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Prepared by:

Alexander H. Levis
Principal Investigator

Tel: (617) 253-7262
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DEVELOPMENT AND APPLICATION OF A METHODOLOGY

FOR SYSTEM EFFECTIVENESS ANALYSIS

ABSTRACT

A quantitative methodology for assessing the effectiveness of command and control systems is presented. The methodology is based on identifying the system, the mission, and the context or environment in which the system operates in support of the mission. Models are used to derive the measures of performance (MOPs) and, from them, the measures of effectiveness (MOEs). The theoretical framework is applied to two classes of problems: (a) to the use of MOEs in the design of a demonstration for an evolving system, and (b) to assessing the timeliness of command and control systems.

Principal Investigator
Alexander H. Levis

August 1985

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1. INTRODUCTION

The need to arrive at rational, defensible decisions in the development and acquisition of command and control systems has led to the demand for the definition and evaluation of pertinent measures of effectiveness (MOEs). Research on this subject was initiated at the MIT Laboratory for Information and Decision Systems (LIDS) in July 1983 with support from NAVELEX under Contract No. N00039-83-C-0466.. The research was focused on two objectives: (a) to develop a methodology for planning and assessing demonstrations of systems under development, and (b) to develop MOEs to reflect the timeliness of C^3 systems.

Results have been obtained for both objectives. Two theses have been completed, one on each subject. One paper related to MOEs for METANET was presented at the 7th MIT/ONR Workshop on C^3 Systems and has appeared in the published proceedings (Karam and Levis, 1984). Two papers, one from each thesis, have been presented at the 8th MIT/ONR Workshop on C^3 Systems and will appear in the published proceedings in December 1985 (Cothier and Levis, 1985; Karam and Levis, 1985).

The goal of the research was to address both conceptual and methodological issues about MOEs for command and control systems. The focus has been on the class of systems described as "evolving". This name denotes large systems that become operational at some point, but continue to change while remaining operational. The changes may occur because of the introduction of new components (hardware and software), new procedures, or new missions and uses.

In a recent (January 1985) workshop on Measures of Effectiveness (MOEs) held at the Naval Postgraduate School, a set of definitions was developed for concepts relevant to this research. The definitions, edited slightly to reflect the particular orientation of this project, are presented below.

Parameters: Characteristics inherent in the physical entity and the structure under question (i.e., the C^3 systems) even when it is at rest.

Measures of Performance (MOPs): These are also closely related to the inherent characteristics (physical and structural,) but measure behavior.

Measures of Effectiveness (MOEs): They measure how the C^3 system performs its functions within an operational environment.

Measure of Force Effectiveness (MOFE): It measures how a C^3 system and the force of which it is a part perform missions.

The first two quantities are measured inside or within the boundary of the C^3 system — and imaginary closed curve that encompasses all the "components" of the C^3 system and only those. The MOEs and MOFE are measured outside the boundary of the C^3 system, i.e., it is necessary to imbed the system within a larger context in order to evaluate it.

These concepts correspond rather closely with the ones developed in the methodology for System Effectiveness Analysis (Bouthonnier, 1982; Bouthonnier and Levis, 1984; Karam and Levis, 1984; Levis et al., 1984; Washington and Levis, 1985). The "parameters" correspond to the primitives, the MOPs to the attributes , the MOEs to the partial MOEs and the MOFE to the global MOE. Neither set of terms is perfect.

System Effectiveness Analysis (SEA) provides a conceptual framework for the use of models in generating quantities used in measuring effectiveness. Models are used to derive attributes (MOPs) from the system or mission primitives. The mission has implicit in its definition the attainment of one or more goals; the goals, in turn, give rise to a set of attributes that express these goals in an explicit manner. While these attributes can be very general as concepts, their quantitative interpretation is, invariably, highly mission dependent. For example, such attributes as timeliness, responsiveness or robustness cover intuitive concepts rather well. However, a set of variables need to be defined that express these concepts. For example, the ratio of the time cycle through the C^2 process for a task to the interarrival time of tasks may be one of the variables that interpret the concept of timeliness. Usually, more than one variable could be used to interpret each attribute.

In the research carried out thus far and reported in theses and papers, a procedure has been described for mapping system and mission primitives (parameters) into attributes (MOPs) and then computing measures of effectiveness.

Let us consider the following candidate set of attributes that describe the C^2 process in the context of a given set of missions:

- Timeliness
- Robustness
- Flexibility
- Responsiveness
- Capacity

Let us also assume that the mission goal(s) can be translated into two measures:

- Degree of attainment of mission objective
- Survivability of own forces.

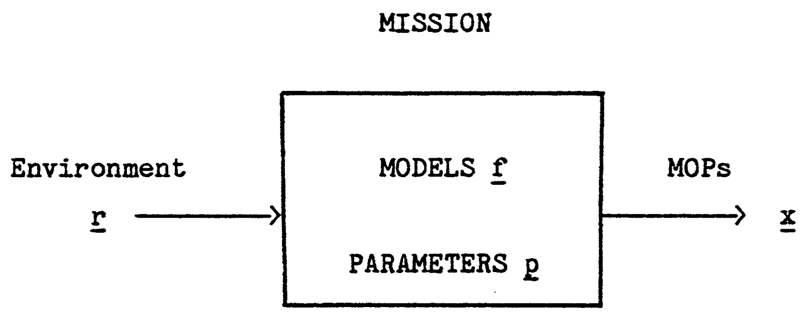
For example, if the mission is anti-submarine warfare, a measure of the degree to which the mission objective has been attained is the number of submarines that have been destroyed. A measure of survivability may be the fraction of ASW resources that are operational at the completion of the mission.

Let the parameters of the C^3 system be denoted by the vector $\underline{p}$. For simplicity of presentation, it will be assumed that the parameters take values that are real numbers ($\underline{p} \in R^m$). However, this need not be the case — some of them may be linguistic taking values such as "fast" or "slow".

Let the environment (or context in the SEA methodology) be described by a vector $\underline{r}$. Then, let the variables that describe the attributes, the MOPs, be denoted by a vector $\underline{x}$. The models of the process allow us to compute the values of these variables as functions of the parameters $\underline{p}$ and the environment descriptors $\underline{r}$.

$$\underline{x} = \underline{f}(\underline{p}, \underline{r}) \qquad (1)$$

The functions f_i represent the various models. This mapping can be represented pictorially as shown below:



While many different model may be used to obtain values for the quantities x_i, it is important that consistent sets of values be obtained. This implies that the various models $\underline{f}$ should be exercised for the same values of $\underline{p}$ and $\underline{r}$ to obtain a mutually consistent set of values of the variables x_i. As the parameters are changed - while the mission and the environment remain fixed — different vectors $\underline{x}$ are obtained.

If the parameter vector $\underline{p}$ can take values $p \in P \quad R^m$, then the variables x_i can take values over a corresponding range in their space, i.e.,

$$\underline{p} \xrightarrow{\underline{f}} \underline{x}$$

$$\underline{p} \in P \subset R^m \qquad \underline{x} \in X \subset R^n$$

Graphically, if the parameter vector is two dimensional and the attribute vector three dimensional, then the mapping of Fig. 1 is obtained.

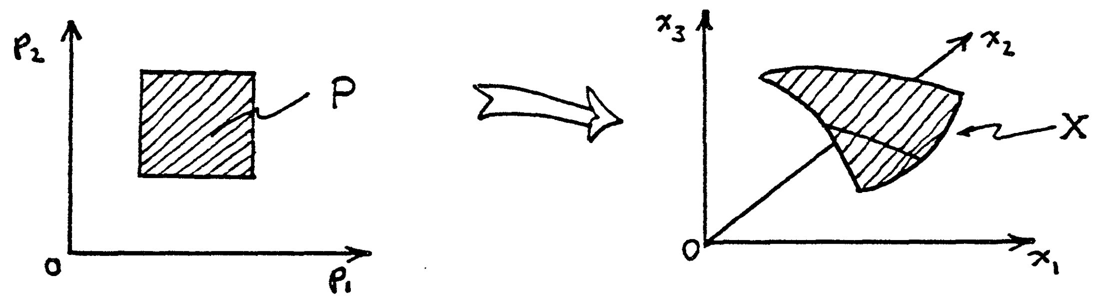


Figure 1. Mapping from Parameter Space to Attribute Space

If the environmental parameters $\underline{r}$ are changed and the procedure repeated, then a new locus $\underline{X}$ will be obtained. Indeed, a whole family of loci can be obtained. Each locus characterizes the performance capabilities of the process for a given mission and for a given set of environmental conditions (or context).

Requirements can be obtained by setting values (or ranges of values) for the MOPs, the attributes x_i. In order to do that, however, it is necessary to go outside the boundary of the C^2 process. Another set of models is required that allows the mapping of the variables x_i to the measures of the mission goals, the MOEs. Two such measures have been introduced as illustrative examples — a measure S_1 that reflects the degree of success in accomplishing the mission and a measure S_2 that reflects survivability:

$$S_1 = g_1(\underline{x},\underline{r}) \tag{2}$$

$$S_2 = g_2(\underline{x},\underline{r}) \tag{3}$$

The evaluation of S_1, and S_2 could be obtained through the use of battle simulation models, or from wargames or exercises.

The set of admissible values of the measures of performance of the C^2 system or process leads to the definition of a mission locus in the attribute space.

Implicit in the notion of assessment or evaluation or measuring the effectiveness of C^2 system is the concept of a standard. If the requirements as expressed by the mission locus represent a standard, then comparison of the measures of performance to the corresponding requirements for these measures leads to measures of effectiveness. Sometimes the comparison is explicit, as when one measures by how much a measure of performance exceeds a given level of performance. Sometimes it is implicit, as when the measure itself is a deviation such as the probability of error.

It has been shown that the requirements can be expressed as a locus in the space spanned by the attribute vector $\underline{x}$. In an analogous manner, there is a locus in that same space that is defined by the values of $\underline{x}$ that can be realized by alternative system designs.

Let the set of admissible values of $\underline{x}$ be denoted by X_a. Let the set of values of $\underline{x}$ realized by a system design be denoted by X_s. One way that a comparison can be made is by analyzing separately each dimension, i.e., each performance measure. A metric can be established for each dimension and a value calculated. For example, the C^2 system may exceed substantially the timeliness requirements, may barely satisfy the robustness and flexibility requirements, may be responsive, but can only support one mission at a time. How does one establish an absolute measure of effectiveness (i.e., this system is very effective) and how does one compare two alternative systems (i.e., the system is more effective than that)?

It is well known that the existence of a vector of MOEs leads to both conceptual and technical problems in evaluating systems. There are problems associated with attempts to map the vector into a scalar by considering weighted averages of the components of the vector. In addition to issues associated with what can be called "naive" approaches, there are subtle issues related to the fact that, while each component of the vector $\underline{x}$ may take values over a range, the n-tuplet itself that corresponds to the vector is constrained to lie on a surface or locus. This means that one cannot take each variable as being able to take values anywhere in its range, independently of the values the other variables take, while evaluating each MOE.

This problem arises especially in large scale systems consisting of many different subsystems. Using a top-down approach, specifications can be determined for each subsystem or component, as shown in Figure 2.

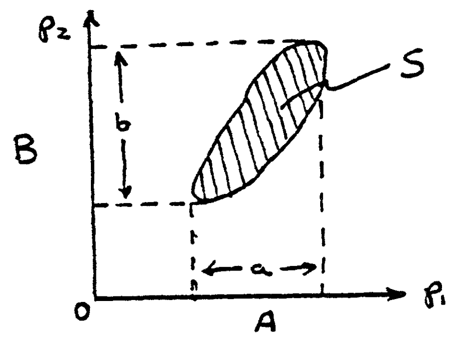


Figure 2. Subsystem Parameter Specifications

Let component A be specified by the parameter p_1 and component B by the parameter p_2. The system is desired to operate in the locus S. Projections of the locus S along p_1 and p_2 establishes ranges (specifications) for each subsystem. Suppose now each subsystem is designed independently to meet its individual specifications. Then the resulting locus is expected to be the one shown in Figure 3a.

However, the interconnection of the two subsystems does not allow all points of S′ to be reachable; the real locus is now S′′ which is very different from the desired one. This is one reason why great care must be taken in decomposing hierarchically a large scale system design into component designs.

