Flexibility in Operational-Level Logistics

Dr. Moshe Kress

CEMA, (T1)

kress@ie.technion.ac.mil

...The flexible employment of forces is the central task in directing a war, a task most difficult to perform well... flexibility in command can be realized only through the discovery of order, light, and certainty admist such circumstances peculiar to war as confusion, darkness and uncertainty.

Mao Tse-Tung, ***On the Protracted War***, Foreign Language Press, Peking, 1954, p-101.

It is no great matter to change tactical plans in a hurry and send troops off in new directions. But adjusting supply plans to the altered tactical scheme is far more difficult

Walter Bedell Smith, ***Eisenhower's Six Great Decisions***, Longmans, Green, New York, 1956, pp 59–85.

ABSTRACT

Flexibility is always preferred to rigidity. This self-evident, almost trivial, statement is true in particular in the military environment that is characterized by friction, uncertainty and even chaos. In particular, logistics systems, which are supposed to support and sustain combat operations, must be capable to respond effectively to changing conditions and circumstances at the theater of operations. To achieve this goal, logistics systems must be flexible too.

In this article we explore the meaning of the term *flexibility* in combat operations in general and in logistics in particular. The two facets of logistical flexibility—intrinsic and structural—are identified and formalized by means of quantitative measures.

INTRODUCTION

The need for flexibility in the planning and execution of military operations is recognized by field commanders as well as by military scholars. In operational art the concept of flexibility is embedded in the tenet of *freedom of action.* At any given time before or during a military operation, the commander seeks to maximize the number of feasible courses of actions that he may take. The more the operational options that are available for possible implementation, the larger is his flexibility and his freedom of action. In the decision-sciences literature, flexibility is sometimes defined similarly as the *number of optional alternatives left over after one has made an initial decision* (see Gupta and Rosenhead [1968] and Rosenhead et al. [1972]). By increasing the range of optional alternatives, flexibility essentially reduces the number and the severity of operational constraints on the commander's courses of action. The need for flexibility is derived by the uncertainty that is embedded in any facet of the battlefield.

Battlefield uncertainty is a result of several factors. The foremost factor is the *enemy* who invests considerable effort to hide his intentions and plans from the friendly forces and thus enhancing his uncertainty and confusion. This effort is confronted by attempts of the friendly forces' intelligence to reveal as much as possible of the enemy's plans. These attempts have never been, and probably will never be, fully successful (see Kovacs [1997]). Intelligence information is fuzzy, it may be polluted with noise and, in many cases, it is only partial.

The other cause for uncertainty at the battlefield is the synergistic effect of two phenomena—environmental one and behavioral one. On the one hand the environment—the terrain and the elements—impose operational constraints that depend on factors such as road conditions, ground obstacles, weather and visibility. The type and impact of these environmental factors may change over time in a random manner. On the other hand, the cognitive and behavioral effects of confusion, misunderstandings and misinterpretations may have a severe impact on the way missions are executed. The combined effect of the environmental random impacts and the human behavioral confusion leads to a phenomenon that is called by von Clausevitz the *friction of war* (von Clausevitz [1976]).

The uncertainty at the battlefield alter operational plans and generate new combat situations to which the commander must respond effectively and in a timely manner. Field commanders are aware of this unstable, and even chaotic, environment. They are known to describe war as the "kingdom of uncertainty." *Flexibility* is an attribute that can mollify the effect of battlefield uncertainty.

Flexibility in combat has several facets. First, flexibility must be integrated in the operational vision of the commander. Schneider [1994] defines this quality as *mental agility*—the cognitive ability to react to changes in the combat situation faster than they occur. The second aspect of flexibility applies to the command and control structure, and to the decision-making process that is associated with it. As an organization, a command post must demon-

OR METHODOLOGY:
Decision Analysis
APPLICATION AREA:
Resources-Logistics

strate behavioral flexibility that is manifested in rapid structural and functional adjustments to changing situations. Standard operational procedures (SOP) and C^4I systems must be set such that these adjustments could be implemented fast. The combined effect of the *cognitive flexibility* of the commander and the *functional flexibility* of its staff facilitate a creative environment in which as many as possible alternative courses of actions may continuously be generated and reviewed. This process creates the *potential* for an efficient response to battlefield changes. The *actual* realization of this rapid-response potential depends on the third facet of battlefield flexibility—the *physical flexibility*.

Physical flexibility applies to the physical attributes of the force at the theater of operations. In manufacturing systems physical flexibility is manifested in the design of production processes, in the equipment that is used, in the working manpower organization and in the materials management. Similarly, physical flexibility (or lack of it) in military operations is derived from the force size, its mix and the way it is deployed at the theater of operations. In particular, physical flexibility depends on the layout of the logistics facilities, on the choice of lines of communications, on the logistics-chain schedule and on the allocation of resources among the command levels and units. These factors and activities characterize *Operational Logistics*—the logistics at the operational level of war. The focus of this article is on the physical flexibility of operational logistics systems.

The objectives of our analysis are to briefly discuss the general implications of physical flexibility on the operational level of war, to identify logistical parameters that affect physical flexibility and finally to propose a methodology for evaluating it in an operational logistics setting. For brevity, we will drop the *physical* part from the term and refer henceforth simply to *flexibility*.

FLEXIBILITY IN MILITARY OPERATIONS

Flexibility is an attribute that is associated with systems (Mandelbaum and Buzacott [1990]). A system is a collection of entities and processes that are united by common objectives. A system is said to be *flexible* if its entities and processes can quickly respond to new constraints, demands and environmental changes in such a way that its objectives can still be achieved effectively.

A military operation can be viewed as a system. The entities of the system are combat forces, weapons, command and control systems, logistics units and facilities, etc. The processes are fire, maneuver, information transfer, supply, etc. The commander of the operation commands the entities and initiates and controls the processes.

The imbedded operational flexibility in a certain state of the operation depends on the spatial layout of the force, on the mix of its combat units, on the position of the enemy and on the environment. Unlike manufacturing system where flexibility has some permanent or at least long-range effect, flexibility or freedom of action in military operations is temporal—it may change very rapidly over time as the battlefield conditions change. Higher versatility of combat units and weapon systems enhances flexibility. The concept of *combined arms* has emerged as a result of the need for higher versatility, and thus flexibility, in employing forces in the modern battlefield. Flexibility is enhanced also when the commander can postpone the decision regarding commitments of units to a particular combat zone as long as possible. Figure 1 demonstrates in simple and generic terms one aspect of this property.

