of a statistic's variation and a measure of how widely values are dispersed from the average value. A standard deviation of 0.15 for a γ value of 0.17 in the random network means that the actual value could be almost 0 (same as the minimally connected network. s.d. = 0 when not listed.

network while retaining some regularity.

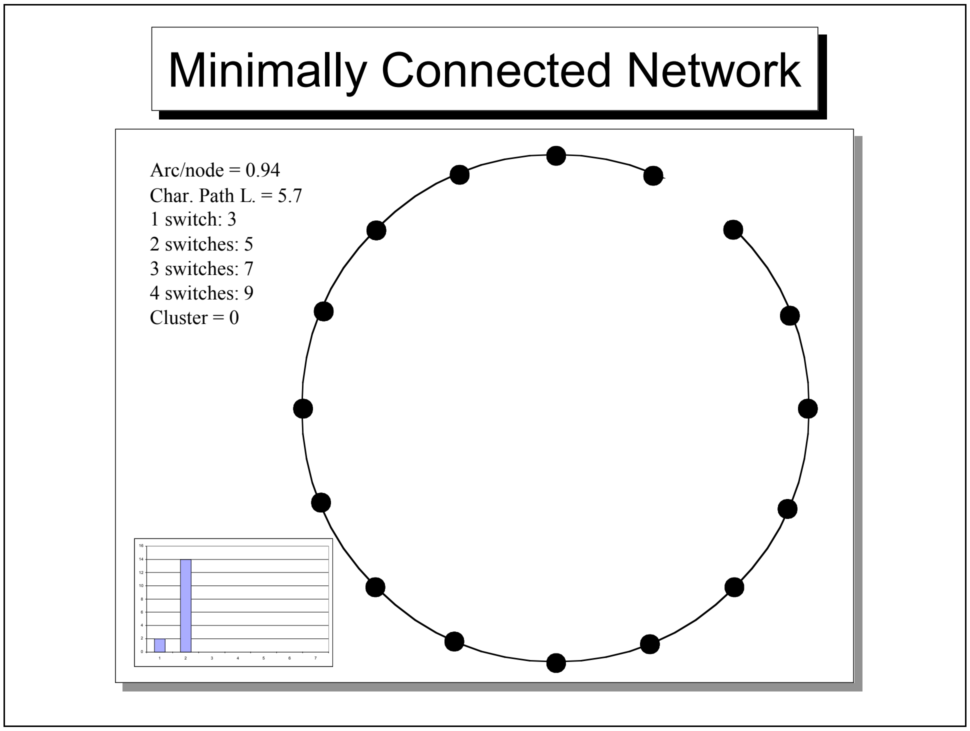
Network	**Arcs**	**Nodes**	**Arc/ Node**	***L***	**1 Arc (Nodes)**	**2 Arcs (Nodes)**	**3 Arcs (Nodes)**	**4 Arcs (Nodes)**	**γ**
Minimally Connected	**15**	**16**	**0.94**	**5.7** ***(3.7)***	**3**	**5**	**7**	**9**	**0**
Maximally Connected	**120**	**16**	**7.5**	**1.0**	**16**	**16**	**16**	**16**	**1**
Random ***(s.d)***	**32**	**16**	**2**	**1.9** ***(0.73)***	**5.1** ***(1.8)***	**12.1** ***(2.1)***	**15.9** ***(0.6)***	**16**	**0.17** ***(0.15)***
“Regular”	**32**	**16**	**2**	**2.3** ***(1.1)***	**5**	**9**	**13**	**16**	**0.25**
Small World ***(s.d.)***	**32**	**16**	**2**	**1.9** ***(0.75)***	**5** ***(0.6)***	**12** ***(1.2)***	**16**	**16**	**0.25** ***(0.1)***

Table 1

The preceding analysis demonstrates that the arrangement of arcs and nodes affects the behavior and performance of a network. Operational requirements determine this arrangement. Some theories of Information Age refer to "fully-netted" forces; Section III shows that confusing "fully-netted" with maximal connectivity will produce unnecessary cost and complexity. Minimal connectivity, however, will not produce satisfactory network performance and redundancy. Therefore, the connectivity of warfare networks must be at some "sufficient" level. Table 1 suggests that Small World networks are simpler, perform better and require lower overhead than other networks.