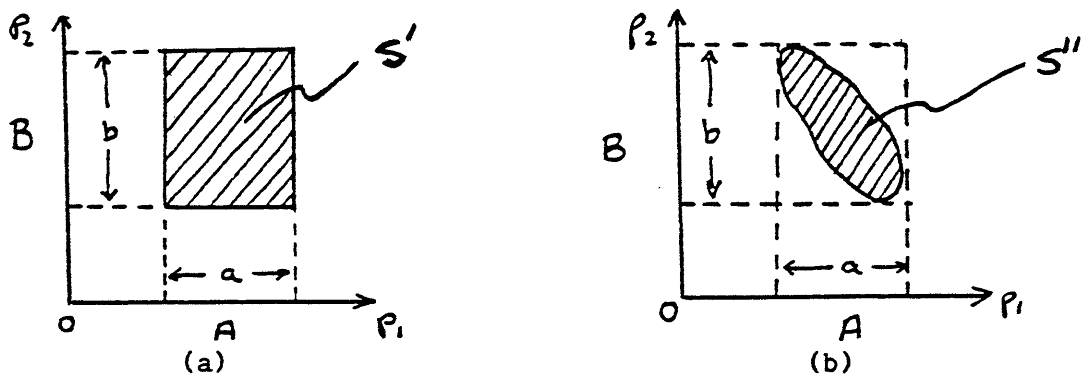


Figure 3. (a) Expected and (b) Actual Locus of Operations

One possible approach that avoids these problems is based on an intuitive notion. If a system meets or exceeds all the performance requirements derived from the considerations described earlier, then this would be an effective system. If a system does not meet any of the requirements, then it is ineffective. Since a system's performance is not characterized by a single point in the space $\underline{X}$ (the space of MOPs), the usual case is that one portion of the locus X_s, the performance locus, will satisfy all requirements, while the other portion will satisfy only some of the requirements. A possible metric that allows ordering of alternative systems and the computation of an absolute value of effectiveness is the extent to which the locus X_s lies within the admissible region X_S. This approach has already been used in measuring the effectiveness of developed systems (Bouthonnier and Levis, 1984; Levis et al., 1984; Washington and Levis, 1985) Its extension to evolving systems and to MOEs that reflect timeliness was the focus of the research project.

Consider first that as one varies the environmental parameters $\underline{r}$ one obtains different values of $\underline{x}$. If most of these values of $\underline{x}$ meet the requirements, then the C^2 system would be effective for this mission. Furthermore, one may parameterize over missions and again compare the resulting set of $\underline{x}$ values to the requirements. Mathematically, this can be formulated as follows. Let M be a measure in the space of x. It may be the area of the surface defined by X_s. If X_s consists of a finite set of points, it may be the number of points. Then

$$y = M(X_s) \tag{4}$$

Now consider the portion of X_s that meets the requirements, i.e., the portion of the surface that is within the region defined by the requirements. This can be expressed as the intersection of the two sets (or loci)

$$X_e = X_s \cap X_a \tag{5}$$

If all points satisfy the requirements, then

$$X_e = X_s \tag{6}$$

If no points satisfy the requirements, then

$$X_e = \phi \tag{7}$$

A scaled measure of effectiveness is then the fraction of the system performance locus that satisfies the requirements:

$$MOE = \frac{M(X_e)}{M(X_s)} = \frac{M(X_s \cap X_a)}{M(X_s)} \tag{8}$$

This very simple measure does not distinguish between value of $\underline{x}$ that barely exceed the requirements and values of $\underline{x}$ that exceed the requirements by much. This can be accommodated, if the commander's preferences are known. Styles of command, expressed in terms of risk taking behavior, or as intuitive vs. deliberate styles, could be modeled through a weighting function $w(\underline{x})$ introduced into the measure M. That assigns different values to different portions of the requirements locus.

In this section, a mathematical framework has been outlined that attempts to interpret some of the technical issues in measuring effectiveness. The mathematical formalism (vectors, sets, spaces, surfaces, etc.) was chosen only for illustrative purposes and in order to make the discussion more concrete. However, there is no indication that the variables have to take real, numerical values, that they are continuous, or that the various f, g, h or M are constrained to be functions of real variables, etc. Indeed, other types of mathematics can be used (e.g., fuzzy sets) as appropriate, although such an investigation was outside the scope of the work.

In the next two sections, the specific problems addressed by this research and the results that were obtained are discussed.

2. RESULTS I: EFFECTIVENESS ANALYSIS OF EVOLVING SYSTEMS*

2.1 INTRODUCTION

Consider an organization that is developing a large-scale system (for example, a large communication network). The completion of this system will take a number of years and require sustained funding. The latter, however, is contigent on (a) the progress made in developing the system, and (b) the prospects it has for meeting the needs for which it is being

*This section is based on the work of J. G. Karam as documented in his MS Thesis and the two papers referenced in Section 5.

designed. One way of checking whether these conditions are met is to set up a timetable in which several demonstrations are scheduled. The focus of these demonstrations will be to show that real progress has been made in developing the system, and that the latter will be capable of performing the tasks for which it was designed. The question then becomes: how should the organization go about demonstrating the system given (i) the extent to which the components of the system are actually operational, and (ii) the expectations of the various participants (developers, system users, and decisionmakers.

One feature of evolving systems is that they are not complete. But this alone doesn't make them different for the purpose of applying the System Effectiveness Analysis methodology developed by Dersin and Levis (1981) and then applied to C^3 systems by Bouthonnier and Levis (1984). The specific features of evolving systems affect all aspects of the System Effectiveness Analysis methodology. Indeed, they appear on the system side, the mission side, and the context, and contribute to the definition of the relevant attributes.

On the system side, the notions of operational components and useful configurations is critical. The context is that of a demonstration following a selected scenario. On the mission side, several groups of participants are identified, and their goals or expectations assessed and quantified. Finally, two types of attributes are revelant to the analysis of evolving systems: those that apply to systems in general (Type 1 attributes) and those that are specific to evolving systems (Type 2 attributes).

Figure 4 suggests the intimate interaction between the basic aspects of the methodology. It shows the system-context and mission-context interactions. Also, it sketches the joint contribution of the system, mission, and context, to the definition of the relevant attributes.

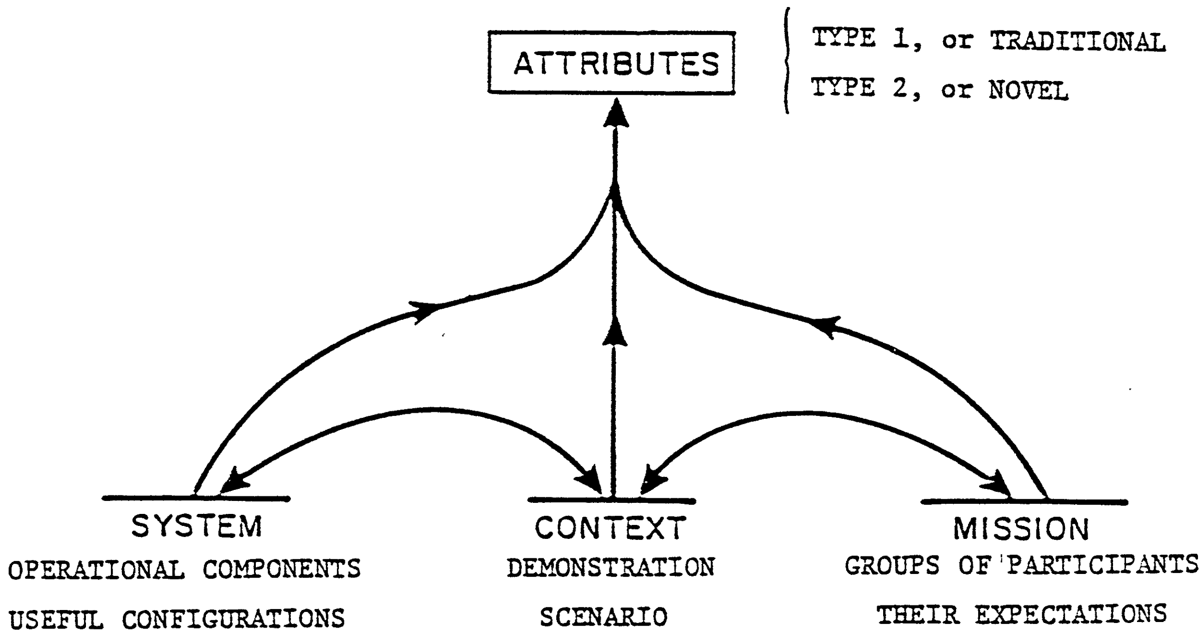


Figure 4. Evolving Systems: The Overall Picture

2.2 PROBLEM FORMULATION

An evolving system typically undergoes a series of demonstrations. Such demonstrations consist, in general, of a succession of stages or events. A stage can be aimed at demonstrating a specific technology, carrying out a given function, or both. The sequence of events and their contents correspond to a scenario. Depending on the scenario adopted, the demonstration will be shaped differently. Hence, the choice of a scenario is a decision variable; the objective is to optimize the effectiveness of the demonstration.

2.2.1 The System

Let T_j denote the j-th component/technology of the system that is being developed:

$$S_\infty = \{T_1, T_2, \ldots, T_j, \ldots, T_J\} \quad (9)$$

The components T_j can be physical components, i.e., nodes of the network or gates between nets, or even switches, or they can be software implemented on specific hardware.

Since this is an evolving system, at any time t, a component T_j may not be fully operational. If $\lambda_j(t)$ denotes the degree to which T_j is functional, i.e.,

$$0 \leq \lambda_j(t) \leq 1 \tag{10}$$

and if $\underline{\lambda}_j$ denotes a threshold of operability for component j, then S(t) is the subset of S that is operational at time t:

$$S(t) = \{ T_j(t) \; ; \; \lambda_j(t) \geq \underline{\lambda}_j \} \tag{11}$$

i.e., it consists of the elements T_j that have reached or exceed their threshold of oeprability. As time increases, the subset S(t) should expand until, at the end of the project period, it is equal to S_∞ (all component parts are completed).

Now, assume that at any time there is a collection of components that are operational. These form the set S(t). Out of these components, some system architectures can be configured that are suitable for demonstration. Not all configurations include all the operational components, and not all configurations are equally effective for the demonstration. These concepts can be stated formally as follows:

Let P(t) be the set of all subsets P of S(t),

$$P(t) = \{P, P \subset S(t)\} \tag{12}$$

For example, if

$$S(t) = \{T_1, T_2\} \tag{13}$$

then

$$P(t) = \{\phi, \{T_1\}, \{T_2\}, \{T_1, T_2\}\} \tag{14}$$

where ϕ is the null element. If S(t) contains #T elements, then the number of subsets in P(t) is $2^{\#T}$, which is a very large number of subsets. However, not all of them lead to useful configurations. Let $\tilde{P}(t)$ be the subset of P(t) that merits consideration. It is expected that few non-trivial configurations would be possible at any time. The procedure for determining the set $\tilde{P}(t)$ of useful configurations is sketched out in Figure 5.

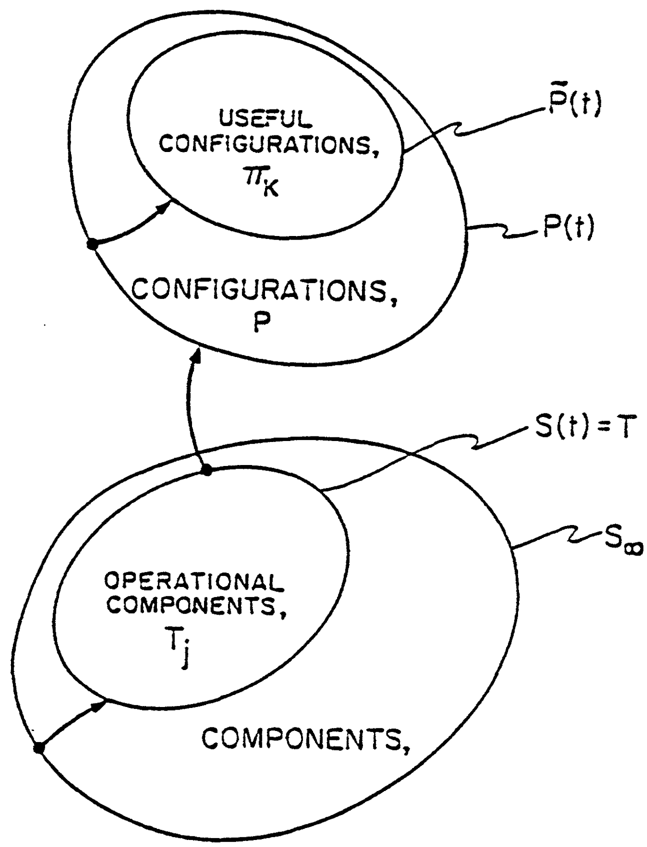


Figure 5. From the Ultimate System S_∞ to the Set $\tilde{P}(t)$ of Useful Configurations

This conceptual framework is applied now to the determination of $\tilde{P}(t)$. Let t_1 be the time at which the design of selected components is fixed so that prototype operational versions can be developed and let t_2 be the time of the proposed demonstration. Then the procedure can be described as follows:

(a) Consult with contractors to determine the components T_j that can be considered operational at time t_1 in the future.

(b) Consult with users to determine existing components and subsystems that could be made available for the demonstration at time t_2.

(c) Combine the results of (a) and (b) to determine set $S(t_2)$.

(d) Out of the elements in $S(t_2)$, design alternative system configurations, i.e., construct $\tilde{P}(t_2)$.

(e) Elements of $S(t_2)$ that have not been used in any of the candidate configurations in $\tilde{P}(t_2)$ should be dropped from further consideration for the demonstration at t_2.

The above procedure establishes the alternative system configurations for the demonstration. But to select the most effective one, the goals of the demonstration must be established.

2.2.2 The Mission

The demonstration of an evolving system has a dual role. First, it should show the capabilities of the system that is being developed (Type 1). In addition, it should demonstrate progress and accomplishments in developing the system (Type 2). This goal may be only partially shared by the various participants in the demonstrations. There are four major sets of participants. The first one consists of the contractors, the engineers and scientists who are developing the components, both hardware and software, and who are concerned with system integration.