Figure 1 depicts a rear staging area and three possible forward combat zones where forces may be employed. The lines represent lines of communication. The extent of this employment is uncertain and therefore it is not clear what should be the proper deployment of the forces among these three zones. In Figure 1a the entire force is held back at a staging area out from which it can be rapidly deployed in any of the three zones. In Figure 1b the force has been divided and allocated to the three zones. As time advances and the battlefield's characteristics and intensities in the three zones unfold, the force can be deployed in a much more efficient way in case (a) than in case (b) where force adjustments can be accomplished directly only between zones II and III. Notwithstanding other operational constraints (such as mobility capabilities), it is clear that the posture in 1a is inherently more flexible than that in 1b. It is more robust to possible variance in the realization of battlefield parameters.

The attainment of operational flexibility is affected by the ability of the supporting and sustaining systems to respond quickly and ef-

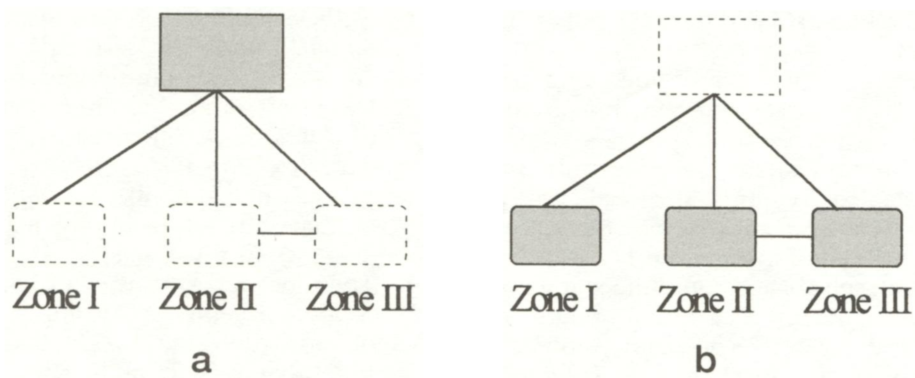

Figure 1a. Rear Deployment
Figure 1b. Forward Deployment

fectively to changing demands. In other words—it is affected by *logistical flexibility.*

THE NEED FOR FLEXIBILITY IN LOGISTICS

Operational flexibility—the ability to react swiftly and effectively to changing conditions at the theater of operations—may be attained only if the operational plans can be adequately sustained. To accomplish this requirement, the supporting logistics system must be flexible too. Moreover, flexibility in logistics is essential even in relatively stable operational situations where the overall level of uncertainty is low. Within a given operational situation there is much room for tactical variability that stems from the random effect of combat phenomena such as fire and maneuver. This tactical uncertainty is manifested, among other things, by high variance in consumption and attrition rates that translate into variable demands for logistics resources. The four dimensional variable that represents logistics demands—quantity, mix, time and location—is constantly changing, according to the tactical situations, in a manner that is not completely predictable. The random demands for logistics resources, such as ammunition, fuel and spare parts may require frequent and unforeseen shifts in their allocations. In order to be able to adequately respond to the changing demands, the logistics system must be flexible. The need for flexibility is prevalent in particular if logistics responsiveness is dependent more on efficient delivery rather than on stocks on site. When large humps of logistics stocks in combat units are traded for speed and precision in delivery (Williams [1997]) flexibility becomes an essential property to achieve responsiveness. Thus, flexibility is one of the key elements of operational logistics (Brabham [1994]).

DEFINING LOGISTICS FLEXIBILITY

Logistics flexibility may be defined similarly to operational flexibility as *the ability to quickly respond and satisfy changing demands for logistics resources.* This definition is simple, clear and it reasonably describes the nature of flexibility in the logistical context. However, it is too general and abstract for any practical analysis. This definition tells us what are the capabilities that compose logistics flexibility but it cannot be used to measure, or even to formally identify, these capabilities in any given logistical deployment. The question is: what are the features that give a certain logistical posture "the ability to quickly respond. . ." or, what are the physical or tangible attributes that generate logistics flexibility.

There are essentially two attributes that characterize logistics flexibility: *technical or intrinsic flexibility* and *structural flexibility.*

INTRINSIC FLEXIBILITY

Intrinsic flexibility has two aspects. The first aspect is derived from the functional interrelationships among logistics assets such as the one between transportation means and the various types of supplies. The second aspect applies to the operational interrelations between combat units (the "customers") and logistics assets (the "providers").

Logistics assets may be divided into two types: logistics resources and logistics support resources. Logistics resources, such as ammunition, fuel, food and maintenance units are logistics assets that contribute directly to the combat effort. The logistics support resources, such as transportation means, storage facilities and command, control and communication systems, relate to the processing, shipping and handling of the logistics resources. The intrinsic flexibility among logistics assets is enhanced when the average number of resources that can be handled by a single logistics support resource in a given period of time is increased. In other words, one logistics system is more intrinsically flexible than another system if its transportation, storage and handling means are more versatile.

A relatively recent example of a logistics support resource with embedded intrinsic flexibility is the Palletized Load System (PLS) (see Haas [1996]). PLS is a transportation concept that is based on the idea of separating between the truck and its load. This conceptual separation facilitates the ability to quickly switch from carrying one type of load (e.g. ammunition) to carrying another type (e.g. fuel). Intrinsic flexibility is presented here in the capability to adapt trucks to carry a wide range of logistics resources. Another example is the Movement Tracking System (MTS) that can track individual vehicles and cargo throughout the battlefield. In the presence of enhanced visibility of logistics assets, control over these assets is tighter and hence the response to changing circumstances is more effective.

The second aspect of intrinsic flexibility is manifested in the match between the customers—weapon systems, combat equipment and personnel—and the mix of logistics resources that are to satisfy their demands. It represents the extent to which customers are interchangeable with respect to a given resource, and resources are interchangeable with respect to a certain customer. The more customers can be served by a certain logistics resource, or the more types of resources can satisfy the demands of a certain weapon system—the higher is the intrinsic flexibility. For example, a certain type of fuel that is suitable for a wide range of combat vehicles embodies intrinsic flexibility. Other examples are a maintenance unit that can fix a large variety of tanks and armored fighting vehicles, and a weapon system, such as aircraft, helicopter and artillery, that can deliver an assortment of munitions. Conversely, if a combat unit at the theater of operations comprises a large assortment of weapon systems, and each weapon system requires specifically designated and specialized maintenance services, then intrinsic flexibility with regard to maintenance is minimal.