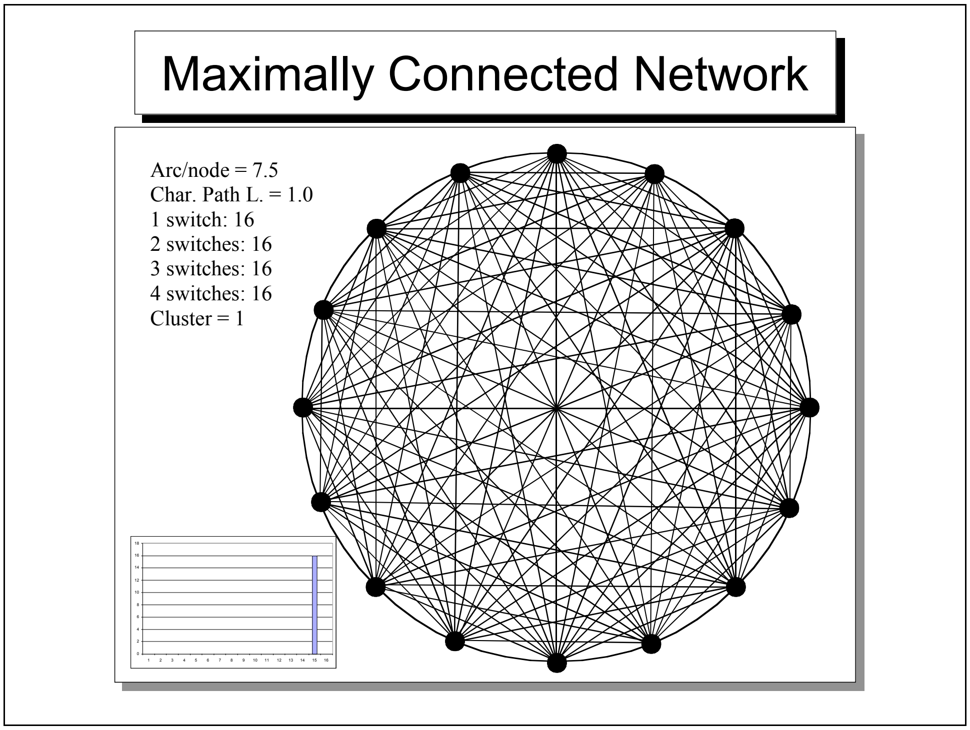
V. Conclusion

This paper has presented a variety of networks, network behaviors and network statistics. In addition, it showed how collective choice schemes could adversely affect network operations. The networks listed here are mathematical abstractions of real-world phenomena. In real-world networks, the operational requirements for which a network is designed define how the network will be configured. Moreover, the rational behind the design is derived from organizational principles and organization theory. Therefore, the best configuration for a network should be an extension of the purposes and intent implied by the function, roles and behavior of the agents that operate the network, the nature of the tasks required of the networked group and the physical restrictions that may impact the logical connections.



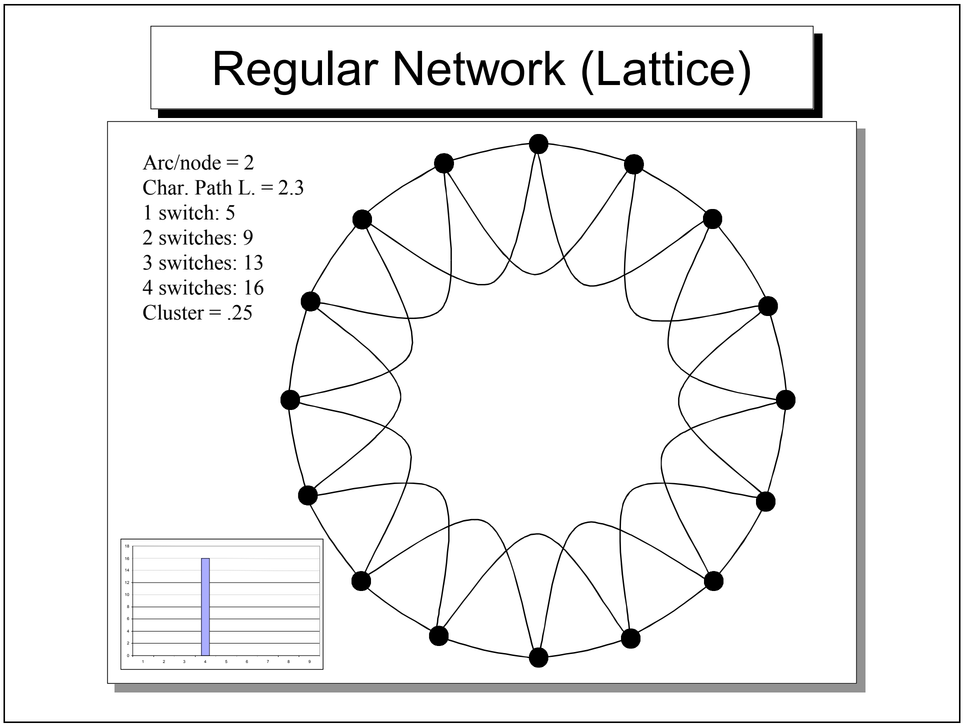
Minimally Connected Network

Arc/node = 0.94
Char. Path L. = 5.7
1 switch: 3
2 switches: 5
3 switches: 7
4 switches: 9
Cluster = 0



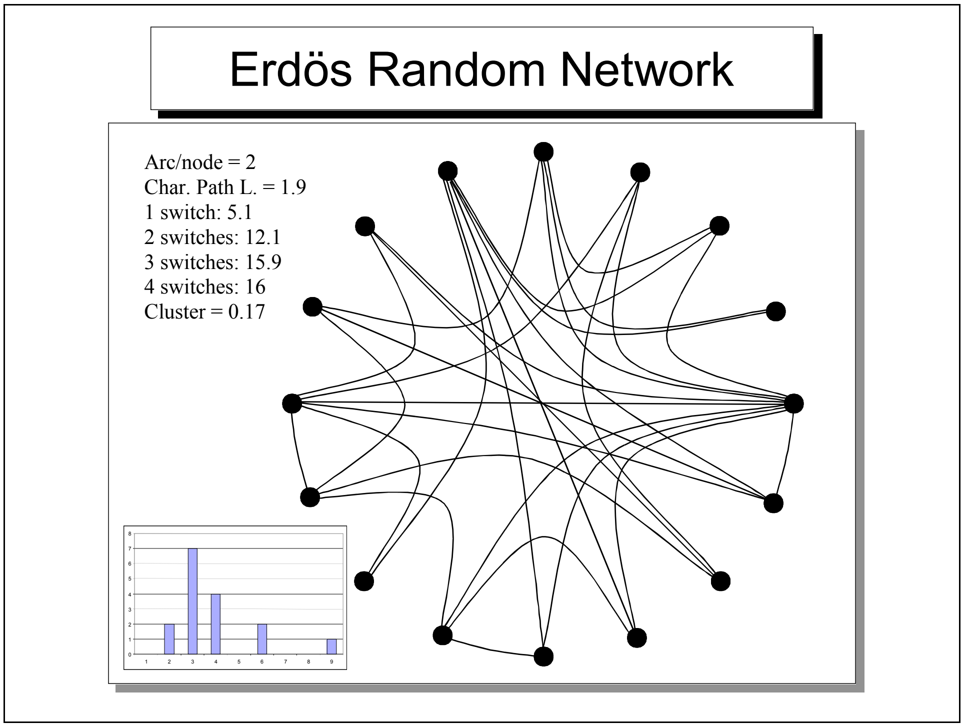
Maximally Connected Network

Arc/node = 7.5
Char. Path L. = 1.0
1 switch: 16
2 switches: 16
3 switches: 16
4 switches: 16
Cluster = 1