The second participant is the agency that is the program sponsor and manager. The system contractors, I, and the agency, A_g, can be taken together to constitute a combined group, the developers (A).

The third set of participants (B) consists of the system's users, the persons who are going to use it in carrying out their duties (ultimately as well as during the demonstration).

Finally, there is the group of decisionmakers (C), who will observe the demonstration, and can make decisions about the program's continuation and eventual implementation.

These groups share some, but not all the criteria for evaluating the demonstration. Indeed, all of them would like the demonstration to "perform well". In addition to this common concern, group A would like to see more components demonstrated. Typically, each developer in group A would focus on "his" technologies and see to it that they are included in the demonstration. Conversely, group C would like to see more functions carried out during the demonstration. Typically, each decisionmaker in group C has a set of functions which he believes the demonstration should execute. The concept of function is used in contrast to that of end-product embodied by the components or technologies. In command and control, a function would be, for example, the interaction between commanders, or between a commander and a unit or organization. Let T and F denote the set of technologies and functions, respectively. Note that T is nothing but the set S(t) introduced in the system model.

After having specified the context and developed the system and mission models, the attributes can now be introduced.

2.2.3 System Attributes

System attributes are used to describe the system properties in a specific context. They depend on variables (the system primitives) which describe the system's characteristics and on the context. In a given context, a system is not expected to realize a specific combination of values of its attributes $x_1,\ldots,x_n$ with probability one. Instead, a set of realizable combinations L_s exists, each corresponding to a set of values taken by the system attributes. This set is the locus of the system attributes; it is called the system locus, L_S. Any point $\underline{x}$ that belongs to L_S has a non-zero probability of being actually achieved by the system. To model this concept, a probability distribution f is introduced which is a complete description of the system's performance in the specified context.

For each useful configuration π, $\pi \in \tilde{P}(t)$, let f_π be the probability distribution of the system attributes $\underline{x}$.

<u>Type 1 Attributes</u>: Type 1 attributes are those that apply to systems considered statically; that is, if the systems have none of the specific features of evolving systems that were singled out previsouly. Type 1 attributes are measures of performance or MOPs; they form a vector $\underline{y} = (y_1,\ldots,y_n)$. In the case of communication networks, reliability, input flow, and time delay are examples of MOPs

In general, the Type 1 system attributes are continuous random variables. Let L_S' denote the system locus in the Type 1 attribute space, i.e.,

$$L_S'(\pi) = \{\underline{y} \quad ; \quad g_\pi(\underline{y}) > 0\} \tag{15}$$

In the absence of better information, distribution g_π is assumed to be uniform over L_S'. In this case, it is equal to:

$$g_\pi = \frac{1}{\mathrm{Vol}(L_S'(\pi))} \tag{16}$$

<u>Type 2 Attributes</u>: The second stated goal of the demonstration is to show

progress and accomplishments in developing the system. The achievement of this goal is expressed in terms of a new set of attributes, denoted by the vector $\underline{z}$. Two such attributes are z_A, the weighted fraction of the technologies used in the demonstration, and z_C, the weighted fraction of functions carried out:

$$z_A = \frac{\sum_{i=1}^{\#T} \omega_A(T_i)\ \tau(T_i)}{\sum_{i=1}^{\#T} \omega_A(T_i)} \tag{17}$$

and

$$z_C = \frac{\sum_{j=1}^{\#F} \omega_C(F_j)\ \phi(F_j)}{\sum_{j=1}^{\#F} \omega_C(F_j)} \tag{18}$$

where

T_i denotes technology i , $i=1,\ldots,\#T$

F_j denotes function j , $j=1,\ldots,\#F$

$$\tau(T_i) = \begin{cases} 1 & \text{if technology } i \text{ is included in the demonstration} \\ 0 & \text{otherwise} \end{cases}$$

$$\phi(F_j) = \begin{cases} 1 & \text{if function } j \text{ is carried out in the demonstration} \\ 0 & \text{otherwise} \end{cases}$$

$\omega_A(T_i)$ weighting of technology i by the developers (group A)

$\omega_C(F_j)$ weighting of function j by the decisionmakers (group C)

The Type 2 attributes z_A and z_C defined by Eqs. (17) and (18) take discrete values between zero and one. For each system configuration π, a specific subset of the technologies T is used and a specific subset of the functions F carried out. The values taken by z_A and z_C are hence known with certainty:

$$z_A = z_A(\pi) \quad ; \quad z_C = z_C(\pi) \tag{19}$$

The Type 1 and 2 attributes form a vector, $\underline{x} = (\underline{y},\underline{z})$, which takes values in a subset of the (n+2) dimensional space.

The distribution f_π is a Dirac function δ in the plane (z_A,z_C) at the point $(z_A(\pi),z_C(\pi))$. Distribution f_π can thus be written as follows:

$$f_\pi(\underline{x}) = g_\pi(\underline{y})\ h_\pi(\underline{z}) \tag{20}$$

where

$$h_\pi(\underline{z}) = \delta(\underline{z} - (z_A(\pi),z_C(\pi))) \tag{21}$$

The function $g_\pi(\underline{y})$, the component of $f_\pi(\underline{x})$ in the Type 1 attribute space, remains to be defined.

2.2.4 Mission Attributes

<u>Mission attributes</u> refer to the attributes when they are used to describe the mission requirements in a specific context. Hence, they depend on variables (the mission primitives) which describe the mission characteristics and the context. Let L_M be the set of combinations of attribute values that satisfy the requirements of the mission, L_M. This requirement set is the locus of the mission attributes; it is called the mission locus. Any point $\underline{x}$ that belongs to L_M satisfies, to some extent, the mission. However, all such points are not, in general, equally satisfactory. To model this concept, a utility function u is introduced.

$$u = u(\underline{x}) = u(\underline{y},\underline{z}) \qquad (22)$$

The utility function u translates into a real number (between zero and one) the desirability, from the point of view of the mission, of each combination of attribute values. One feature of utility functions is that they are monotonically non-decreasing with respect to each of the attributes. Hence, the attributes should be defined in a way such that a higher value of any one attribute is more or equally desirable, other things being equal.

In order to introduce the global utility u of the demonstration as a function of the attributes $\underline{x}$, the utilities u_A, U_b, and u_C of the three groups of participants A, B, and C need to be assessed. These are called partial utilities.

Each group expresses its satisfaction — or dissatisfaction — with the demonstration through some of the attributes. While all three groups are concerned about the values taken by the attributes $\underline{y}$, group A is, in addition, interested in the attribute z_A, and group C in the attribute z_C (see Figure 6). The partial utilities u_A, u_B, and u_C of groups A, B, and C respectively, can be written as:

$$u_A(\underline{x}) = v_A(\underline{y})\, w_A(z_A) \qquad (23)$$

$$u_B(\underline{x}) = v_B(\underline{y}) \qquad (24)$$

$$u_C(\underline{x}) = v_C(\underline{y})\, w_C(z_C) \qquad (25)$$

The global utility is a function of the partial utilities introduced previously. For example,

$$u = a\,u_A + b\,u_B + c\,u_C \qquad \text{(additive)} \qquad (26)$$

or

$$u = u_A^{\,a} \; u_B^{\,b} \; u_C^{\,c} \qquad \text{(multiplicative)} \qquad (27)$$

where $a + b + c = 1$.

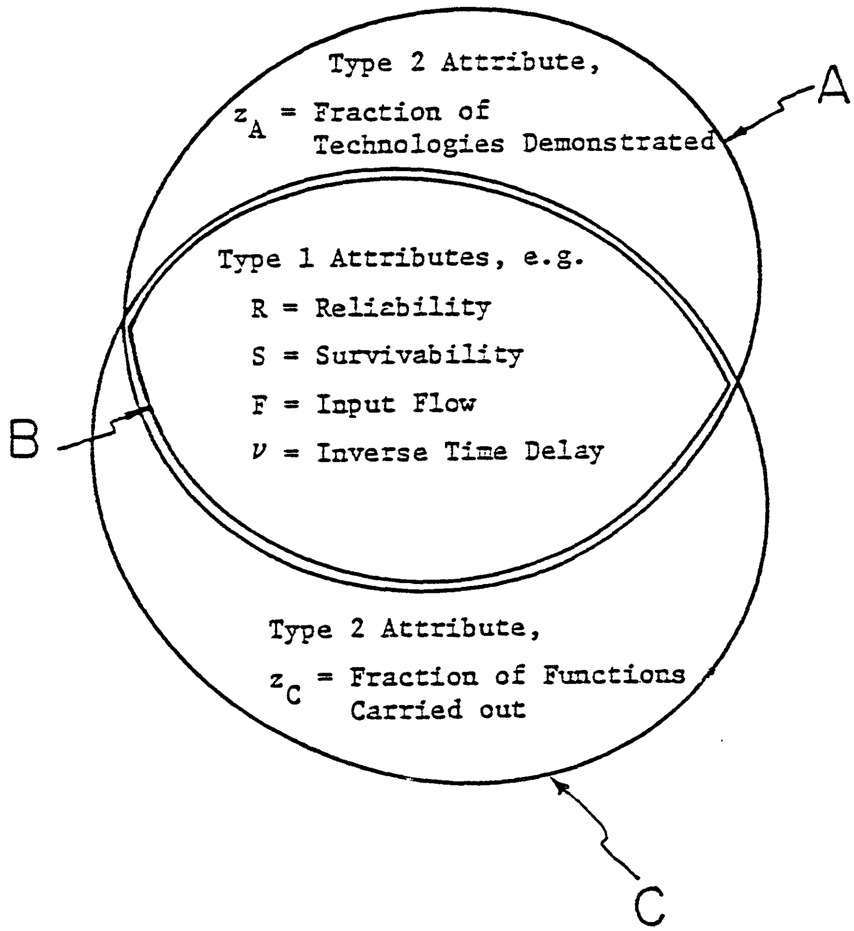


Figure 6. Repartition of Attributes in Utilities of Participant Groups

Weights a, b, and c reflect the participants influence on decisions, regardless of their interaction. In reality, the three groups of participants in a demonstration are not independent. They interact before, during, and after the demonstration. Thus, it is important to sketch a model of the organizational interactions. One such model, motivated by METANET (see Section 2.6), is shown in Figure 7.

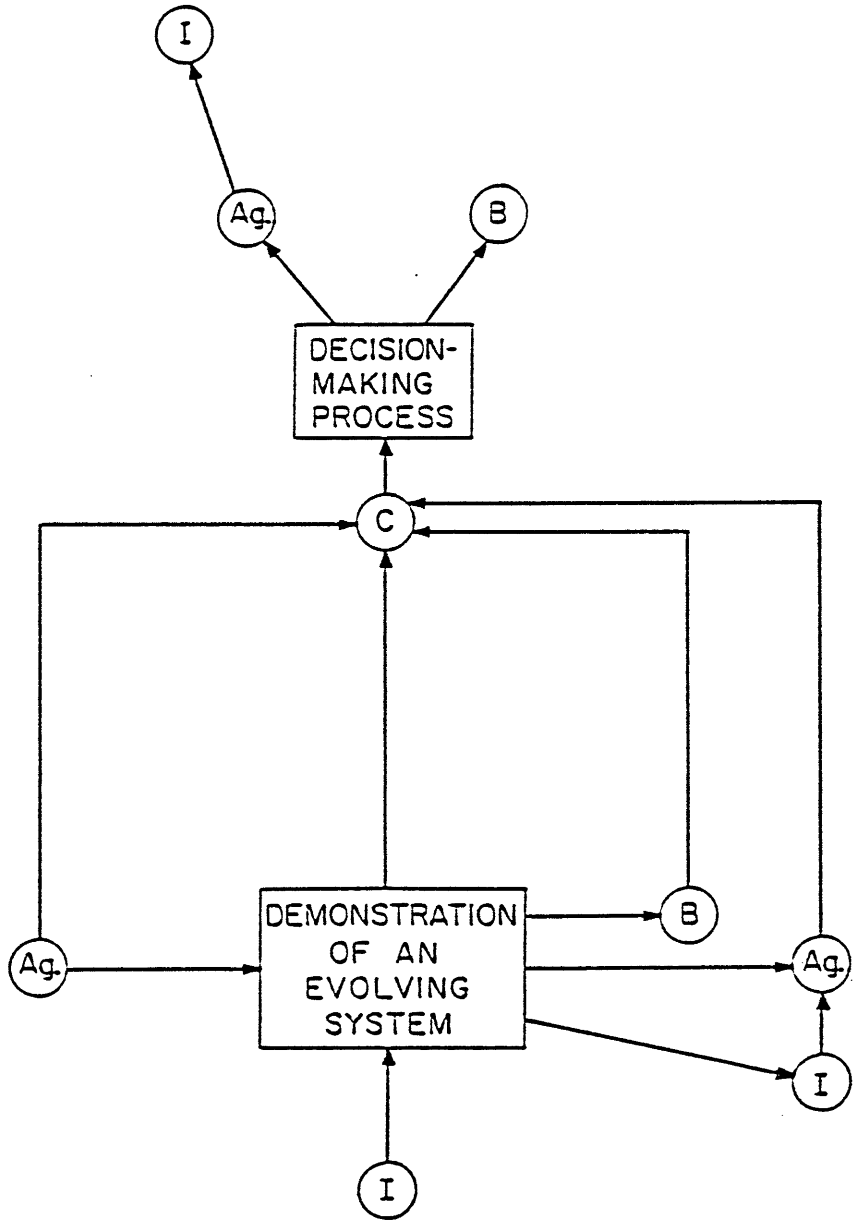


Figure 7. Organizational Interaction of Demonstration Participants

The contractors, denoted by I, provide the operational components of the system S, while the sponsor approves a scenario. All four participants observe the demonstration. The contractors report their observations and recommendations to the sponsors ($I \rightarrow A_g$). The users and the sponsor indicate their findings to the decisionmakers (group C). The sponsors, A_g, have already indicated to the decisionmakers the objectives of the demonstration. On the basis of their own observations and the inputs from the sponsoring agency and the users, the decisionmakers indicate their support for the program to the agency, and instruct the users to continue in assisting with the development and implementation of the system S.