The concept of intrinsic flexibility is similar to the idea of component commonality in Assemble-To-Order systems (Gerchak and Henig [1989] and Gerchak et al. [1988]). The weapon systems at the theater of operations play a similar role to the "products" in the Assemble-To-Order manufacturing system. The commander's operational priorities imply "prices" that are associated with mixtures of weapon systems and the "common components" are common logistics assets.

Thus, intrinsic flexibility is associated with the versatility of equipment and skills which also contributes to the capability to improvise—a basic tenet of operational logistics (FM 100-5 [1993]).

Figure 2 depicts graphically the idea of intrinsic flexibility. Figure 2a represents a situation where the second aspect of intrinsic flexibility exists, while Figure 2b represents no intrinsic flexibility. An edge in the graph corresponds to a possible (physical) match between a customer (a combat unit) and a provider (logistics resource).

STRUCTURAL FLEXIBILITY

While intrinsic flexibility has to do with concrete aspects such as logistical skills, equipment and technical processes, structural flexibility is more general and less tangible. It refers to the basic structural properties of the logistics deployment at the theater of operations. Also, contrary to intrinsic flexibility that is applicable to all types of warfare, structural flexibility is, as we shall see, a meaningful property of land warfare only.

What makes one logistics deployment more structurally flexible than another deployment? Or in other words, what are the structural features of an operational logistics system that make it capable to react swiftly and effectively to changing conditions and requirements at the theater of operations? In order to address these questions we construct a simple concep-

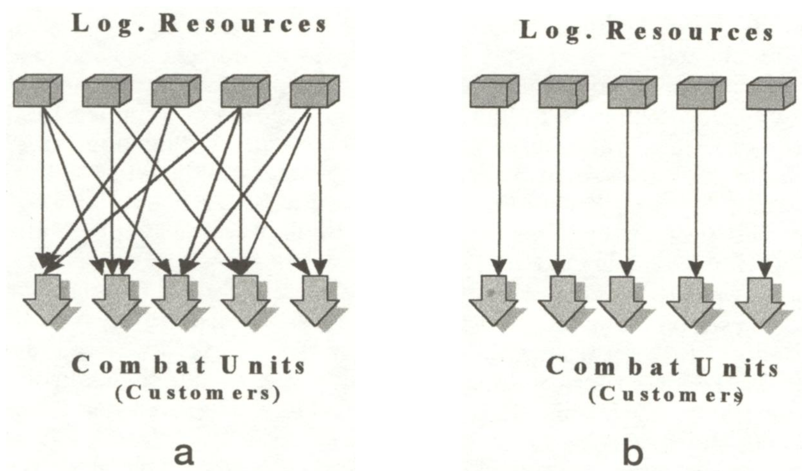

Figure 2a. Intrinsic Flexibility
Figure 2b. No Intrinsic Flexibility

tual model of an operational logistics system that can represent its structural features. This model is the *logistics network.*

Logistics Network

Following the traditional definition of a *network,* the logistics network comprises two basic entities: a graph and a flow. The *graph* of the logistics network is shown in Figure 3. It constitutes the basic structure of the logistics system and it represents its topological features. The *flow* that traverses this graph represents the dynamic part of the system. The nodes of the graph are logistics facilities, logistics units and combat units (the customers). The edges are the lines of communications (LOCs) that connect the nodes. The (multi-commodity) flow represents logistics resources that move between nodes—through the edges of the graph. Note that the flow on a certain edge may have two directions. Some "commodities" such as fuel, ammunition and spare-parts move in the direction from the rear to the front, while the flow of casualties, damaged equipment and prisoners-of-war move backwards—from the front to the rear.

The set of nodes in the logistics network is divided into three types: source nodes, intermediate nodes and destination nodes. The source

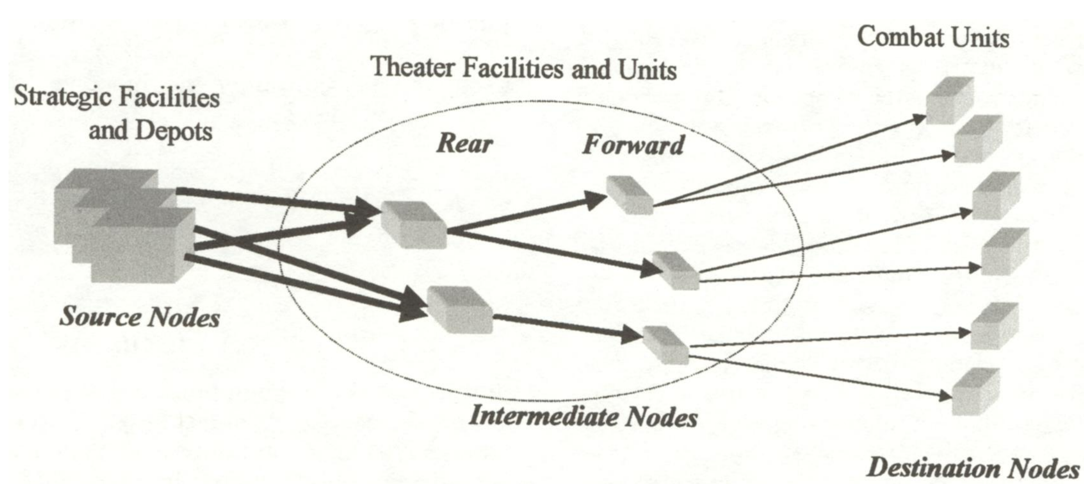

Figure 3. The Logistics Network

nodes correspond to the permanent strategic depots and industrial facilities that feed the military operation with logistics supplies and services. These nodes represent ammunition arsenals, arms depots, military warehouses, major fuel storage areas, home-bases of military units and ports of embarkation. The intermediate nodes are central theater facilities such as major ammunition dumps, makeshift maintenance areas, field hospitals, midway airfields and ports of debarkation. The destination nodes, at the bottom of the logistics graph, are the end-customers of the logistics supplies and services—the tactical units. Each type of nodes may be divided into two levels or more. For example, the intermediate nodes may be separated into rear theater facilities such as sea ports and airfields and forward theater facilities such as corps logistics units (Foxton [1993]). Because of the strict hierarchical form of the military command structure, we assume that, except for rare emergencies, no meaningful lateral flow exists among nodes at the same command level. Thus, the network graph is essentially a ***tree***.

Unlike the source nodes that are deterministic and fixed, the destination nodes and a portion of the intermediate nodes may be variable. This variability reflects the imbedded dynamics of the battlefield. Combat units may change positions and formations and mobile logistics facilities at the theater of operations may move and change their composition according to the changes in the operational circumstances. Thus, the location of these nodes and their composition may vary in time and may affect, in particular, the length of the lines of communications that connect them. Nodes may also be generated and deleted in the course of the campaign e.g. when new logistics units enter the theater of operations or when a combat unit is killed. This phenomenon of *"variable nodes"* (and hence—*variable edges*) is typical to the battlefield environment.