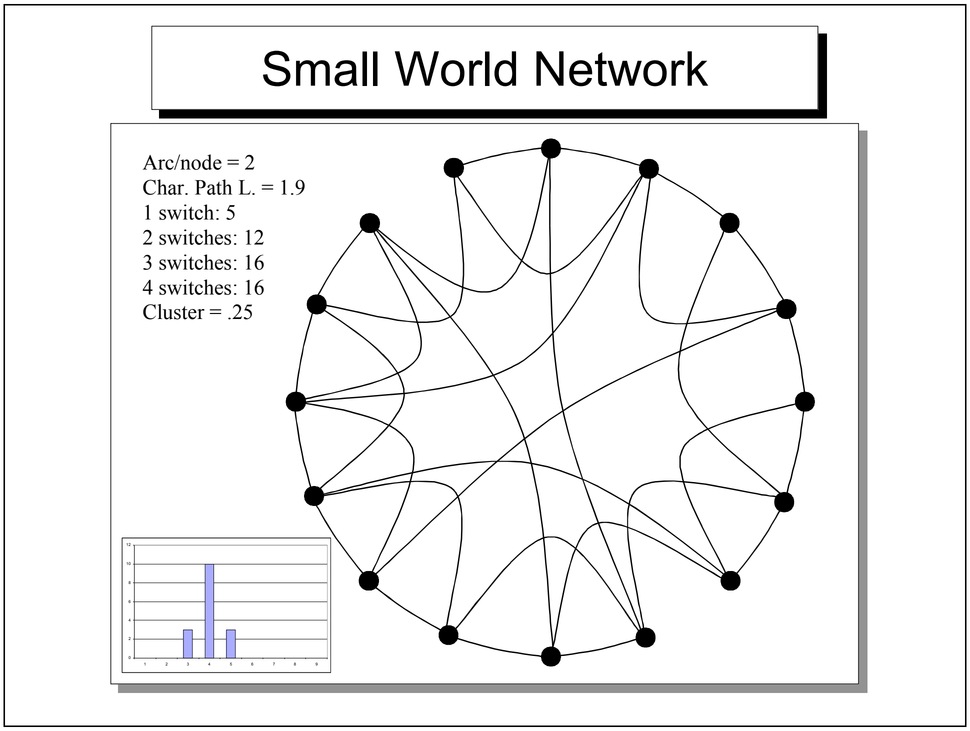
Regular Network (Lattice)

Arc/node = 2
Char. Path L. = 2.3
1 switch: 5
2 switches: 9
3 switches: 13
4 switches: 16
Cluster = .25



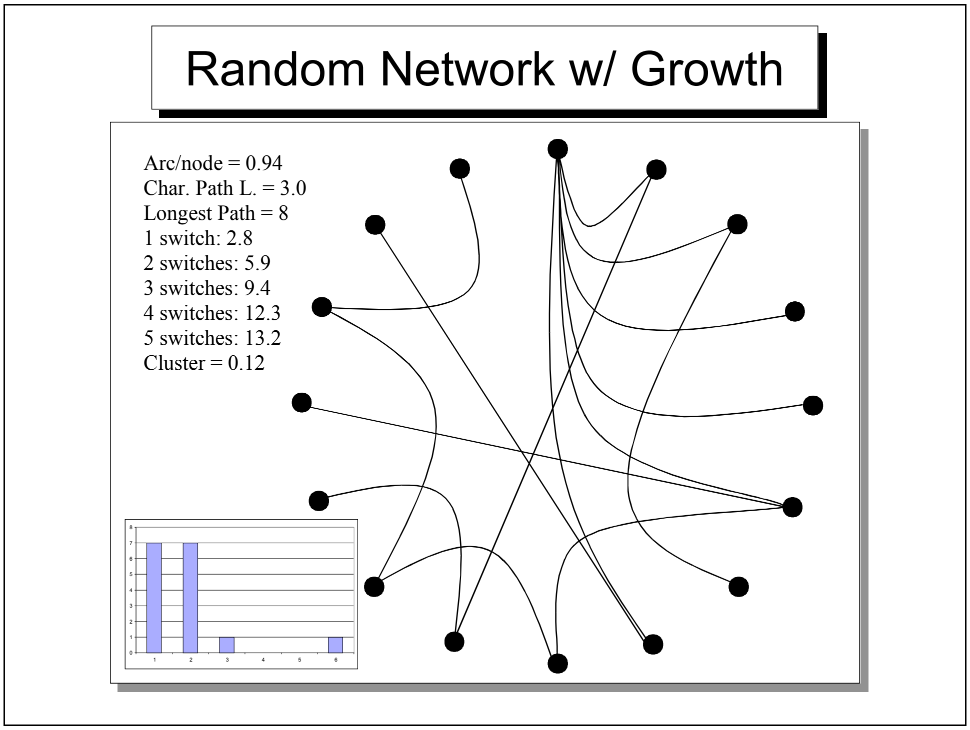
Erdös Random Network

Arc/node = 2
Char. Path L. = 1.9
1 switch: 5.1
2 switches: 12.1
3 switches: 15.9
4 switches: 16
Cluster = 0.17