Therefore, it is not inappropriate to express the utility of the demonstration as being that which is ultimately perceived by the decisionmakers. Indeed, the partial utilities u_A, u_B, and u_C result from the direct observation by the participants in groups A, B, and C, respectively, regardless of the interaction of those participants. After groups A and B report their observations to group C, the decisionmakers aggregate all three partial utilities in a global one. Hence, the global utility of the demonstration is an aggregation, by the decisionmakers, of the partial utilities of the developers, the system users, and the decisionmakers themselves.

$$u = u_C'(u_A, u_B, u_C) \tag{28}$$

Function u_C' can be a direct weighting of u_A, u_B, and u_C, as in expressions (26) and (27). In this case, the implication of the model is that weights a, b, and c are fixed by the decisionmakers.

2.3 THE DESIGN OPTIMIZATION PROBLEM

A system is most effective with regard to a mission if, operating in a given context, it is most likely to achieve those combinations of attribute values that are highly desirable; that is, if the points $\underline{x}$ for which $f(\underline{x})$ is high coincide with those for which the utility u is high. An effectiveness measure that expresses this notion is given by the expected utility, i.e.,

$$E_\pi(u) = \int_{\underline{X}} f_\pi(\underline{x})\, u(\underline{x})\, d\underline{x} \tag{29}$$

Expression (29) defines a functional which assigns a value to each useful configuration π; it is a measure of effectiveness of π with respect to the demonstration's goals:

$$\pi \longrightarrow E_{\pi}(u) \tag{30}$$

The design objective is then to maximize the effectiveness of the demonstration by selecting the appropriate configuration π:

$$E_{\pi^*}(u) = E^* = \max_{\pi \, \varepsilon \, \tilde{P}(t)} E_{\pi}(u) \tag{31}$$

The determination of π^* cannot be done analytically; each configuration must be evaluated and the corresponding values of the effectiveness measure rank ordered. The procedure is impractical, if $\tilde{P}(t)$ includes all $2^{\#T}$ configurations. However, if the design of the alternative system configurations has been carried out properly, only several configurations need to be evaluated. The steps of the procedure for selecting the optimal configuration for the demonstration, shown in Figure 8, can be summarized as follows:

(a) For a given mission utility function u, and for the configuration π defining the probability distribution f_{π}, evaluate $E_{\pi}(u)$.

(b) Repeat step (a) for each configuration $\pi \, \varepsilon \, \tilde{P}(t)$.

(c) Rank order the configurations π in $\tilde{P}(t)$ according to the values of $E_{\pi}(u)$.

(d) Select the configuration that maximizes expected utility.

2.4 ASSESSMENT OF UTILITIES

The object of this section is to assess the functions v and w defining the partial utilities in Eqs. (23) to (25). These functions are given in the following form:

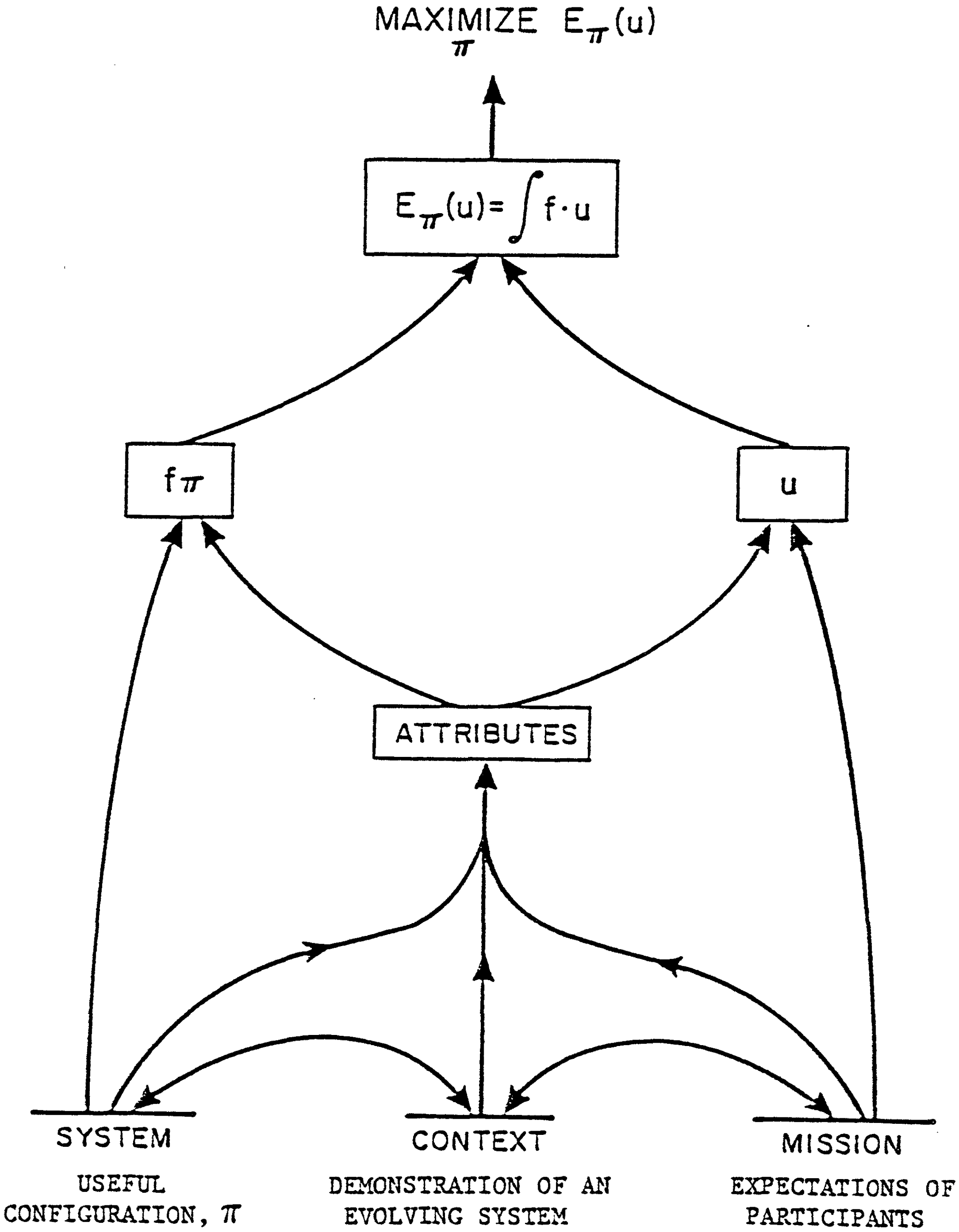


Figure 8. Methodology for Selecting the Optimal System Configuration

$$v_i(\underline{y}) = 1 - \frac{(1-Y)^t\, Q_i\, (1-Y)}{1^t\, Q_i\, 1} \qquad (32)$$

$$w_A(z_A) = (z_A)^{\alpha} \quad ; \quad w_C(z_C) = (z_C)^{\gamma} \tag{33}$$

where

Q_i is a positive matrix with all elements non negative

i = A, B, or C.

$Y^t = (y_1\ y_2\ \dots\ y_{n_1})$ row vector of the type 1 attributes

$\mathbf{1}^t = (1\ 1\ \dots\ 1)$

α and γ are real numbers between 0 and 1.

Assessment of the partial utilities reduces to determining three matrices, Q_A, Q_B, and Q_C, and two real numbers α and γ. This will be done in the context of an application - the effectiveness analysis of the METANET demonstration.

The system users are those who are going to use the system during the demonstration. The real system users (those who care about the functions carried out) are included among the group of decisionmakers.

The system users' only concern is that the demonstration "perform well", regardless of the technologies used or the functions carried out. In terms of the attributes, the partial utility of the demonstration as perceived by group B is a function of the Type 1 attributes, and only those

$$u_B(\underline{x}) = v_B(\underline{y}) = 1 - \frac{(\mathbf{1}-Y)^t\ Q_B\ (\mathbf{1}-Y)}{\mathbf{1}^t\ Q_B\ \mathbf{1}} \tag{34}$$

The question then reduces to determining the positive matrix Q_B. To do this, a matrix that relates system users to attributes needs to be introduced first.

Let $\tilde{Y}$ denote the column vector **1**-Y, and $\tilde{B}$ a column vector where element i represents the degree of dissatisfaction of system user i with the demonstration. The higher the $\tilde{Y}_j$'s (j = 1,...,#Y), the higher the degree of dissatisfaction of system user i (i.e., the higher $\tilde{B}_i$). A positive linear transformation from the pseudo-attribute space ($\tilde{Y}$) to the space of the system users' dissatisfaction ($\tilde{B}$) is thus postulated; its matrix is denoted BY for convenience:

$$\tilde{B} = (BY)\ \tilde{Y} \tag{35}$$

Element (i,j) of matrix BY denotes the degree to which system user i is concerned with the values taken by traditional attribute j. Matrix BY can be estimated by interviewing the system users individually. Each system user i is asked to fill in row i of matrix BY, by rating all the traditional attributes on a scale of 0 to 10, for example. The input data are then normalized for each system user, so that:

$$\sum_{j=1}^{\#Y} (BY)_{ij} = 1 \qquad \forall\ i = 1,\ldots,\#B \tag{36}$$

Partial utility u_B is expressed as being one minus the overall dissatisfaction of group B with the outcome of the demonstration (expression (34)). The latter, unnormalized, is a quadratic form of the pseudo-attributes $\tilde{Y}$:

$$q(\tilde{Y}) = \tilde{Y}^t\ Q_B\ \tilde{Y} \qquad \forall\ \tilde{Y} \tag{37}$$

In fact, the overall dissatisfaction of group B is, a priori, a function q' of the $\tilde{B}_i$'s. Because of the existence of the linear transformation (matrix BY) from the space of $\tilde{Y}$ to that of $\tilde{B}$, any quadratic form q' in the $\tilde{B}$ space defines a quadratic form q in the $\tilde{Y}$ space, such that

$$q(\tilde{Y}) = q'((BY)\ \tilde{Y}) \qquad \forall\ \tilde{Y} \tag{38}$$

Indeed, let the overall dissatisfaction of group B be a quadratic form (the simplest) of $\tilde{B}$, i.e.,

$$q'(\tilde{B}) = \tilde{B}^t\ \tilde{B} \tag{39}$$

In other words, the overall dissatisfaction of group B is the sum of the squares of dissatisfaction indices of all system users. Using Eqs. (35) and (39), the overall dissatisfaction of group B can be written as a quadratic from of the pseudo-attributes:

$$q(\tilde{Y}) = \tilde{Y}^t\ (BY)^t\ (BY)\ \tilde{Y} \qquad \forall\ \tilde{Y} \tag{40}$$

By setting Eqs. (37) and (40) equal, matrix Q_B is then equal to:

$$Q_B = (BY)^t\ (BY) \tag{41}$$

The system user by attribute matrix BY is all that is needed to determine Q_B, and hence, the utility of group B.

The developers (contractors and agency) as well as the users are concerned that the demonstration "perform well". However, unlike the participants in group B, their concern is conditioned by which technologies are used in the demonstration. The utility of group A is:

$$u_A(\underline{x}) = (z_A)^{\alpha}\ (1 - \frac{(1-Y)^t\ Q_A\ (1-Y)}{1^t\ Q_A\ 1}) \tag{42}$$

Parameter α is not easy to assess. In practice, a parametric study would be done where α is varied from 0 to 1. Matrix Q_A, however, can be determined as the product of the transpose of a developer by attribute matrix AY by the matrix itself, i.e.,

$$Q_A = (AY)^t (AY) \qquad (43)$$

Element $(AY)_{ij}$ denotes the degree to which developer i is concerned about the values taken by traditional attribute j. The developers' concern is contingent on the demonstration using "their" technologies. In other words, each developer would be satisfied if the demonstration "performed well" in terms of the traditional attributes, provided it did so using "his" technologies. This motivates the model developed next.