The logistics flow—supplies and services—may be accumulated at the nodes as inventories or transported through the edges. The amount of flow in the nodes and its throughput in the edges are constrained by the (technical) capacities of the nodes and the edges and by their reliability.

The nodes' capacities are determined by their storage area, by the facilities that exist there and by the available handling and processing equipment. The edges' capacities are set by the physical characteristics of the LOCs and by the number, speed and load size of the transportation means. The reliability of the nodes and edges is determined by their vulnerability to the actions of the opposing force and by their robustness to the effect of the elements. Hostile activity of the enemy and rough weather conditions may cause cuts in the edges of the logistics network.

The technical capacities of the nodes and edges, coupled with their reliability, determine the *actual capacities* of the network. The actual capacities dictate the realistic mean throughput level in the logistics network and therefore impose critical constraints on the responsiveness of the logistics system to the operational demands. Relaxing, as much as possible, the capacity constraints, by increasing throughput and reliability, is one of the main objectives in operational logistics planning.

Once the capacities are set, the problem is to coordinate and schedule the logistics flow such that maximum responsiveness is attained for the demands at the end nodes—the combat units. Note that the interrelation between the two problems—setting capacities and scheduling the flow—is two ways. On the one hand capacities determine the feasibility of a certain schedule. On the other hand, a certain schedule may require a shift of transportation means from one edge to another or a selection of an alternative, less secure edge. Such changes may affect the capacities of the corresponding edges.

In conclusion, logistics at the operational level of war is essentially a matter of network management (De Landa [1991]). Specifically, the main tasks of the operational logistician are to determine the location and capacities of the intermediate nodes, select efficient (high capacity and secure) edges and set the size and mix of the flow. Accordingly, the questions regarding the meaning of structural flexibility may be restated now using the concepts of logistics network: *What are the (topological) features of the graph, and the dynamic properties of the flow that exhibit structural flexibility in a logistics network?*

Defining Structural Flexibility

The answer for this question is now quite simple. Recall that flexibility was defined as *the number of optional alternatives left over after one has made an initial decision.* From the section on Flexibility in Military Operations it follows that flexibility is enhanced when the logistician can postpone the decision regarding commitments of resources to combat units as long as possible. Combining these two observations we may obtain the following simple sufficient condition for structural flexibility:

Suppose that two operational logistics system A and B share the same graph. System A is ***more structurally flexible*** *than system B if: (1) The distribution of the flow over the logistics network is concentrated in nodes higher up in the graph of A than in the graph of B, (2) The flow capacity of each edge in the graph of A is not smaller than the corresponding edge capacity in B.* Recall that *flow capacity is* determined by two main factors: (a) technical capacity of the LOCs and the transportation means, (b) the reliability of the nodes and the edges. Figure 4 depicts these properties.

The intermediate nodes in Figure 4a have more capacity than the corresponding nodes in Figure 4b while the reverse is true with respect to the destination nodes. It can be seen also that the edge capacities in 4a are not smaller than those in 4b. The system that is depicted by 4a is more flexible than that in 4b.

Structural flexibility has an operational cost; higher structural flexibility may be obtained at the expense of another important logistics attribute—*attainability*.

Attainability is defined as the level of essential logistical assets that are committed to the tactical (combat) units at the beginning of combat operations. Thus, higher level of attainability results in a longer logistics tail at the destination points—the combat units. Attainability provides the ability to respond ***very fast*** to critical logistics demands at the tactical level because it eliminates the supply lead-time in the system. However, since demands for logistical resources are uncertain, and they are likely to have large variances, high level of attainability means also high redundancy at the destination nodes. This redundancy is achieved at the expense of structural flexibility. This situation is depicted in Figure 4b.

There is a fundamental difference between flexibility and attainability. While structural flexibility is an **objective** that is derived from optimization considerations, attainability is present as a result of time **constraints**. If the response-times from the intermediate nodes to the demands at the destination nodes (combat units) is higher than the demand rate, then the effect of attainability—responding fast to the logistical demands—may be achieved by **velocity** as opposed to **mass**. In this case attainability becomes superfluous and structural flexibility becomes the dominant attribute. Thus, as the capacities of the internal LOCs increase and the logistical flow through them is smoother and moves faster, structural flexibility may take over as the main, if not the only, attribute to consider.

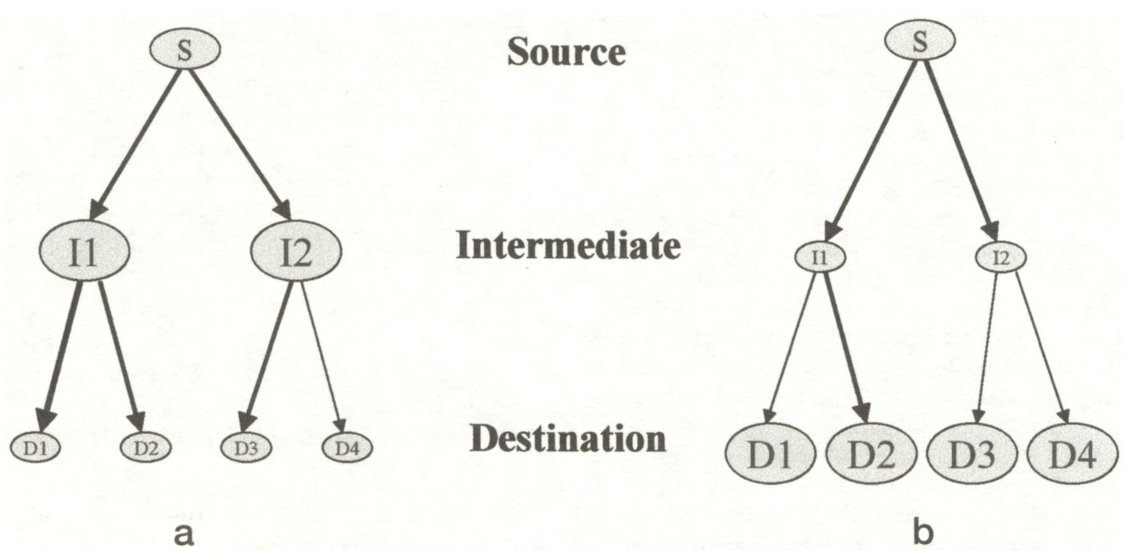

Figure 4a. System A—More Flexible.
Figure 4b. System B—Less Flexible.