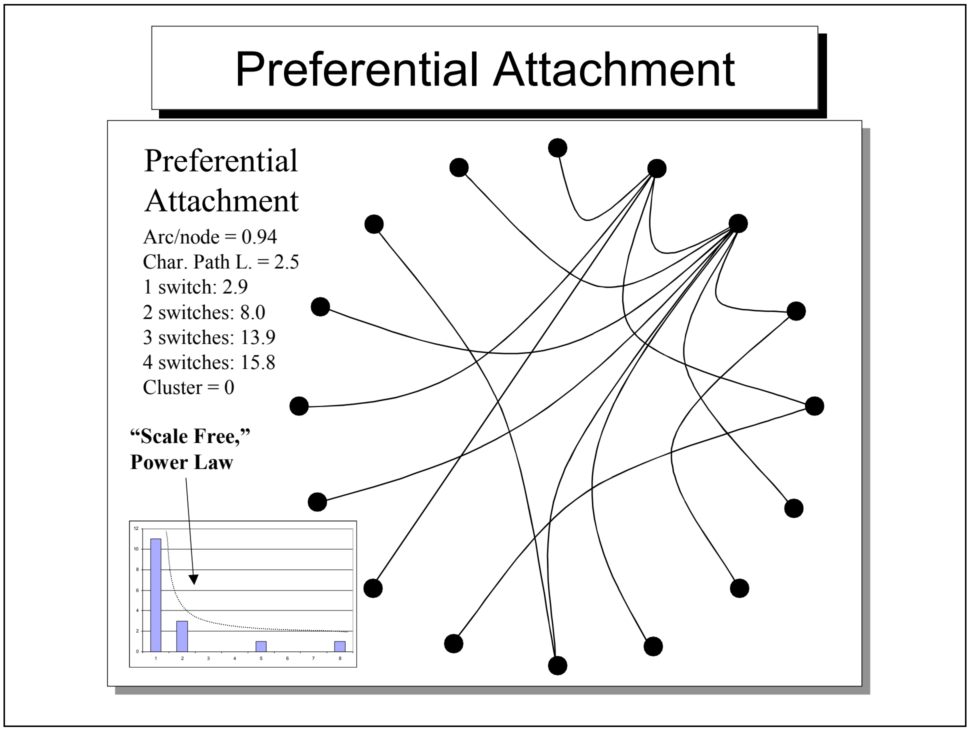
Small World Network

Arc/node = 2
Char. Path L. = 1.9
1 switch: 5
2 switches: 12
3 switches: 16
4 switches: 16
Cluster = .25



Random Network w/ Growth

Arc/node = 0.94
Char. Path L. = 3.0
Longest Path = 8
1 switch: 2.8
2 switches: 5.9
3 switches: 9.4
4 switches: 12.3
5 switches: 13.2
Cluster = 0.12



Preferential Attachment

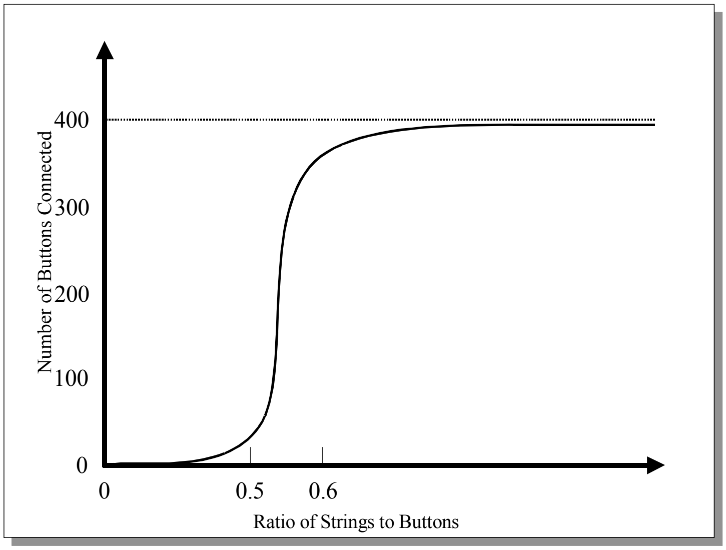
Preferential Attachment

Arc/node = 0.94
Char. Path L. = 2.5
1 switch: 2.9
2 switches: 8.0
3 switches: 13.9
4 switches: 15.8
Cluster = 0

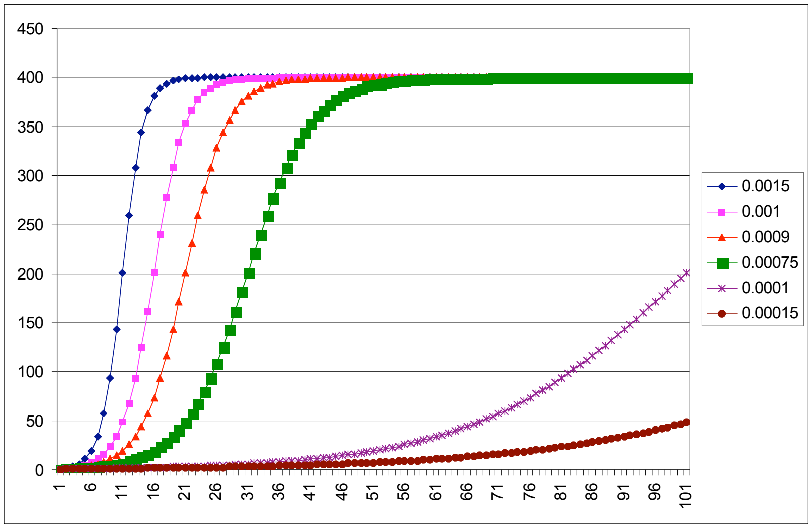
"Scale Free," Power Law

- Minimally Connected Network
  - Too brittle, long CPL, poor clustering, simple pattern, simple control, scaled
- Maximally Connected Network
  - Robust, short CPL, too clustered, simple pattern, complex control, scaled
- Regular Network (Lattice)
  - Robust, long CPL, high cluster, simple pattern, simple control (<k> < 5), scaled
- Erdös Random Network
  - Brittle, short CPL, low cluster, random pattern, complex control, scaled
- Small World Network
  - Robust, short CPL, high cluster, complex pattern, complex control, less scaled
- Random Network with Growth
  - Less brittle, short CPL, low cluster, random pattern, complex control, less scaled
- Network with Preferential Attachment
  - Robust, short CPL, low cluster, complex pattern, complex control, scale free
- Networks do not connect randomly
  - But Random Assumption was still status quo in 1999
- "Scale Free" Networks
  - Hubs distributed by Power Law
  - Short path lengths
  - Good Connectivity
  - VERY robust
- Complex Networks (e.g., diffusion, scale free, etc.)
  - Steepness of profile, shape a function of structure
    - Seed structure, critical mass, spreading rate, inflection points
  - Scale-Free Networks have some of the steepest curves
    - Hubs can disappear/reappear with +/- very few arcs
      - Patterns can disappear/reappear with +/- very few arcs