<u>The Technology by Developer Matrix (TA)</u>: Let TA denote the so-called technology by developer matrix. Element $(TA)_{ij}$ reflects the extent to which developer j would like to see technology i demonstrated. Matrix TA is estimated by asking each developer j (contractors or the agency) to fill in column j, by rating all the technologies on a 0 to 10 scale, for example. The input data are normalized for each developer so that

$$\sum_{i=1}^{\#T} (TA)_{ij} = 1 \qquad \forall\, j = 1,\ldots,\#A \qquad (44)$$

<u>The Technology by Attribute Matrix (TY)</u>: Also, let TY be the so-called technology by attribute matrix. Element $(TY)_{ij}$ is equal to one if the developers believe that a good performance of technology i, when used, depends on the values taken by attribute j; it is equal to zero otherwise. Consider, for example, a cable transmission line. The latter is not jammed, independently of the quality of the line. Hence, the attribute Survivability is not relevant to measuring, even partially, the performance of the cable transmission line. The corresponding element in matrix TY is zero.

Now, what is the developer by attribute matrix AY? Developer i is concerned with the performance of attribute j insofar as attribute j is directly affected by those technologies which developer i would like to see demonstrated, and that these technologies are actually demonstrated. These ideas are expressed by formulating $(AY)_{ij}$ as follows:

$$(AY)_{ij} = \sum_{k=1}^{\#T} \tau(T_k)\ (TA)_{ki} (TY)_{kj} \tag{45}$$

where

$$\tau(T_k) = \begin{cases} 1 & \text{if technology k is included in the demonstration} \\ 0 & \text{otherwise} \end{cases}$$

Equation (45) can be written in matrix form

$$AY = (\underline{TA})^t\ (TY) \tag{46}$$

where

$$(\underline{TA})_{ki} = \tau(T_k)\ (TA)_{ki} \tag{47}$$

The decisionmakers are also concerned that the demonstration "perform well". However, unlike the system users whose concern is direct and explicit, and unlike the developers whose concern is contingent on the demonstration using "their" technologies, the decisionmakers' concern is conditioned by which functions are carried out. The utility of group C is

$$u_C(\underline{x}) = (z_C)^\gamma\ (1 - \frac{(1-Y)^t\ Q_C\ (1-Y)}{1^t\ Q_C\ 1}) \tag{48}$$

Parameter γ is not easy to assess. In practice, a parametric study is done where γ is varied from 0 to 1. Matrix Q_C, however, can be determined. As for groups A and B, matrix Q_C can be written

$$Q_C = (CY)^t (CY) \tag{49}$$

where CY is the decisionmaker by attribute matrix. Element $(CY)_{ij}$ denotes the degree to which decisionmaker i is concerned about the values taken by traditional attribute j. Each decisionmaker would be satisfied if the demonstration "performed well" in terms of the traditional attributes, provided it carried out "his" functions. This motivates the following model.

<u>The Function by Decisionmaker Matrix (FC)</u>: Let FC denote the so-called function by decisionmaker matrix. Element $(FC)_{ij}$ expresses the extent to which decisionmaker j would like to see function i carried out. Matrix FC is determined by asking each decisionmaker j to fill in column j, by rating all the functions on a 0 to 10 scale, for example. Then, the input data are normalized for each decisionmaker, so that:

$$\sum_{i=1}^{\#F} (FC)_{ij} = 1 \qquad \forall\, j = 1,\ldots,\#C \tag{50}$$

<u>The Function by Attribute Matrix (FY)</u>: Also, let FY denote the so-called function by attribute matrix. Element $(FY)_{ij}$ is equal to one if the decisionmakers believe that a good performance of function i is dependent on the values taken by attribute j. It is equal to zero otherwise.

Now, what is the decisionmaker by attribute matrix? Decisionmaker i is concerned about the values taken by attribute j insofar as the functions he would like to see carried out are actually carried out, and the performance of these is contingent on the values taken by attribute j.

Hence, it is not unreasonable to formulate $(CY)_{ij}$ as follows:

$$(CY)_{ij} = \sum_{k=1}^{\#F} \phi(F_k)\ (FC)_{ki} (FY)_{kj} \tag{51}$$

where

$$\phi(F_k) = \begin{cases} 1 & \text{if function k is carried out in the demonstration} \\ 0 & \text{otherwise} \end{cases}$$

Equation (42) can be rewritten in matrix form

$$CY = (\underline{FC})^t\ (FY) \tag{52}$$

where

$$(\underline{FC})_{ki} = \phi(F_k)\ (FC)_{ki} \tag{53}$$

The methodology described thus far will be applied to a simple communication network and to the analysis of the METANET demonstration.

2.5 A SIMPLE COMMUNICATION NETWORK

In this section, an illustrative example (Karam and Levis, 1984) is presented that exhibits some of the generic characteristics or properties of a communication network consisting of heterogeneous nodes and links. Furthermore, it is assumed that this network is being developed and its first demonstration is to be held in the near future. Although this example does not represent any actual system, it is nevertheless very instructive in showing the applicability of the methodology and the types of results it can yield.

2.5.1 The System Model

Suppose that at time t, nineteen components of the network are operational (#T=19): seven nodes and twelve links. These constitute the set S(t) as previously defined. Many configurations can be obtained from these components (in this case, 2^{19}), but not all are useful for the demonstration. Let the objective be to establish communication between nodes 1 and 7, subject to the constraint that at least two non overlapping paths exist between these two nodes. Then, the number of useful configurations reduces to ten forming the set $\tilde{P}(t)$. These configurations are shown in Figure 9. Note that configuration K=9 is the one that includes all nodes and all links, while configuration K=1 contains the fewest components among the 10 configurations.

2.5.2 The Attributes

Six attributes are considered relevant; they are defined so as to take values between 0 and 1. The Type 1 attributes are Reliability, Survivability, Input Flow, and Inverse Time Delay, and form the vector

$$\underline{y} = (y_1=R,\ y_2=S,\ y_3=F,\ y_4=\psi). \tag{54}$$

The Type 2 attributes are the weighted fraction of components used and functions carried out; they form a vector

$$\underline{z} = (z_A,\ z_C). \tag{55}$$

All the attributes form a vector

$$\underline{x} = (R,\ S,\ F,\ \psi,\ z_A,\ z_C) \quad ; \quad \underline{x} \in [0,1]^6 \tag{56}$$

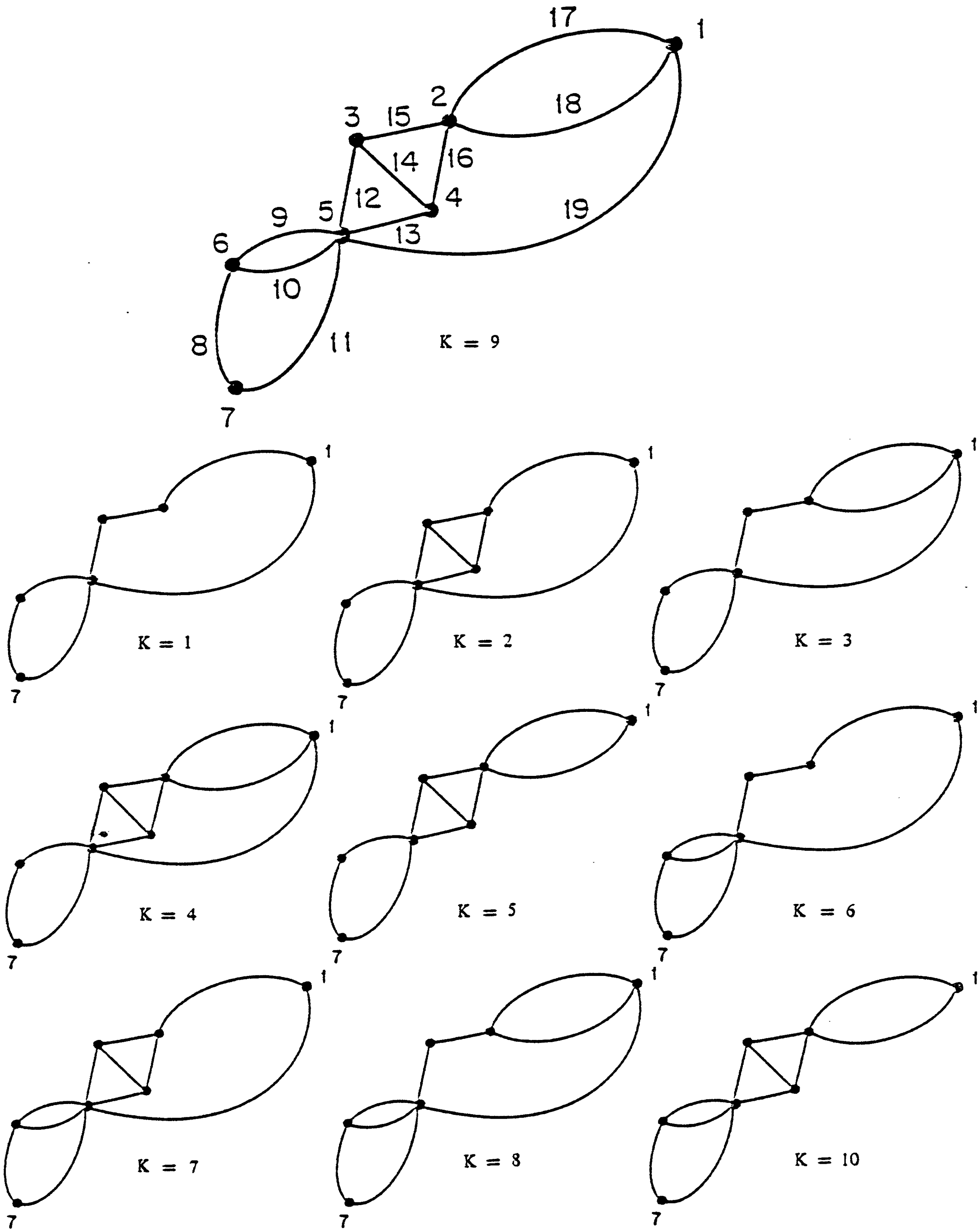


Figure 9. The Ten Useful System Configurations

Reliability denotes the capability of a network to deliver a message from node 7 to node 1 when only the physical properties of the components (links and nodes) are taken into account. In contrast, the attribute Survivability does not depend on the components' physical deterioration, but on the components' capabilities to resist enemy attacks.

Let C be the capacity of any link in bits/sec. Assuming the M/M/1 model of queueing theory, let $1/\mu$ be the mean packet size in bits/packet. If Flow is the input flow on one link (packets/sec.), then the mean time delay ξ for that link, which includes both queueing and transmission time, is:

$$\xi = \frac{1}{\mu C - \text{Flow}} \tag{57}$$

It is more convenient to consider the inverse of time delay. The scaled attributes are then:

$$\underline{\text{Inverse Time Delay:}} \quad = \frac{2}{\mu C \xi} \tag{58}$$

$$\underline{\text{Input Flow:}} \quad F = \frac{\text{Flow}}{\mu C} \tag{59}$$

2.5.3 The Mission Model

Three developers are identified (#A=3): two system contractors and the agency. System contractor number one developed nodes 1 to 7, and is eager to see them demonstrated. System contractor number 2 developed links 8 to 12, and is interested in having each of them demonstrated. Finally, the sponsoring agency has no preference for any single component and would like to see them all demonstrated. Thus it is reasonable to assume (remember, this is not a real example) the following technology by developer matrix:

$$
(TA)_{ij} = \begin{cases} 1/7 & i = 1,\ldots,7 \;; \quad j=1 \\ 1/12 & i = 8,\ldots,19 \;; \quad j=2 \\ 1/19 & i = 1,\ldots,19 \;; \quad j=3 \\ 0 & \text{otherwise} \end{cases} \tag{60}
$$

On the other hand, the attribute survivability cannot be used as an indicator of the good performance of a ground cable link which is included in the demonstration's configuration. However, the good performance of every other component is contingent on the values taken by all four traditional attributes. Hence, the technology by attribute matrix is:

$$
(TY)_{ij} = \begin{cases} 0 & i = 8,\ 9,\ 10,\ 11, \text{ and } 13 \;; \quad j=2 \\ 1 & \text{otherwise} \end{cases} \tag{61}
$$

All system users are assumed to be interested equally in the four traditional attributes, thus

$$
(BY)_{ij} = 0.25 \qquad i = 1,\ldots,\#B \;; \quad j = 1,\ldots,4 \tag{62}
$$

There is only one decisionmaker (#C=1), while three functions can be carried out in the demonstration (#F=3). The function by decisionmaker matrix, which is a column here, is assumed to be:

$$
(FC)_{11} = 0.5 \quad , \quad (FC)_{21} = 0.25 \quad , \quad (FC)_{31} = 0.25 \tag{63}
$$

On the other hand, it is assumed that the good performance of any of three functions is dependent on the values taken by all four traditional attributes. Hence, the function by attribute matrix is:

$$(FY)_{ij} = 1 \qquad i = 1,\ldots,3 \;\; ; \;\; j = 1,\ldots,4 \tag{64}$$

2.5.4 Evaluation of System and Mission Attributes

For each useful system configuration π_K ($K = 1,\ldots,10$), the system attributes take different values.