MEASURING FLEXIBILITY

Both intrinsic flexibility and structural flexibility may be measured quantitatively on a ratio scale. In this section we define indices that evaluate the relative standings of operational logistics systems with respect to these two facets of flexibility.

The Intrinsic Flexibility Index (*IFI*)

The *IFI* reflects the two aspects of intrinsic flexibility: (1) the adaptability of the logistics support resources to the various logistics resources (e.g. PLS trucks), (2) the versatility of logistics resources with regard to demands in combat units (e.g. general-purpose maintenance units). These two aspects are merged into a single index in the following way.

Define an *essential demand unit* (EDU) by a pair (u, l). The first entry u, $u = 1, \ldots, U$, represents a combat unit (e.g. Howitzer battalion, TOW company, Merkava tank battalion). The second entry l, $l = 1, \ldots, L$, represents a *generic* logistics resource that may be consumed by the corresponding combat unit. For example, the pair (battalion 123, tank rounds) may be an EDU if battalion 123 is a tank battalion. It cannot be an EDU if the combat unit is an artillery battalion. Let M denote the number of possible EDUs.

Let $\boldsymbol{R}$ denote the set of all logistics support resources (e.g. trucks, warehouses, forklifts, trailers) and all *specific* logistics resources (e.g. 155mm artillery shells, HE-AP tank rounds, diesel oil, water, **certain** maintenance unit). A component in $\boldsymbol{R}$ is called *logistics asset* and the cardinality of $\boldsymbol{R}$ is K. Let k, $k = 1, \ldots K$ denote the k-th logistics asset in $\boldsymbol{R}$. A logistics asset k is said to be *associated* with a certain EDU (u, l) if it is utilized by the EDU.

Some associations, such as (120mm tank rounds) → (Abrams tank battalion, tank rounds) or (Surgical Company Z) → (Infantry battalion, medical services), are self-evident. Other associations may or may not hold. For example, the existence of the association (Maintenance unit X) → (MLRS battery, MLRS maintenance unit), depends on the qualification and training of the staff of X, on its equipment and on the spare-parts that it holds. Logistics support resources in R are associated with an EDU through the EDU's logistics resource. For example, the association (Trucks) → (Merkava tank battalion, tank rounds) exists because trucks are used to transport ammunition. This reasoning leads to the conclusion that the association (Trucks) → (Merkava tank battalion, Fuel) usually does not exist since regular trucks may seldom carry liquids.

Following the discussion before, we define the intrinsic flexibility index IFI in the following way. First we compute for each logistics asset k the ratio between the number of associations it creates with the set of EDUs and the number of EDUs. This value indicates the versatility of asset k. The index IFI is then computed as the average ratio over the set $\boldsymbol{R}$ of logistics assets. Thus, when a smaller number of logistics assets can cater a larger set of EDUs, intrinsic flexibility is enhanced.

Formally,

$$IFI = \frac{1}{KM} \sum_k \sum_u \sum_l a_{kul}$$

where a_{kul} is equal to 1 if logistic asset k is associated with EDU (u, l), and is equal to 0, otherwise. Note that by taking appropriate weights, this index can be used to reflect also the mix or the relative quantity of each one of the logistics assets in $\boldsymbol{R}$.

It can be verified that $0 \leq IFI \leq 1$. Maximum intrinsic flexibility ($IFI = 1$) is attained when each logistics asset is associated with all EDUs.

Example 1

Combat Units: 10 (dismounted) infantry battalions (InfBat), 20 tank battalions (TnkBat). Logistics Resources: machine-gun ammunition (MGAm), tank ammunition (TKAm), fuel (F).

EDUs: (InfBat, MGAm), (TnkBat, TKAm), (TnkBat, F). (Here $M = 10 + 20 + 20 = 50$).

Logistics Assets: trucks (T), bowsers (B). 0.5 inch rounds (0.5in), 105mm rounds (105mm), diesel oil (DO) ($K = 5$).

Associations: T → (InfBat, MGAm), (10 associations); T → (TnkBat, TKAm), (20 associations); B → (TnkBat, F), (20 associations); 0.5in → (InfBat, MGAm), (10 associations); 105mm → (TnkBat, TKAm), (20 associations); DO → (TnkBat, F), (20 associations).

The intrinsic flexibility index in this case is:

$$IFI = \frac{100}{5 \times 50} = 0.4$$

Suppose that the trucks and bowsers are replaced by a PLS system that is fit to transport both solid and liquid cargo. In this case,
Logistics Assets: PLS (P), 0.5 inch rounds (0.5in), 105mm rounds (105mm), diesel oil (DO) (K = 4).

Associations: P → (InfBat, MGAm), (10 associations); P → (TnkBat, TKAm), (20 associations); P → (TnkBat, F), (20 associations); 0.5in → (InfBat, MGAm), (10 associations); 105mm → (TnkBat, TKAm), (20 associations);
and

$$IFI = \frac{100}{4 \times 50} = 0.5$$

Thus, the introduction of PLS has resulted, in this case in a 25% increase in the intrinsic flexibility.

Example 2:
Combat Units: 10 tank battalions of type X1 (TkBatX1), 10 tank battalions of type X2 (TkBatX2), 10 tank battalions of type X3 (TkBatX3). Logistics Resources: maintenance units (MU), tank ammunition (TkAm).

EDUs: (TkBatXi, MU), (TkBatXi, TkAm), i = 1, 2, 3. (M = 60).

Logistics Assets: maintenance unit of type Xi (MUXi), i = 1, 2, 3; 105mm rounds (105mm). (K = 4).

Associations: MUXi → (TkBatXi, MU), i = 1, 2, 3; 105mm → (TkBatXi, TkAm), i = 1, 2, 3.

Here,

$$IFI = \frac{10 + 10 + 10 + 30}{4 \times 60} = .25$$

If however all thirty battalions are of the same type or each maintenance unit can support all types of tanks, then the intrinsic flexibility index becomes:

$$IFI = \frac{30 + 30}{2 \times 60} = 0.5$$

which is the maximal attainable intrinsic flexibility for this logistics situation.

The Structural Flexibility Index (*SFI*)

The *SFI* is a relative measure that represents the embedded flexibility in a given deployment of logistics assets in the theater of operations. It is determined by the command structure of the forces at the theater of operations and by the distribution of assets among the various command levels—battalion, brigade, division, corps and army. We have already seen that a higher up concentration of logistics assets in the command hierarchy, and a larger capacity of reliable LOCs, imply greater structural flexibility. This observation leads to the following definition of *SFI*.