Erdös Connectivity Profile



Generic Diffusion Profiles



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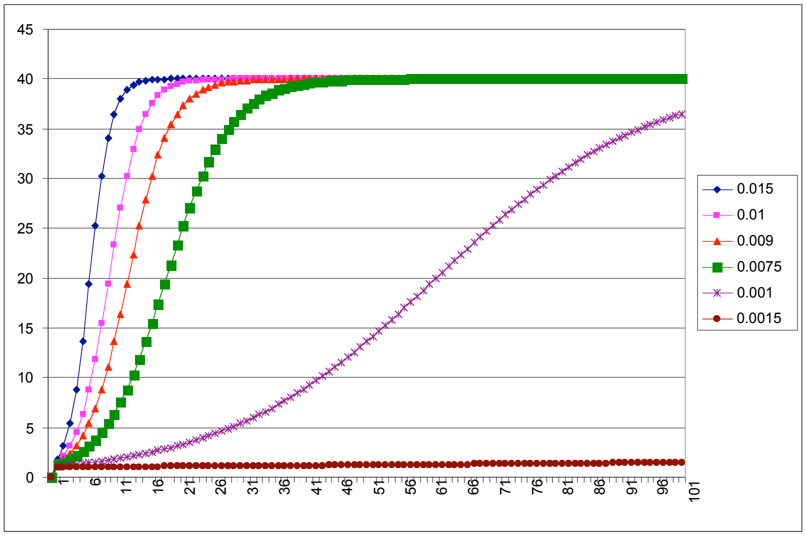
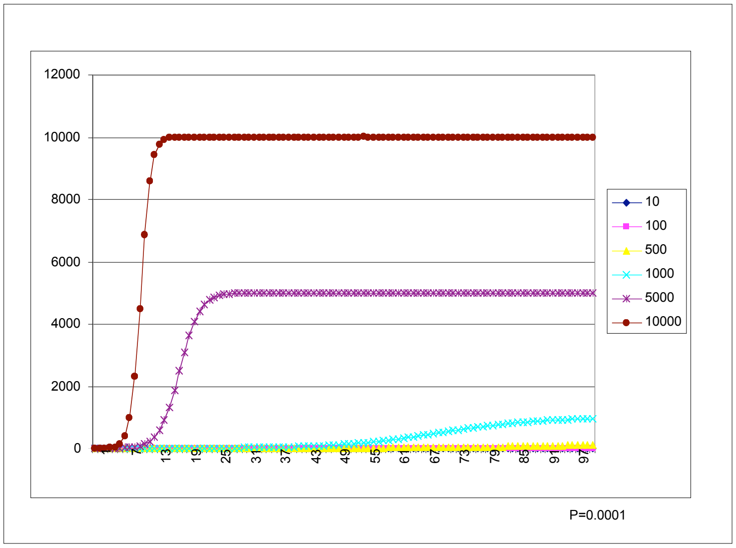
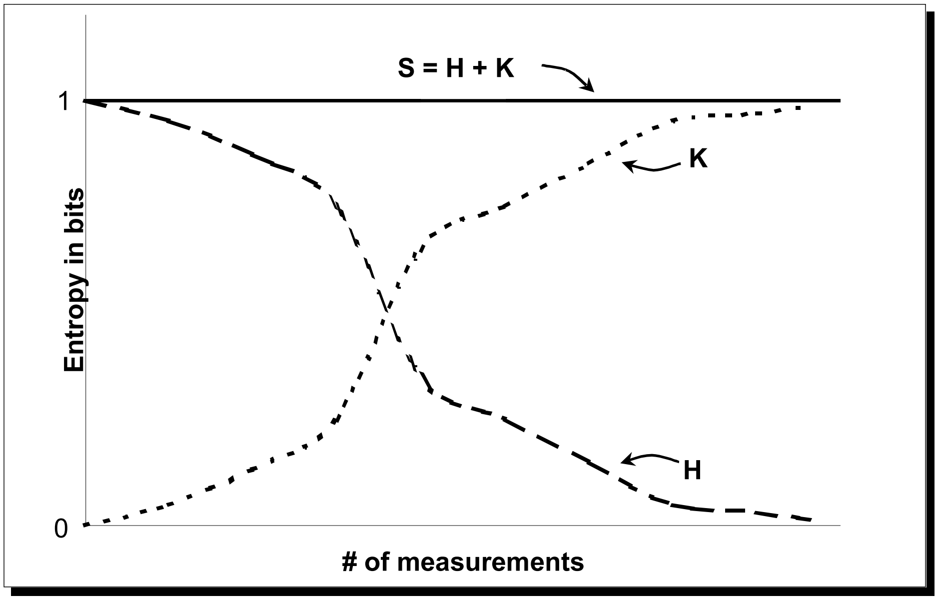


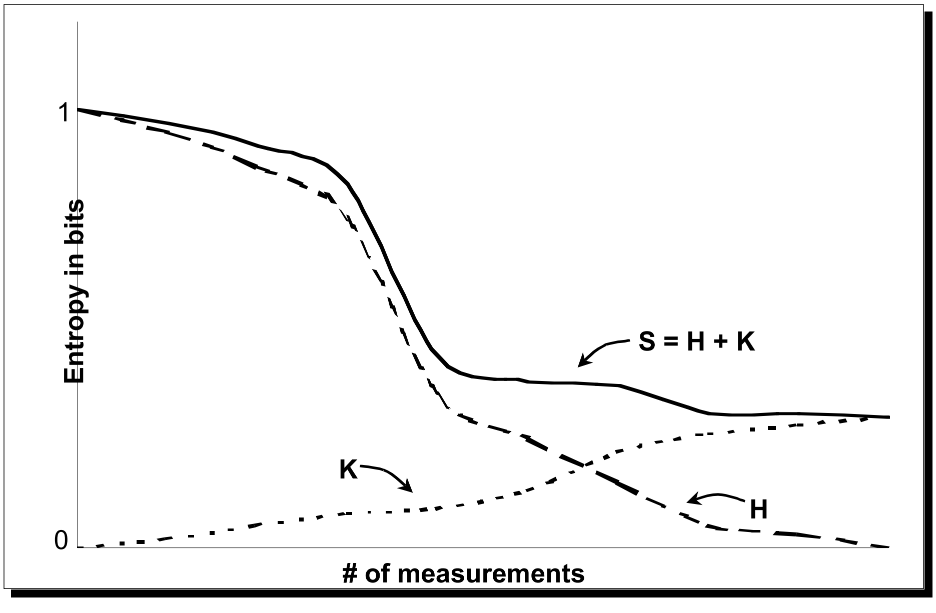
Generic Diffusion Profiles



More Information is not always More Information



More Information can be More Information



Abstract

The sustainment performance of a single LLP is compared to that of two AOE's within the context of the Evaluation Game scenario. The measure of performance is the average combat power in the force as a function of the average demand per day for ordnance replenishment. The combat power is assumed to be proportional to the ordnance available on board combatants that can be committed to the fight. The average demand is assumed to represent the intensity of the fight. At the highest level of intensity observed in the Evaluation Wargame the LLP concept yields more than twice as much combat power as the two AOE concept.