The weighted fraction of technologies/components used is determined if the components T_i included in the configuration and the weights $\omega_A(T_i)$ assigned to them (see Eq. (17)) are known. Figure 9 indicates which components are included in each configuration. On the other hand, weight $\omega_A(T_i)$ denotes the extent to which group A would like to see component T_i demonstrated; it is the sum over all developers j, of the extent to which developer j would like to see component i demonstrated:

$$\omega_A(T_i) = \sum_{j=1}^{3} (TA)_{ij} \tag{65}$$

Similarly, the weighted fraction of functions carried out is determined if the function(s) F_i and the weights $\omega_C(F_i)$ assigned to them (see Eq. (18)) are known. Assume configurations π_1, π_3, π_6, and π_8 carry out function 1, configurations π_2, π_4, π_7, and π_9, function 2, and configurations π_5 and π_{10}, function 3. The weights $\omega_C(F_j)$ are given by

$$\omega_C(F_j) = (FC)_{j1} \tag{66}$$

They depend on the probability of failure of the system components:

$1 - p$ = probability of failure of ground link (cable)
(links 8, 9, 10, 11, and 13)

$1 - q$ = probability of failure of satellite link (links 12, 14, 15, 16, 17, 18, and 19)

$1 - r$ = probability of failure of node (platform) (nodes 1, 2, 3, 4, 6, and 7)

$1 - s$ = probability of failure of node (central) (node 5)

For each configuration π_K (K = 1 to 10), a Reliability/Survivability index, denoted RS, is computed as a function of the four probabilities p,q,r, and s. Depending on whether the attribute Reliability or Survivability is computed, each of these probabilities is bounded to vary in a different interval of [0,1]. For example, the probability of failure of a ground link, 1-p, is set equal to zero in computing S because ground links are assumed in this example not to be jammed. Hence, R and S vary in intervals, the limits of which are easily computed:

$$R_{min}(K) \leq R \leq R_{max}(K) \tag{67}$$

$$S_{min}(K) \leq S \leq S_{max}(K) \tag{68}$$

For each configuration π_K, the <u>mean time delay</u> ξ may vary between ξ_{min} and ξ_{max}, depending on the routing algorithm. Indeed,

$$\frac{L_{min}(K)}{\mu C - Flow} \leq \xi \leq \frac{L_{max}(K)}{\mu C - Flow} \tag{69}$$

where $L_{min}(K)$ and $L_{max}(K)$ are, respectively, the minimum and maximum number of links contained in a path going from node 7 to node 1.

Using the scaled attributed, the inequalities (69) can be written as

$$ {}_{min}(K)\ (1 - F) \le y \le {}_{max}(K)\ (1 - F) \tag{70} $$

The global utility of the demonstration is the weighted sum of the partial utilities u_A, u_B, and u_C:

$$ u = a\ u_A + b\ u_B + c\ u_C \tag{71} $$

where $a + b + c = 1$.

The partial utilities are known if matrices Q_A, Q_B, and Q_C, and parameters α and γ are determined. The matrices can be computed (for each configuration) by manipulating the data (see Karam, 1985).

2.5.5. Results

Having computed the system locus and the global utility of the demonstration the measure of effectiveness of configuration π_K, namely,

$$ E(K) = \int f_{\pi_K}(\underline{x})\ u(\underline{x})\ d\underline{x} \tag{72} $$

can be computed. This measure is computed for each one of the ten candidate configurations. The optimal configuration is that configuration π_K* for which the measure of effectiveness is maximum, i.e.,

$$ E^* = E(K^*) = \underset{K=1,10}{\text{Max}}\ E(K) \tag{73} $$

The Reliability/Survivability index, denoted by RS is a function of the four probabilities p,q,r, and s that describe the failure characteristics of the system components in the demonstration context. For a given system configuration and a given set of failure probabilities, the

RS index can be computed (for details, see Karam, 1985). However, more insight is obtained, if the value of RS is plotted as a function of each one of the four primitives, while the other three are set equal to unity. This isolates the effect different types of components have on the system's reliability and survivability. The results of such an analysis are shown in Figure 10 for configuration K=9 which contains the maximum number of components. Four monotonically non-decreasing curves are shown; each one shows the Reliability/Survivability index RS as a function of one of the four probabilities: p, q for links and r,s for nodes. The results in Figure 10 confirm that node failures have a more pronounced effect than link failures, inasmuch as they reduce the RS index to a greater extent. Indeed, the values of the indices RS(p) and RS(q) are higher than the values of the underlying probabilities, i.e.,

$$RS(p) > p \quad ; \quad RS(q) > q \tag{74}$$

while the values of RS(r) and RS(s) are lower than or equal to the corresponding probabilities, i.e.,

$$RS(r) < r \quad ; \quad RS(s) = s. \tag{75}$$

The determination of the <u>optimal configuration</u> depends on the values taken by the system and mission primitives. These primitives can be placed into three groups:

(a) Primitives whose values are dictated by the physical characteristics of the system or the context in which it operates, i.e., the system primitives (e.g., probabilities p, q, r, and s).

(b) Primitives that reflect the utilities of the participants in the demonstration, i.e., the mission primitives. These include the matrices Q_A, Q_B, and Q_C that appear in the partial utility functions as well as the exponents α and γ.

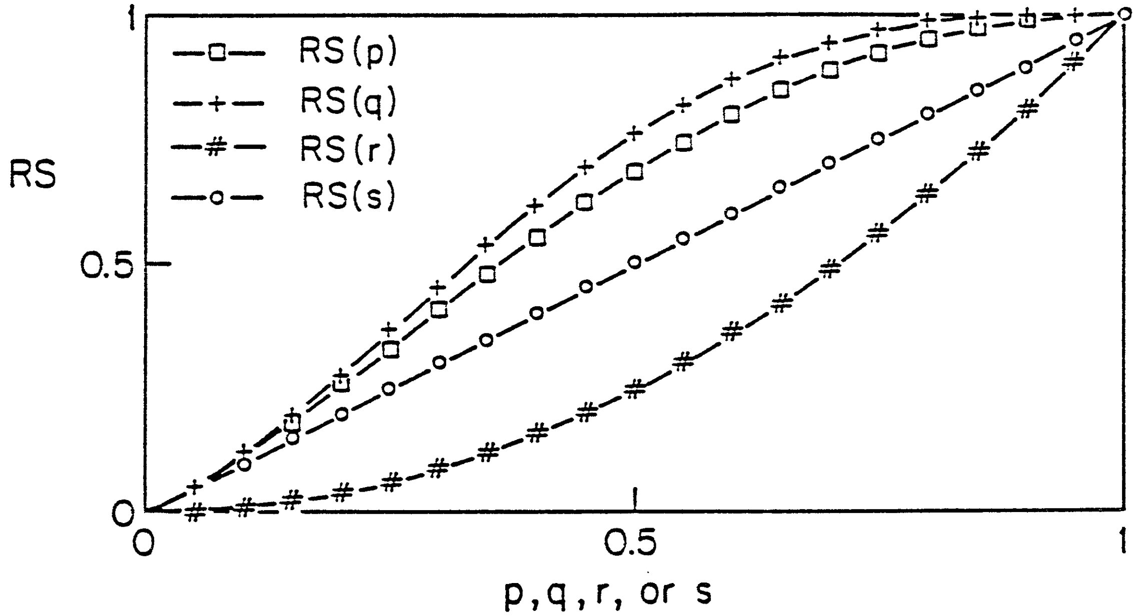


Figure 10. Reliability/Survivability Index as a Function of its Primitives

(c) Primitives that depend on the analyst's perception of the relative influence the various participants have on the demonstration's outcome and evaluation. The coefficients a, b, and c used to construct the global utility function belong to this group.

Parametric studies can be carried out for all three categories of primitives. Since the effect of the failure probabilities was already analyzed in computing the RS index, and since matrices Q can be and were estimated, the parametric studies were focused on the exponents α and γ and on the coefficients a, b, and c.

Consider first the effect of the exponents α and γ on the selection of the optimal configuration. To study this effect, coefficients a, b, and c were fixed and given an equal value:

$$a = b = c = \frac{1}{3}$$

Then, exponents α and γ were varied from 0 to 1 in increments of 0.1, and the procedure for determining the optimal configuration was repeated. The results are shown in Figure 11.

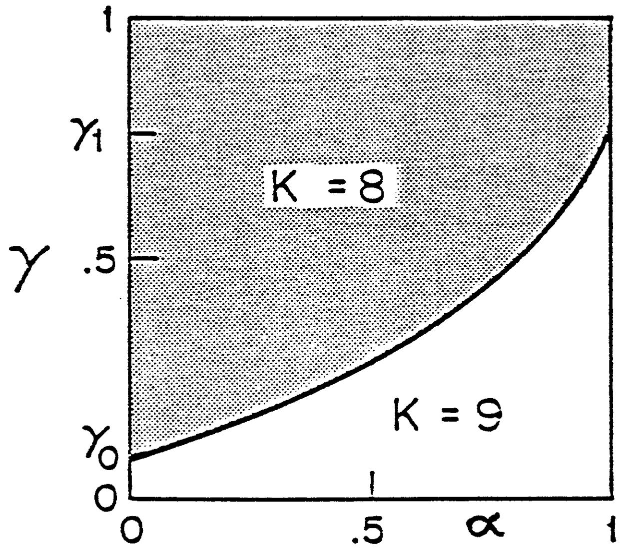


Figure 11. The Optimal Configuration as a Function of Exponents (α,γ)

Depending on the value of the couple (α,γ), either configuration π_8 or π_9 is optimal. Indeed, a higher value of γ implies that the decisionmaker has a more pronounced preference for configuration π_8 over π_9. Recall that configuration π_8 carries out function 1, while π_9 carries out function 2; in addition, the decisionmaker is twice as much interested in seeing function 1 carried out than function 2 ($(FC)_{11} = 0.5$, $(FC)_{21} = 0.25$). Similarly, a higher value of α implies that the developers have a more pronounced preference for configuration π_9 over π_8. However, when γ is high ($\gamma > \gamma_1$), the decisionmaker's preference will always prevail, even when α is equal to 1. Conversely, when γ is low ($\gamma < \gamma_0$) the developers' preference prevails, even when they are not explicitly concerned about how many technologies are demonstrated ($\alpha = 0$). When the value of γ is intermediate ($\gamma_0 < \gamma < \gamma_1$), the trade-off between the decisionmaker's preference and the developers' reappears when α is varied from 0 to 1.

The conclusion to draw is the following: If exponent γ is known to be smaller then γ_0 or greater than γ_1, the value of exponent α becomes irrelevant to the selection of the optimal configuration. For example, if in early demonstrations the decisionmaker considers the nature of the functions carried out to have less priority (γ close to 0), then configuration π_9 will be selected.

Finally, the effect of the weighted coefficients a, b, and c on the selection of the optimal configuration is analyzed. For that, the two exponents α and γ were set at 0.8. Then, coefficient a was varied in increments of 0.1. For each value of a, c was varied from 0 to 1-a in increments of 0.1. Then b was given by

$$b = 1 - c - a$$

The procedure for determining the optimal configuration was repeated for each set of values of (a,b,c); the results are shown in Figures 12 and 13.

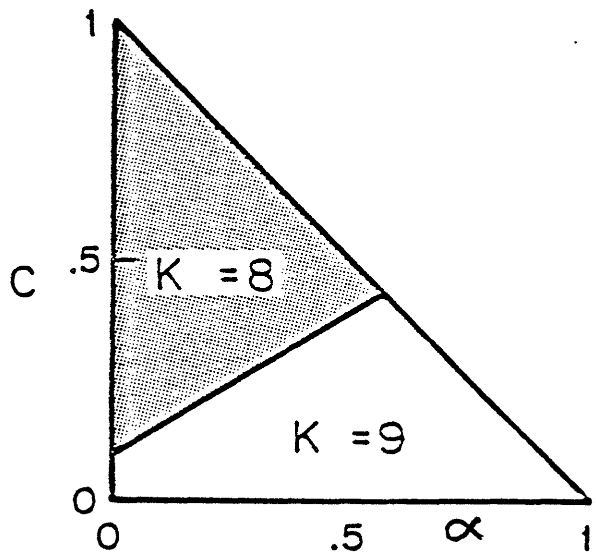


Figure 12. The Optimal Configuration as a Function of Coefficients (a,c)

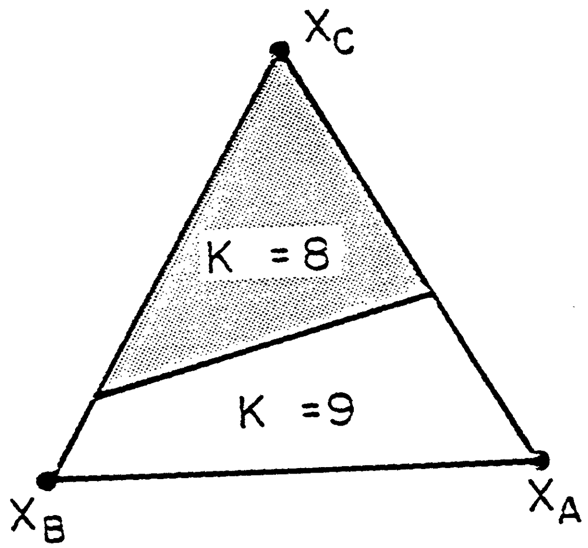


Figure 13. The Optimal Configuration in the plane (a + b + c = 1)

Figure 12 shows a plot in the (a,c) plane. The set of possible values of (a,c) is the triangle $a \geq 0$, $c \geq 0$, $a + c \leq 1$; it is divided in two regions separated by a straight line. In the region below that line, configuration π_9 is optimal: when the developers' utility is given greater relative weight (a close to 1), the configuration that includes all nodes and links (π_9) is optimal. In the upper region where the decisionmaker's utility is given greater relative weight (c close to 1), configuration π_8 is optimal. What happens when the system users' utility u_B is given greater relative weight? The answer can be given by Figure 12, but it is more straightforward, if the same results were plotted in the plane (a + b + c = 1). This is done in Figure 13, which shows that configuration π_9 is also optimal when the system users' utility is given greater weight. This happens because the configuration that includes all nodes and all links is also the one that "performs best" in terms of the traditional attributes.