Consider the Hierarchy in Figure 5.

The indices i = 1, 2, 3, 4, 5 denote the command levels: army, corps, division, brigade and battalion, respectively. The pair (i, j) denotes the j-th unit at level i, i = 1, . . . , 5. For example, (4, 3) indicates the third brigade in the force. Define J_i as the number of units at level i. For example, $J_2 = 2$ and $J_4 = 9$. Without loss of generality we assume that $J_1 = 1$. The hierarchical structure creates a tree in which a battalion belongs to one brigade, a brigade belongs to one division, etc.

Let S_{ik} be the "subordinate set" of (i, k). That is,

$$S_{ik} = \{(5, j); (5, j) \text{ is a subordinate battalion of unit } (i, k)\}.$$

For example, $S_{32} = \{(5, 5), \ldots, (5, 12)\}$ and $S_{47} = \{(5, 15), (5, 16)\}$. The hierarchy in the command structure implies that $S_{ik} \cap S_{im} = \phi$ for any two units (i, k) and (i, m). The cardinality of S_{ik} is denoted by N_{ik}. For example, $N_{32} = 8$ and $N_{47} = 2$. Since $N_{5k} = 1$ for all k then

$$\sum_{k=1}^{J_i} N_{ik} = J_5, \quad i = 1, \ldots, 5.$$

Next we define the following variables and parameters:

- X_j — A random variable that represents the (daily) demand for a certain logistics resource at combat unit (battalion) (5, j).
- C_i — A random variable that represents the average lead-time from a logistics unit at level i to a subordinate unit at level i + 1. For example, C_3 is the average time that it takes for a load of tank rounds to move from a division Support Battalion to any of its brigades. The parameter C_5 is the

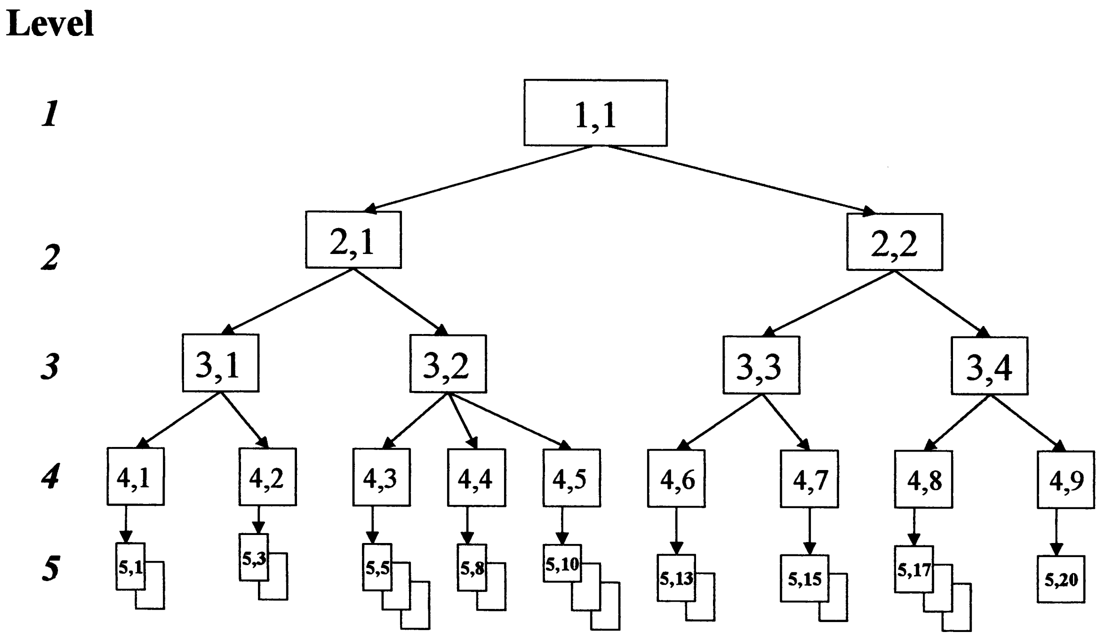

Figure 5. A Five-Levels Hierarchy

response time from the battalion support unit at the rear of the Forward Line of Own Troops (FLOT) to the combat forces at the front. Arguably, C_i is the reciprocal of the actual capacity. Therefore it is a function of the technical capacity and the reliability of the corresponding LOCs.

c_{i0} — A threshold value for the lead-time from command level i to command level i + 1. This parameter indicates operationally acceptable logistical response-time from one command level to the next.

Q — Total quantity of a certain logistics resource that is deployed at the theater of operations.

r_i — A decision variable that indicates the proportion of Q that is allocated to command level i.

$$\sum_{i=1}^{5} r_i = 1$$

The *SFI* is constructed on the premise that structural flexibility is directly related to the *potential* of a "quantum" of logistics resources to support the battalions. We call this potential *flexibility potential.* The flexibility potential is a measure that is associated with a given command level i and it depends on the quantity of the resource that is allocated at that level, on the number of units, J_i, on the distribution of subordinate battalions, $\{S_{i1}, \ldots, S_{iJ_i}\}$ on the lead times $(C_i, \ldots, C_5)$ and on the demands X_j.

The flexibility potential of command level i may be defined in terms of the *probability of responsiveness* if all the quantity Q of the logistics resource is distributed among the logistics units at command level i. The allocation of the resource to each unit (i, j) at level i is proportional to the size N_{ij} of its subordinate battalions set S_{ij}. That is, the flexibility potential is the probability that the quantities

$$q_{ij} = \frac{N_{ij}Q}{J_5}, \quad j = 1, \ldots, J_i$$

of the resource that are allocated to units (i, j) $j = 1, \ldots, J_i$ are *sufficient* to supply the demand, and that this resource can reach the battalions on *time.* If we denote the *"sufficiency"* probability at command level i by $P_S(i)$ and the *"timeliness"* probability by $P_T(i)$, then the flexibility potential of command level i is the product $P_S(i)P_T(i)$. The SFI is constructed as the weighted geometric mean of the flexibility potentials over the five command levels. This construction is described next.

The Sufficiency Probability

The probability that the amount q_{ik} at unit (i, k) is sufficient to supply the demands at its subordinate battalions is:

$$P_S(i, k) = \Pr\left[\sum_{j \in S_{ik}} X_j \leq q_{ik}\right]$$

Assuming independence of the demands among the battalions, the sufficiency probability at level i is:

$$P_S(i) = \prod_{k=1}^{J_i} P_S(i, k)$$

Notice that since

$$\Pr\left[\sum_{k=1}^{n} X_k \leq nA\right] \geq \prod_{k=1}^{n} \Pr[X_k \leq A]$$

always holds, the topology of the hierarchical command structure implies that concentrating supplies in higher command levels provides higher sufficiency probabilities.