Introduction

Based on the experience of the SSG XVII Evaluation Wargame, it appears that ordnance is the critical sustainment item for a force projecting decisive power ashore. Unless replenished, the combat power of any ship decreases directly as ordnance is expended in the act of projecting power. A ship with an empty magazine has virtually no power projection capability irrespective of whatever other attributes it might have. It follows that timely replenishment of expended ordnance is directly related to the combat power of the force.

As a simple example consider, two situations for a given ship: (1) resupply occurs when $(1-R_{new})$ is expended and (2) resupply occurs when $1-R_{old}$ is expended. These situations are sketch in Figure 1.

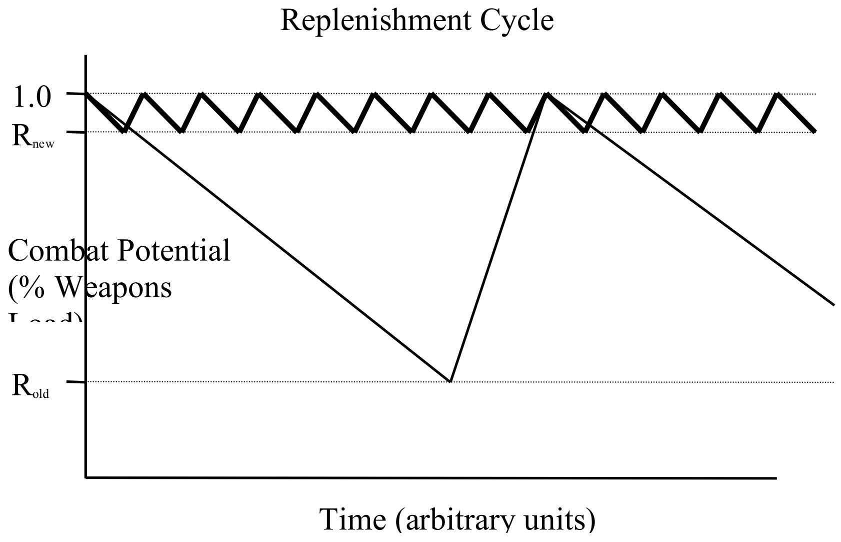


Figure 1

Over the course of time as munitions are expended the combat power decreases. When the lower limit is reached, the ship is replenished and its combat power restored. The solid heavy line represents case (1) and the light solid line represents case (2). The average combat power, <CP>, in either case is

$$\langle CP\rangle = \{1 + R\}/2.$$

The interesting point is that Case (1), the more aggressive replenishment, yields a higher <CP> than Case(2). The more aggressive resupply acts a force multiplier factor. The force multiplier factor, FP, is given by

$$FP = \{1 + R_{new}\}/\{1 + R_{old}\}.$$

Figure 2 shows this factor as a function of R_{old} for various values of R_{new}. This simple example show the impact that timely sustainment can have on combat power.

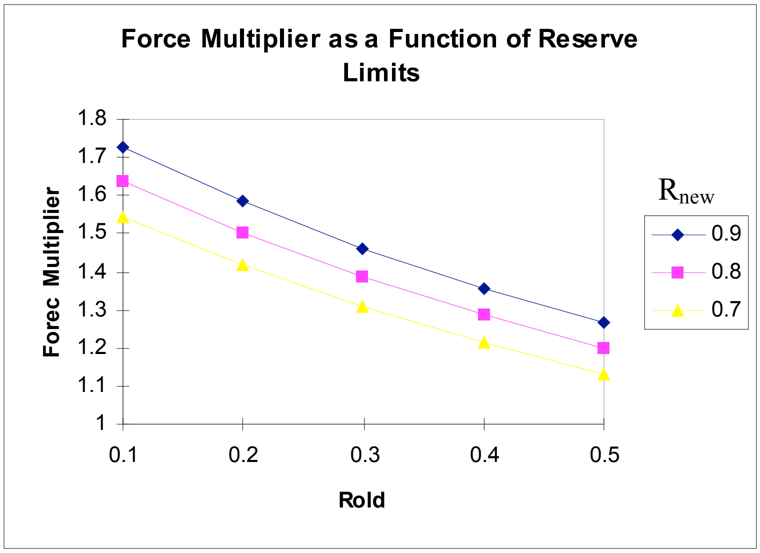


Figure 2

Sustainment of the Forward Deployed Force (FDF)

Now consider a more realistic scenario, sustainment of an FDF involved in a combat operation. The FDF consists of 12 ships: 2 SSN, 1 SSGN, 4 SC, 2 CGA, 2 LES, and 1 LLP. We will compare the sustainment performance of the single LLP versus two AOE's. Assumptions are as follows:

(1) the force is randomly distribute throughout SSG XVII's notional 400 nm X 300 nm box.
(2) the force is engaged in halting the advance of 6 armored corps (wargame scenario).
(3) the SSN's and SSGN are not resupplied from the sea base.

The characteristics of the LLP and AOE are shown in Table 1

Table 1

	LLP	AOE
Server Method	LCAC$^+$ Shuttle	Alongside
# of Servers	4	2

Service Increment [note (1)]	90T	90T
Service Duration (HR) [note 2]	1	4.0
Server Transit Time (HR) [note (3)]	6.18	4.6

Notes:

(1) Basic lift of LCAC is 90T. AOE increment chosen to match LCAC.