Figure 13 can help the designer select with more confidence the configuration that will maximize the effectiveness of the demonstration, when there is uncertainty about the accuracy of the relative weights a, b, and c. For example, if in early demonstrations the utility of groups B and C is not critical (low b and c), then configuration π_9 will be selected, i.e., the configuration with large number of components provided it "performed well" in terms of the traditional attributes.

This section focused on showing the applicability of the methodology, using an illustrative example. Sensitivity analyses were conducted to show the types of results that can be obtained. The next section analyzes the effectiveness of METANET, a network of networks.

2.6 EFFECTIVENESS ANALYSIS OF THE METANET DEMONSTRATION

METANET, a multi-year program sponsored by NAVELEX, can be described as a network of networks, where the objective is to demonstrate the feasibility of effective, reliable communication between a large heterogeneous set of nodes. A demonstration of some aspects of METANET was being planned for 1985. The plan was to freeze a set of components, select a set of nodes and links, and develop a scenario that will (a) demonstrate the capabilities and potential of METANET, and (b) indicate research and development needs (Mathis, 1983).

6.2.1 The System Model

Fifteen components/technologies were frozen some time ago for the purpose of being eventually used in the first demonstration of METANET (#T=15); they constitute the set S(t) of operational component. These technologies, numbered from 1 to 15, are introduced next.

<u>Operational Technologies:</u>

T_1 Tactical Situtation Assessment: performs part of the situation assessment function of C^2 and runs on operating system X.

T_2 Briefing Aid: allows a user to present briefings using computer graphics display hardware; runs on operating system X.

T_3 Weather Editor: allows a user to select a geographical area of the world and an environmental data field to be displayed; runs on operating system X.

T_4 Warfare Environment Simulator: provides a computer derived simulated naval war environment for both instructional and strategy testing purposes; runs on operating system X.

T_5 Local Area Network 1 (LAN1): generalized data communication network using data bus technology.

T_6 Multimedia Mail: to extend text mail, graphics, and vocoded voice; interactive interface with user connected to workstation, accessed from workstation (C^2WS).

T_7 Natural Language/Database: provides natural language access to Database (T_{10}), also includes the design and implementation of communication links among command and control workstations and Database; runs on workstation's computer.

T_8 Speech: to interface speech commands and queries to the Natural Language system, to synthesize responses from the query system into speech for the user; runs on workstation's computer.

T_9 METANET Gateway (GWY): to provide link between the workstations' local area network and other networks, including: LAN1, LAN2 (T_{12}), SANET (see T_{13}), and MILNET.

T_{10} Database: software system, allows a user to query multiple pre-existing, heterogeneous databases, using a single language and a simple integrated view of the available data.

T_{11} Data Management System (DMS): provides a graphical user interface to information, designed to be used directly by the decisionmaker; installed on board ship.

T_{12} Local Area Network 2 (LAN2): data communication network using ring technology.

T_{13} P-3C Radio Modifications: installation of a SANET (Satellite Network) node on a P-3 aircraft.

T_{14} SAT: enables linkage to SANET (see T_{13}).

T_{15} PLI: cryptographic device, enables linkage to MILNET.

Many system configurations can be obtained from these technologies, but not all are useful for the demonstration. The useful configurations will be specified in conjunction with the possible scenarios.

2.6.2 The Attributes

The same six attributes as in the simple network of the previous section are considered relevant. The scaled inverse of time delay ν has a different constant:

$$\nu = \frac{1}{\mu C \xi} \tag{76}$$

2.6.3 The Mission Model

Six major developers can be identified (#A = 6): five system contractors and the sponsoring agency. Each developer contributed to the development of some or all the operational technologies (i.e., a subset of S(t)), and is particularly eager to see those demonstrated. The technology by developer matrix, obtained by interviewing some of the developers, was found to be:

$$TA = \begin{bmatrix} 6/28 & 0 & 0 & 0 & 0 & 1/15 \\ 6/28 & 0 & 0 & 0 & 0 & 1/15 \\ 3/28 & 0 & 0 & 0 & 0 & 1/15 \\ 3/28 & 0 & 0 & 0 & 0 & 1/15 \\ 10/28 & 0 & 0 & 5/29 & 0 & 1/15 \\ 0 & 10/30 & 0 & 0 & 0 & 1/15 \\ 0 & 5/30 & 0 & 0 & 0 & 1/15 \\ 0 & 8/30 & 0 & 0 & 0 & 1/15 \\ 0 & 7/30 & 0 & 0 & 0 & 1/15 \\ 0 & 0 & 10/15 & 0 & 0 & 1/15 \\ 0 & 0 & 5/15 & 0 & 0 & 1/15 \\ 0 & 0 & 0 & 5/29 & 0 & 1/15 \\ 0 & 0 & 0 & 10/29 & 10/10 & 1/15 \\ 0 & 0 & 0 & 8/29 & 0 & 1/15 \\ 0 & 0 & 0 & 1/29 & 0 & 1/15 \end{bmatrix} \qquad (77)$$

The physical characteristic of the system's components and the context of the demonstrations dictate the following technology by attribute matrix:

$$TY = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \qquad (78)$$

The group of system users includes those persons who will use the system during the demonstration, and only those. The system user by attribute matrix is then

$$(BY)_{ij} = 1/4 \qquad i = 1,\ldots,\#B \;;\; j = 1,\ldots,4 \tag{79}$$

i.e., all the participants in group B are equally interested in each of the four type 1 attributes.

There are four decisionmakers (#C = 4), while four functions can be carried out by the demonstration of METANET (#F = 4). Decisionmakers 1 to 3 are commanders in the Armed Forces; they are the real system users. Decisionmaker 4 represents a decisionmaking entity. Function 1 and 3 correspond to the interactions between commanders 1 and 2, and commanders 2 and 3, respectively. Function 2 (respectively, function 4) denotes the interaction between commander 2 (respectively, commander 3) and his staff.

The next step is the determination of the function by decisionmaker matrix, Eq. (80).

$$FC = \begin{bmatrix} 1 & 1/3 & 0 & 1/4 \\ 0 & 1/3 & 0 & 1/4 \\ 0 & 1/3 & 1/2 & 1/4 \\ 0 & 0 & 1/2 & 1/4 \end{bmatrix} \tag{80}$$

The first three columns of the matrix result directly from the interaction scheme described previously. Indeed, consider commander 2: he interacts with commanders 1 and 3, and also with his staff. Thus, he is eager to see how METANET will carry out functions 1, 3, and 2; hence the second column of matrix FC. Decisionmaker 4 is equally interested in seeing the four functions carried out. This leads to the fourth column of matrix FC.

The decisionmakers unanimously believe that any of the four functions should be carried out with maximum reliability, survivability, and input flow of data, and with minimum time delay. The function by attribute matrix is then:

$$(FY)_{ij} = 1 \qquad i = 1,\ldots,4 \ ; \ j = 1,\ldots,4 \qquad (81)$$

2.6.4 Useful Configurations

Four facilities are available to house the METANET demonstration. An important set of hardware and software technologies can be made available at facilities 1 and 4. Facility 2 is the generator of weather data (DG), while facility 3 is a ship in the high seas. As it turns out, the use by the demonstration of facility 4 is a decision variable. Depending on whether three facilities (case a) or four facilities (case b) are used, the total network configuration will be slightly different (see Figures 14 and 15). It is assumed that facility 3, as well as the satellite (SANET) and P-3 nodes are in a hostile environment. Survivability is hence an issue for any technology using these nodes. (Hence the second column of matrix TY).

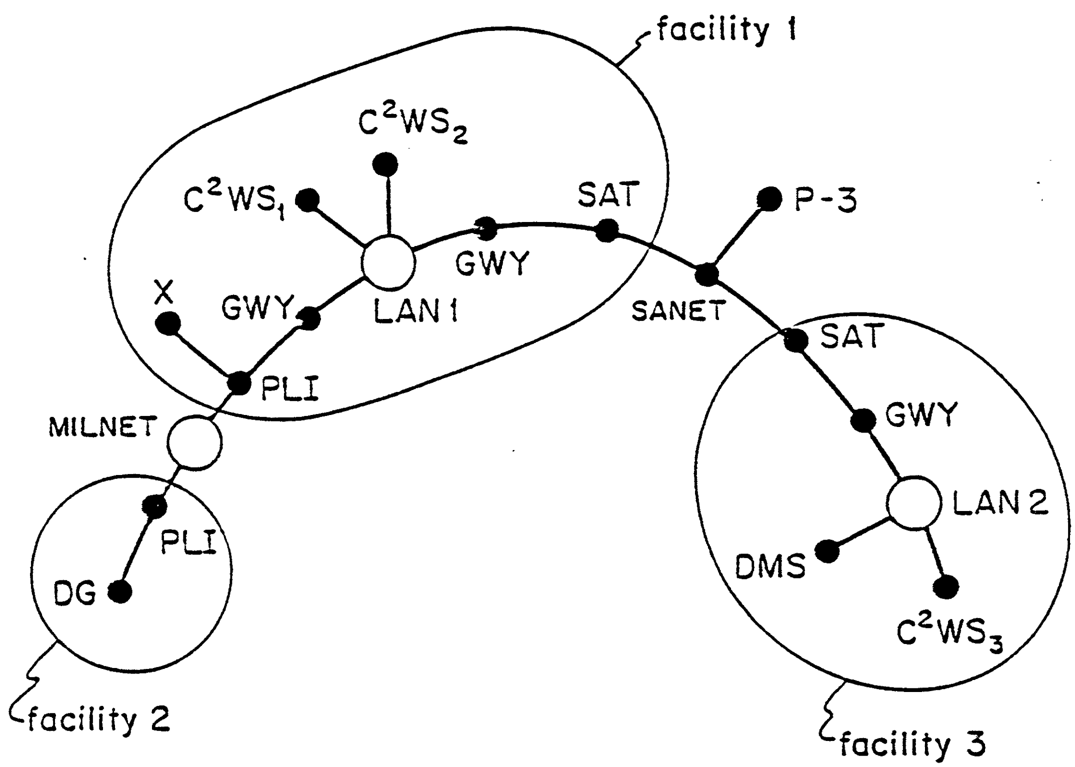


Figure 14. Total Network Configuration when Three Facilities are Used (Case a)

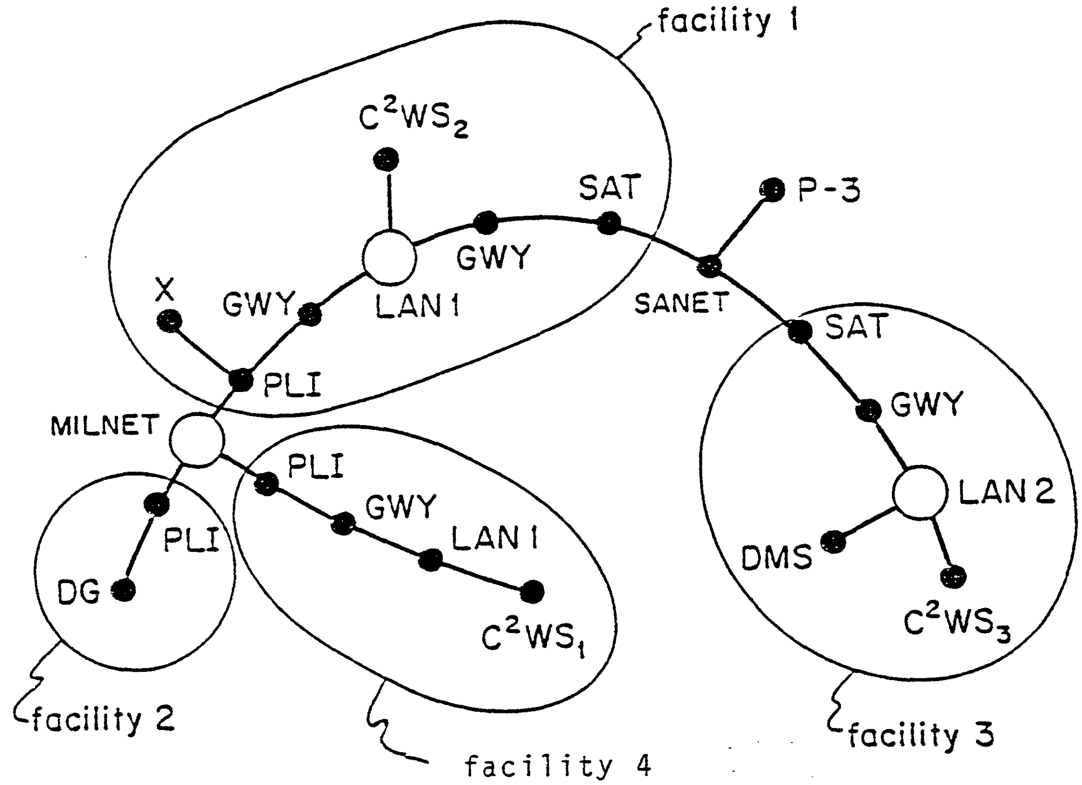


Figure 15. Total Network Configuration when Four Facilities are Used (Case b)

The scenario according to which the demonstration is run consists of several stages. An origin-destination pair, a session, is demonstrated at each stage; it performs one of the four functions described in Section 2.6.3. Seven sessions are identified. Session 1 is designed to carry out function 1. Sessions 2 and 3 execute function 2 each. Function 3 is carried out by session 4, while sessions 5, 6, and 7 carry out function 4.