The Timeliness Probability

We assume that the lead-time from one command level to the next may be adequately described by a single random variable that represents the average time over the corresponding LOCs. Thus,

$$P_T(i) = \prod_{m=i}^{5} \Pr[C_m \leq c_{m0}]$$

Unlike the sufficiency probability above that increases when supplies are concentrated at a higher echelon, higher command level implies longer lead-time and therefore lower timeliness probability. Moreover, it is evident that the sufficiency probability is dependent on the actual allocation q_{ik} of the resources. This is not the case for the timeliness probability. We assume that $P_T(i)$ is independent of the resource allocation among the command levels. This assumption may not be always true. It is likely that in certain situations this probability will be affected by scale: the timeliness of 10000 gallons of needed fuel may not be the same as the timeliness of 100000 gallons. The functional dependency between scale and timeliness is difficult to capture and it is beyond the scope of this article. We postpone the analysis of this type of issues to future research.

The *flexibility potential* of command level i is given now by the product $P_S(i)P_T(i)$. Because of the multiplicative nature of the probability measure, the SFI is defined as the weighted geometric mean of the commands' level flexibility potentials. That is

$$SFI = \prod_{i=1}^{5} [P_S(i)\, P_T(i)]^{r_i}$$

where r_i is the proportion of the resource that is assigned to level i.

The SFI is a relative measure that can be used to compare two logistical deployments with respect to their embedded flexibility (see example below). Also note that the SFI incorporates to some extent the tradeoff between economy and attainability. The *sufficiency* measure P_S represents the effect of economies while the *timeliness* measure P_T relates to the attainability objective.

Example. Consider two operational postures that comprise a corps (command level 2) with two divisions (command level 3). The command hierarchies of posture A and B are shown in Figures 6a and 6b, respectively. The symbols: XXX, XX, X and II represent corps, division, brigade and battalion, respectively.

The consumption rates X_j at the battalions are independent random variables and

$$X_j \sim N(\mu, \sigma), \quad j = 1, \ldots, J_5$$

The relative deployments $(r_2, \ldots, r_5)$ of logistics assets in the five command levels are $r_A = (0.2, 0.3, 0.3, 0.2)$ and $r_B = (0.3, 0.3, 0.3, 0.1)$ for postures A and B, respectively. $P_T(i) = 0.9, 0.8, 0.9, 1$ for $i = 2, 3, 4, 5$, respectively, in both postures.

To make this measure independent of the consumption rate, we assume that $Q = \alpha\mu$ and $\sigma = \mu\beta$, where μ is the expected value of the

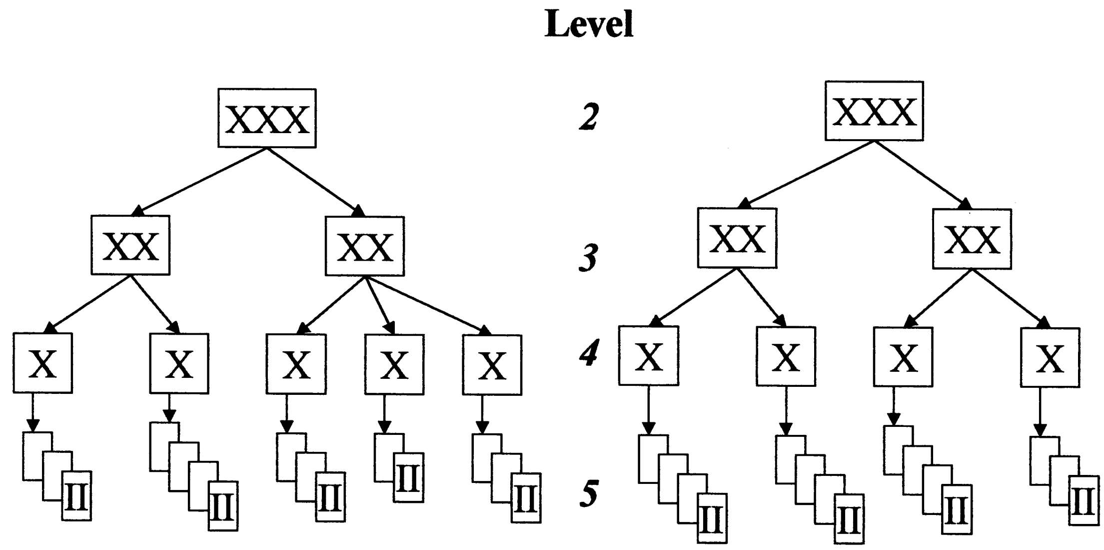

Figure 6a. Force Structure—Posture A
Figure 6b. Force Structure—Posture B

demand. Thus, the *SFI* dependents only on the ratio α between the total amount of the resource at the theater of operations and its expected demand by a battalion, and on the coefficient of variation β of this demand.

Since in both postures the timeliness probabilities $P_T(i)$ and the number of battalions J_5 are the same, it follows that the flexibility potentials of each command level 2 and 5 are equal in both postures. This equality also holds for i = 3 since

$$P_S^A(3) = \Pr\left[\sum_{j=1}^{7} X_j \le \frac{7}{15}Q\right] \cdot \left\{\Pr\left[\sum_{j=1}^{8} X_j \le \frac{8}{15}Q\right]\right. = \Pr\left[\sum_{j=1}^{8} X_j \le \frac{8}{15}Q\right] \cdot \left\{\Pr\left[\sum_{j=1}^{7} X_j \le \frac{7}{15}Q\right]\right. = P_S^B(3)$$

This is not the case however at command level 4 since the sufficiency probability there in Posture A is different than the one in Posture B:

$$P_S^A(4) = \Pr\left[\sum_{j=1}^{4} X_j \le \frac{4}{15}Q\right] \cdot \left\{\Pr\left[\sum_{j=1}^{3} X_j \le \frac{1}{5}Q\right]\right\}^3 \Pr\left[\sum_{j=1}^{2} X_j \le \frac{2}{15}Q\right]$$

$$P_S^B(4) = \left\{\Pr\left[\sum_{j=1}^{4} X_j \le \frac{4}{15}Q\right]\right\}^3 \cdot \Pr\left[\sum_{j=1}^{3} X_j \le \frac{1}{5}Q\right]$$

Table 1 presents the *SFI* values of Posture A and Posture B for $\alpha = (18, 20, 22)$ and $\beta = (1, 1/2, 1/3, 1/4, 1/5, 1/6)$. The values of α are selected such that the total quantity Q at the theater of operations is between 20% and 50% over the total expected demand (15 μ).