(2) LCAC is RO-RO with 0.5 hours turn around at either end. AOE can transfer 36T/hr with 1.5 hour added for setup and breakdown.

(3) The average distance of the 8 combatants from the LLP is 123.5 nm (LLP positioned at centroid of combatants). Round trip travel time for the 40 knot LCAC+ is 6.18 hours. The average distance between all combatants in the box is 183.8. Assuming the combatant meets the AOE half way, the one way travel time of half the distance for the AOE at 20 knots is 4.60 hours. (This does not account for optimal routing of the AOE's. However, in this scenario, the resupply is not routine servicing to top off but rather demand servicing based on real need. The AOE does not get to choose where to go next.)

The data in Table 1 were input to the Queuing module of the STORM analysis package. The waiting time for service for each implementation of resupply (LLP or AOE) was calculated as a function of the average time interval between service requests. It is assumed that the interval between service requests reflects the expenditure rate of ordnance. Figure 3 shows the results of this calculation. where the interval between service requests has been converted to demands foe service per day for convenience of display.

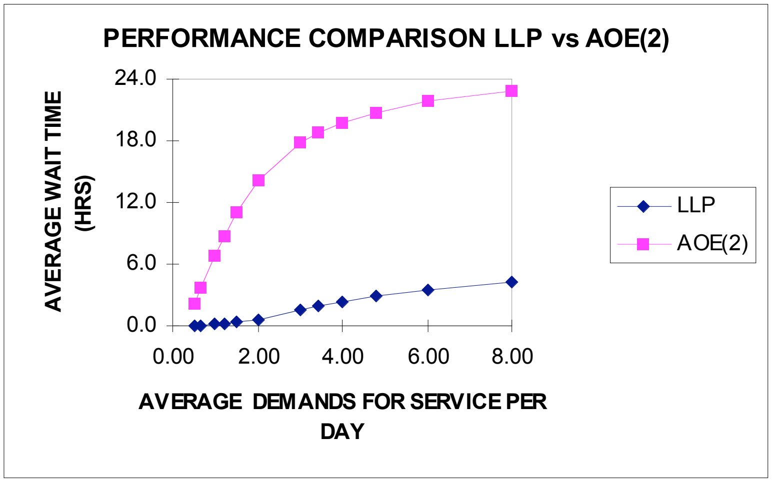


Figure 3

It is obvious that the LLP is superior to the AOE(2) in terms of waiting time. Next we translate the effect of waiting time into the effect on average combat power, <CP>, for the FDF. We assume a linear expenditure of ordnance and linear decrease in combat power over the duration of a demand interval, T_d, to the point where some reserve threshold, R, is reached. At that point the commander has two choices: (1) stop shooting and wait for replenishment, or (2) keep shooting (perhaps a reduced rate) until supplies are exhausted. In the first case the combat power falls to zero while waiting since power that can't be committed is no power at all. In the second case the combat power will continue to decrease and will eventually reach zero if the waiting time., T_w, is long. Combat power then rises to by the increment of ordnance delivered over the over the duration of the service time, T_s. Case (2) is beyond the scope of this analysis since the average demand rate is no longer an appropriate descriptor of the queuing problem. The average combat power for case (1) is computed from the relation

$$<CP> = \{T_d/2 * (1 + R) + T_w * 0.0 + T_s/2 * (1 + R)\} / \{T_d + T_w + T_s\}.$$

The average combat power of the FDF under the two sustainment approaches is plotted in Figure 4 with R = 0.63. The value of R was determined by the calculating the total tonnage of ordnance resident in the FDF, dividing that by the number of platforms and then calculating the fraction of that average tonnage per platform represented by the 90 T unit of delivery. R is equal to 1.0 minus that fraction. The figure also includes a curve of the ratio of the <CP> for each resupply approach representing the effective force multiplication, EFM, achieved by the LLP approach relative to the AOE approach. The arrow in the lower right hand corner indicates the operating range of demand observed during the SSG XVII Evaluation Wargame to provide the fires necessary to halt the advance of two mechanized corps.

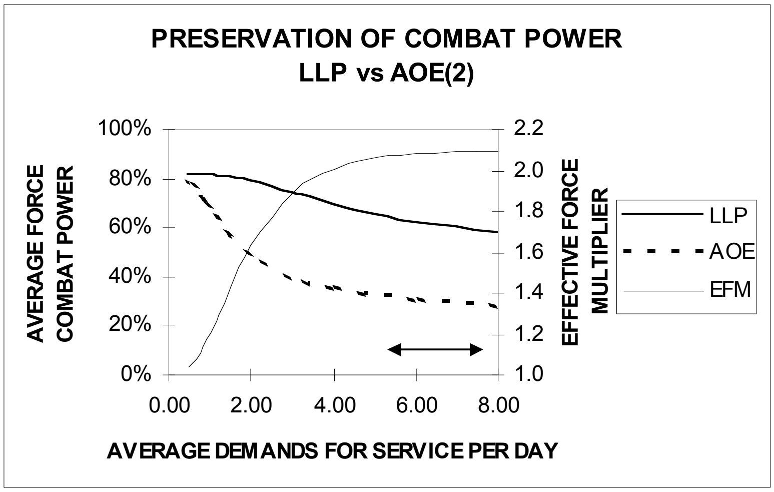


Figure 4

The analysis is admittedly broad brush but it shows the gross features of what's going on. With low tempo of operations when demands for service are low, both systems are capable to meeting the demand. But as the action heats up the two AOE's are unable to keep up with demand. Under the most demanding circumstance, when the FDF is trying to halt the advance of two corps, the effective combat power of the force sustained by the AOE's is reduced to about half of what it might be. The LLP concept is much more robust and preserves significantly more combat power even at the highest tempo of operations observed in the wargame. In a very real sense, the LLP concept results in over twice as much fighting capability as would be available with the evolutionary sustainment concept consisting of two AOE's.

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[1] "Future Warfare: America's Military Preparing for Tomorrow," http://www.dtic.mil/jv2020/.

[2] Joint Publication 4-0, Doctrine for the Logistics Support of Joint Operations, 6 April 2000, http://www.dtic.mil/doctrine/jel/new_pubs/jp4_0.pdf, accessed 10 Oct 2002.

[3] For example, see the Joint Vision 2020 concept at, http://www.dtic.mil/jv2020/jv2020a.pdf, accessed 10 Oct 2002.

[4] The inspiration for and most of the language used to describe Sense and Respond Logistics comes from Stephen H. Haeckel, *Adaptive Enterprise: Creating and Leading Sense and Respond Organizations*, (Harvard Business School Press, Boston, MA, 1999). Since, as Dr. Haeckel notes, "no complete exemplars of the sense-and-respond model exist," (p. xix), this paper comprises a pioneering effort to more fully and formally define the mechanisms by which an sense and respond system can provide extraordinary advantage over its traditional, Industrial Age counterpart.

[5] The link between management, control and optimization is evidenced by the curricula at most Masters in Business Administration (MBA) programs. See, for example, Harvard (www.hbs.edu/mba), MIT (http://sloanserver.mit.edu/courses) or Stanford (www.gsb.stanford.edu/mba). All websites accessed 10 Oct 2002.

[6] For mathematical detail on and discussion of makespan, just-in-time manufacturing and the Toyota production system see http://www.toyotaproductionsystem.net, accessed 10 Oct 2002.

[7] Jeffrey R. Cares, Raymond J. Christian, Robert C. Manke, *Fundamentals of Distributed, Networked Military Forces and the Engineering of Distributed Systems,* NUWC-NPT Technical Report 11,366, 9 May 2002, NUWC Division Newport, 1.

[8] For a full mathematical treatment of complexity and scale in complex systems see Section 8.3 of Yaneer Bar-Yam, *Dynamics of Complex Systems,* (Addison-Wesley, Reading, MA, 1997).

[9] For a complete discussion of the impact of complexity and scale on littoral operations, see Yaneer Bar-Yam, "Multiscale Analysis of Littoral Warfare," CNO Strategic Studies Technical Paper, 2002.

[10] The concept of multi-scale representation has direct application to military command and control problems. For a short definition of this concept, see http://www.necsi.org/guide/concepts/multiscale.html, accessed 10 Oct 2002.

[11] David H. Wolpert and William G. Macready, "No Free Lunches For Search," Santa Fe Institute Working Paper 95-02-010, http://www.santafe.edu/sfi/publications/wpabstract/199502010, accessed 10 Oct 2002.

[12] As long as the degree is less than 5. Chaotic, uncontrollable behavior can emerge with 5 links per node or more. See Stuart A. Kauffman, *The Origins of Order,* (Oxford University Press, New York, 1993), 192-3.

[13] This newly defined class of networks is explored by Duncan Watts in *Small Worlds,* (Princeton University Press, Princeton, NJ, 2000). Networks in this class include the web of actors listed in the Internet Movie Database, which can be interactively explored at http://www.cs.virginia.edu/oracle/, accessed 11 Oct 2002.

[14] See Albert-Laszlo Barabasi, *Linked: The New Science of Networks,* (Perseus Publishing, Cambridge MA, 2002), for a review of the relevant research. In one way, it is misleading to say these networks were "discovered," since these structures are found in very many systems that have existed for centuries, if not millennia. As a tool for describing these structures, however, such networks have been known to researchers for only a very short time.

[15] The literature on such diffusion curves is quite rich, including Thomas C. Shelling, *Micromotives and Macrobehavior,* (W.W. Norton & Company, New York, 1978), Everett M. Rogers, *Diffusion of Innovations, 4th Edition,* (Free Press, New York, 1995), Thomas W. Valente, *Network Models of the Diffusion of Innovations,* (Hampton Press, Cresskill, NJ, 1999), and Stuart A. Kauffman, *At Home in the Universe*, (Oxford University Press, New York, 1995).

[16] The case for treating military systems as open systems is made by the Deputy Director, J8 (Wargaming, Simulation & Analysis), The Joint Staff, Vincent P. Roske, Jr., in "Opening Up Military Analysis: Exploring Beyond The Boundaries," *Phalanx,* (Online) June 2002, Volume 35, Number 2, http://www.mors.org/publications/phalanx/jun02/lead.htm, accessed 10 Oct 2002.

[17] This thesis is explored in Robert Axelrod, *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration,* (Princeton University Press, Princeton, NJ, 1997).

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[18] True noise is the equivalent, in military lexicon to classic Clausewitzian "fog and friction." See Barry D. Watts, *Clausewitzian Friction and Future War*, McNair Paper Number 52, October 1996 at http://www.ndu.edu/inss/macnair/mcnair52/m52cont.html, accessed 10 Oct 2002. Chapter 7, "The Inaccessibility of Critical Information," is particularly pertinent to control in complex systems.

[19] See Seth Lloyd, "Control in Complex Systems," *SFI Bulletin,* Spring 1995, at http://www.santafe.edu/sfi/publications/Bulletins/bulletin-spr95/10control.html. Haeckel, Chapter 5, directly connects Lloyd's theory of control to sense and respond systems.

[20] For a formal proof of this statement and a complete treatment of the concepts of randomness, sense-making and Information Theory, see Gregory J. Chaitin, *The Limits of Mathematics: A Course on Information Theory and the Limits of Formal Reasoning,* (Springer-Verlag, New York, 1998), *The Unknowable (Springer Series in Discrete Mathematics and Theoretical Computer Science,* (Springer-Verlag, New York, 1999) and *Exploring Randomness (Discrete Mathematics and Theoretical Computer Science),* (Springer-Verlag, New York, 2001). For an application of these principles to distributed systems, see Jon Barwise and Jerry Seligman, *Information Flow: The Logic of Distributed Systems,* (Cambridge University Press, New York, 1997).

[21] *Fundamentals of Distributed, Networked Military Forces and the Engineering of Distributed Systems,* Jeffrey R. Cares, Raymond J. Christian, Robert C. Manke, NUWC-NPT Technical Report 11,366, 9 May 2002, NUWC Division Newport, 1.