The entries in Table 1 are the weighted geometric means of the flexibility potentials at the four command levels where the weights are (0.2, 0.3, 0.3, 0.2) for Posture A and (0.3, 0.3, 0.3, 0.1) for Posture B. For example,

α	18		20		22	
β	Posture A	Posture B	Posture A	Posture B	Posture A	Posture B
1	.035	.153	.065	.231	.106	.314
1/2	.084	.273	.187	.429	.318	.550
1/3	.157	.393	.353	.574	.546	.575
1/4	.250	.495	.517	.603	.698	.735
1/5	.353	.574	.644	.716	.770	.759
1/6	.454	.633	.725	.744	.795	.768

Table 1: *SFI* values for the two postures

$$SFI(A) = \left(\left(\Pr\left[\sum_{j=1}^{15} X_j \le Q\right]\right) \times 0.9 \times 0.8 \times 0.9\right)^{0.2}$$

$$\left(\left(\Pr\left[\sum_{j=1}^{7} X_j \le \frac{7}{15} Q\right]\right)\right.$$

$$\cdot \left(\Pr\left[\sum_{j=1}^{8} X_j \le \frac{8}{15} Q\right]\right) \times 0.8 \times 0.9\Bigg)^{0.3}$$

$$\times \left(\left(\Pr\left[\sum_{j=1}^{4} X_j \le \frac{4}{15} Q\right]\right)\left(\Pr\left[\sum_{j=1}^{3} X_j \le \frac{1}{5} Q\right]\right)\right)^{3}$$

$$\left(\Pr\left[\sum_{j=1}^{2} X_j \le \frac{2}{15} Q\right]\right) \times 0.9\Bigg)^{0.3}$$

$$\cdot \left(\Pr\left[X_j \le \frac{1}{15} Q\right]\right)^{15\times 0.2}$$

We can observe that Posture B is generally more flexible than Posture A. For example, if Q is 33% more than the total expected demand ($\alpha = 20$), and the coefficient of variation is 1/3, then the *SFI* of Posture B (.574) is over 60% higher than that of Posture A (.353). However, when Q is relatively large ($\alpha = 22$) and the standard deviation is small compared to the mean (small values of β) it is seen that this order is reversed. For example, when $\beta = 1/6$ then *SFI*(A) = .795 while *SFI*(B) = .768. This happens because in this case the sufficiency probability is very high (close to 1) in both postures and therefore the timeliness probability, which is evidently higher in posture A than in Posture B, becomes the major factor in determining the values of the *SFI*. In other words, if the supply is in abundance, then the efficiencies that are gained by concentrating the supplies higher up in the command tree are redundant. In this case the time factor becomes dominant.

SUMMARY AND CONCLUSION

Flexibility—the capability to efficiently adjust to new circumstances and requirements—is a desired attribute of any system. This attribute becomes critical in the singular, uncertain, and even chaotic, phenomenon of warfare. In particular, it is necessary that the logistics system that supports combat should be flexible and responsive to constantly changing demands.

In this article an attempt was made to explore the concrete meaning of this attribute in the context of operational logistics. The two facets of flexibility—intrinsic and structural—where defined, discussed and formalized by a quantitative index. The tradeoff between economy and attainability was captured in the definition of the Structural Flexibility Index—*SFI*—by incorporating the measures of sufficiency and timeliness.

Combining the *IFI* and the *SFI* into one overall index of flexibility is difficult, or at least not straightforward. These two indices measure two loosely related facets of flexibility. The *IFI* measures the inherent technical flexibility of the logistics components, while the *SFI* measures the overall structural flexibility of the logistics system deployment at the theater of operations. These two indices may be combined into a two-dimensional index. The weights of its two components—the relative importance of intrinsic flexibility and structural flexibility—may be determined by the operational logistics planner according to the theater posture and the operational objectives.

The formalization of flexibility may be helpful in the evaluation of in-context operational logistics plans, a process that Eccles [1982] has called "logistics planning". Given the order of battle at the theater of operations and the logistics resources that are available, the method that is presented in this article can be utilized to analyze the logistics impact of alternative deployments of forces and logistics assets.

REFERENCES

Brabham, MajGen J. A., (1994), "Operational Logistics: Defining the Art of the Possible," *Marine Corps Gazette*, April 1994, p 27.

De Landa, M., (1991), *War in the Age of Intelligent Machines*, Swerve Editions, NY, p 107.

Eccles, H. E., (1982), "Logistics, What is it?", *Proceedings*, US Naval Institute, 1953, pp 645–653. Reappeared in Logistics Spectrum, V. 16, No. 2, pp 10–16.

FM 100-5, (1993), *Operations*, Department of the Army, Washington DC, p 12–3.

Foxton, P. D., (1993), *Powering War: Modern Land Force Logistics*, Brasseys, p 12.

Gerchak, Y. and Henig, M., (1989), "Component Commonality in Assemble-to-Order Systems: Models and Properties,", *Naval Research Logistics*, 36, pp 61–68.

Gerchak, Y., Magazine, M. J., and Gamble, B., (1988), "Component Commonality with Service Level Requirements,", *Management Science*, V. 34, No. 6, pp 753–760.

Gupta, S. K., and Rosenhead, J., (1968), "Robustness in sequential investment decisions", *Management Science* 15, B18–B29.

Haas, P. M., (1996), "Palletized Loading System: Not Just Another Truck", *Army Logistician*, September–October 1996, p 14.

IDF, (1998), **IDF Battles Database**, *IDF, Systems Analysis Branch, Israel.*

Kovacs, A., (1997), "Using Intelligence", *Intelligence and National Security*, 12, No. 4, pp: 145–164.

Mandelbaum, M., and Buzacott, J., (1990), "Flexibility and Decision Making", *European Journal of Operational Research*, V. 44, No. 5, pp 17–27.

Resenhead, J., Elton, M., and Gupta, S. K., (1972), "Robustness and Optimality as Criteria for Strategic Decisions", *Operational Research Quarterly* 23, 413–441.

Schneider, J. J., (1994), *The Structure of Strategic Revolution*, Presidio, Novato CA, p. 51.

von Clausewitz, C., (1976), *On War*, Princeton University Press, p 119.

Williams, N., (1997), "The Revolution in Military Logistics", *Military Technology*, V. 21, No. 11, pp 50–51.