All the sessions do not have to be included in the demonstration: out of the seven sessions mentioned previously, only some may end up taking place during the demonstration of METANET. If s sessions are actually demonstrated ($1 \leq s \leq 7$), then the scenario consists of s stages. A useful system configuration corresponds to each such scenario; it includes the s origin-destination pairs. There are, hence, $2^7-1 = 127$ (the null element ϕ is excluded) useful configurations in case a, and just as many in case b. Sessions 1 to 7 are drawn in Figure 16. Note that only session 1 has a different topology depending on whether three or four facilities are used.

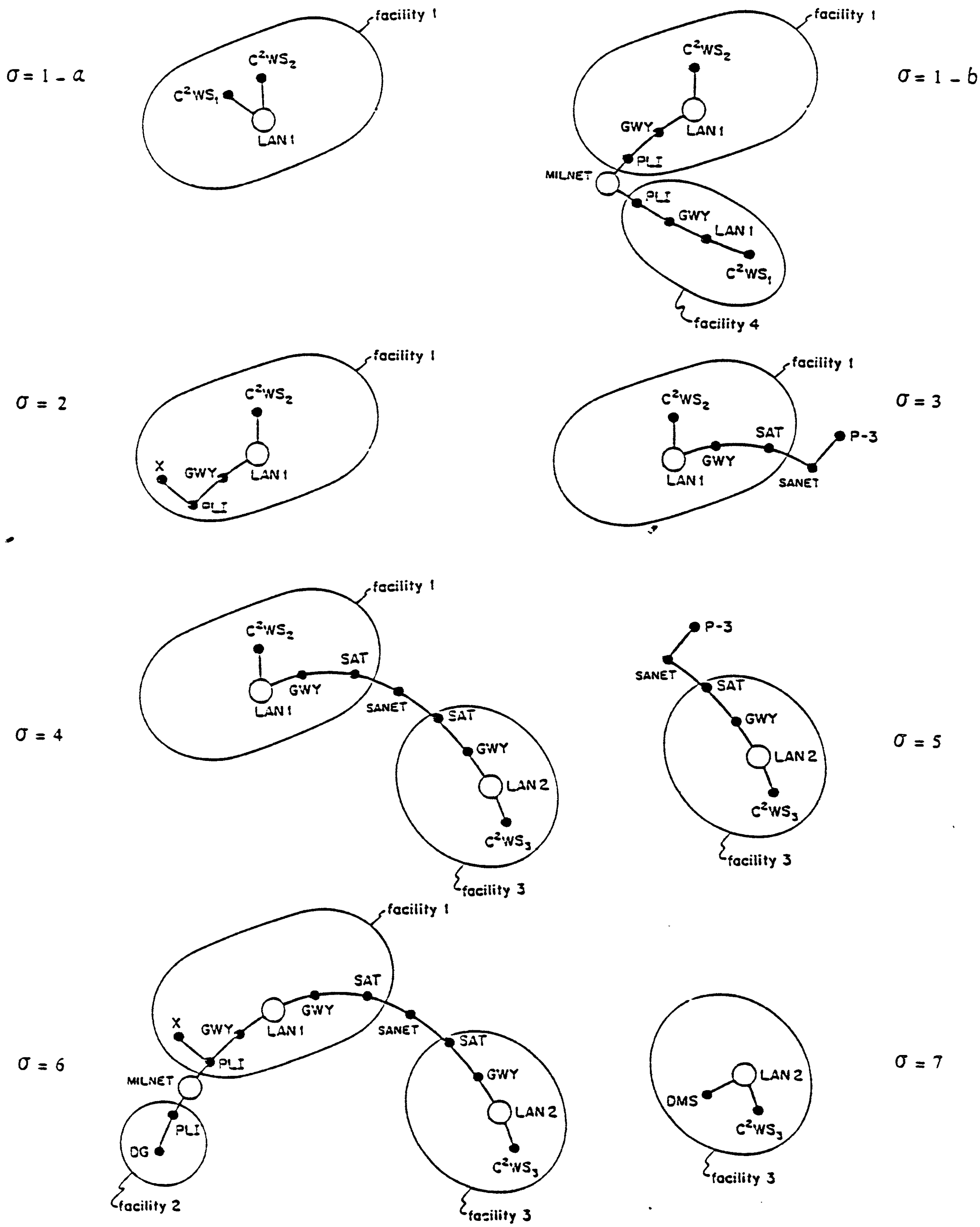


Figure 16. Topology of the Sessions

Each useful configuration π_K is characterized by the value taken by the binary variables $K(\sigma)$ for $\sigma = 1$ to 7, defined as follows:

$$K(\sigma) = \begin{cases} 1 & \text{if session } \sigma \text{ is included in configuration } \pi_K \\ 0 & \text{if it is not} \end{cases} \quad (82)$$

For example, configuration $\pi_{(1100001)}$ is the one that includes sessions 1, 2, and 7.

The measure of effectiveness of a demonstration of METANET using π_K is:

$$E(K) = \int g_{\pi_K}(\underline{y})\ h_{\pi_K}(\underline{z})\ u(\underline{y},\underline{z})\ d\underline{y}\ d\underline{z} \quad (83)$$

$$E(K) = a\ (z_A(K))^{\alpha} \int g_{\pi_K}(\underline{y})\ v_A(\underline{y})\ d\underline{y} + b \int g_{\pi_K}(\underline{y})\ v_B(\underline{y})\ d\underline{y}$$

$$+ c\ (z_C(K))^{\gamma} \int g_{\pi_K}(\underline{y})\ v_C(\underline{y})\ d\underline{y} \quad (84)$$

The probability distribution g is well defined when configuration π_K contains only one origin-destination pair. Let then

$$E_i(\sigma) = \int g_{\sigma}(\underline{y})\ v_i(\underline{y})\ d\underline{y} \quad (85)$$

where i = A, B, or C and $\sigma = 1,\ldots,7$. For each useful configuration π_K, let $\bar{E}_i(K)$ be the average of the $E_i(\sigma)$'s for all sessions σ included in configuration π_K, i.e.,

$$\bar{E}_i(K) = \frac{\sum_{\sigma=1}^{7} K(\sigma)\ E_i(\sigma)}{\sum_{\sigma=1}^{7} K(\sigma)} \tag{86}$$

Expression (86) replaces the term $\int g_\pi(y)v_i(y)dy$ when configuration π_K contains more than one session. The measure of effectiveness of a demonstration of METANET using π_K is then:

$$E(K) = a\ (z_A(K))^{\alpha}\ \bar{E}_A(K) + b\ \bar{E}_B(K) + c\ (z_C(K))^{\gamma}\ \bar{E}_C(K) \tag{87}$$

The design optimization problem is then to

$$\underset{\substack{K=(K(1),\ldots,K(7)) \\ \text{case a or b}}}{\text{maximize}} \quad E(K)$$

2.6.5 Evaluation of System Attributes

Weights $\omega_A(T_i)$ and $\omega_C(F_i)$ used in expressions (17) and (18) defining the weighted fractions of Technologies and Functions are given by the following equations.

$$\omega_A(T_i) = \sum_{k=1}^{6} (TA)_{ik} \qquad i = 1,\ldots,15 \tag{88}$$

$$\omega_C(F_j) = \sum_{k=1}^{4} (FC)_{jk} \qquad j = 1,\ldots,4 \tag{89}$$

On the other hand, a technology i is said to be included in a configuration π_K (i.e., $\tau(T_i)=1$) whenever it is used by at least one session in that configuration. Similarly, a function j is said to be carried out by the demonstration ($\phi(F_j)=1$) if it is executed by at least one session in configuration π_K.

The Reliability and Survivability attributes depend on the probability of failure of the components (in the event of an enemy attack for the attribute Survivability). Each failure probability is allowed to vary in a different interval of [0,1], depending on whether Reliability or Survivability is computed. Hence, for each session σ

$$R_{min}(\sigma) \leq R \leq R_{max}(\sigma) \tag{90}$$

$$S_{min}(\sigma) \leq S \leq S_{max}(\sigma) \tag{91}$$

For each session σ, the time delay between origin and destination is

$$\xi = \frac{L(\sigma)}{\mu C\text{-Flow}} \tag{92}$$

where $L(\sigma)$ is the number of links in session σ between the origin and the destination. Using the scaled attributes for input flow and inverse time delay Eq. (92) becomes

$$\nu = \nu_o\ (\sigma)\ (1-F) \tag{93}$$

where

$$\nu_o(\sigma) = \frac{1}{L(\sigma)} \tag{94}$$

2.6.6 The Mission Attributes

The utility of the demonstration is an additive average of the partial utilities, i.e.,

$$u = a\,u_A + b\,u_B + c\,u_C \tag{95}$$

where a + b + c = 1. The Q matrices can be computed (for each session σ) by manipulating the data in the matrices (77) - (81). Parameters α and γ are set equal to 0.5, while coefficients a, b, and c are set equal to 1/3. Sensitivity analyzes with respect to α, γ, a, b, and c can be found in Karam (1985).

2.6.7 Results

For each session σ, the quantities $E_A(\sigma)$, $E_B(\sigma)$, and $E_C(\sigma)$ were computed. The effectiveness of each configuration π_K was then computed according to Eq. (87). For each case (a or b), the configurations were then rank ordered. The results are given next.

Case a: Three Facilities

The first ten configurations are listed in Table 1 in order of decreasing effectiveness. Each configuration π_K is identified by the values of the binary variables $K(\sigma)$, σ= 1 to 7. For example, the configuration that ranks #1 includes all sessions but sessions 5 and 6, has a measure of effectiveness of 0.799, and a z_A and z_C equal to 0.98 and 1, respectively. Table 1 gives also the values of the system attributes z_A and z_C. Several remarks can be made about the results shown in this table.

First, the configuration including all sessions (K=(1 1 ... 1)) is not the optimal one, it ranks #9. The interpretation is the following: some sessions had better be ignored altogether in the first demonstration of METANET if they are not adequately developed, specially if they do not execute an additional function. It can be noted, with this respect, that the first seven configurations carry all four functions (z_C=1). However, configuration #8 has a z_C of 0.85: there is at least one function which is carried out by none of the sessions included in this configuration.

Table 1 The First Ten Configurations (Case a)

Rank	Configuration π_K σ = 1 2 3 4 5 6 7	Effectiveness	z_A	z_C
1	1 1 1 1 0 0 1	0.799	0.98	1
2	1 1 0 1 1 0 1	0.793	0.98	1
3	1 1 1 1 1 0 1	0.787	0.98	1
4	1 0 1 1 0 0 1	0.785	0.83	1
5	1 1 1 1 0 1 1	0.782	1	1
6	1 1 0 1 1 1 1	0.778	1	1
7	1 1 0 1 0 0 1	0.777	0.75	1
8	1 1 1 0 0 0 1	0.777	0.98	0.73
9	1 1 1 1 1 1 1	0.775	1	1
10	1 0 1 0 0 0 1	0.771	0.83	0.73

Configuration #8 carries out fewer functions than configuration #9 (smaller z_C) and includes fewer technologies (smaller z_A); nevertheless, it is more effective for the first demonstration of METANET. In fact, all first four configurations have a z_A smaller than 1; i.e., none of them includes all fifteen technologies.

It can be inferred from these results that showing an additional technology or carrying out an additional function at the time of the METANET demonstration may be at the expense of the overall effectiveness of such a demonstration.

Case b: Four Facilities

The same type of results is obtained when four facilities are used, and hence the same conclusions can be drawn. Table 2 shows the first ten configurations, together with their effectiveness measure, and the values of system attributes z_A and z_C.

Note that the configuration including all sessions now ranks #5, and that its effectiveness is reduced compared to case a. In fact, all configurations that include session σ=1 have their effectiveness reduced if four facilities are used rather than three. When the mission primitives were given the following extreme values

$$a = 1 \quad , \quad b = c = 0$$

$$\alpha = 1 \quad , \quad \gamma = 1$$

this basic result remained unchanged: the top ranking configurations were still more effective when three facilities are used rather than four. The conclusion is then the following: given the values of the system primitives, the model predicts that, for the first demonstration of METANET, it will always be more effective to use three facilities, and sessions 1, 2, 3, 4, and 7 with the corresponding scenario.

Table 2. The First Ten Configurations (Case b)

Rank	Configuration π_K σ = 1 2 3 4 5 6 7	Effectiveness	z_A	z_C
1	1 1 1 1 0 0 1	0.775	0.98	1
2	1 1 0 1 1 0 1	0.770	0.98	1
3	1 1 1 1 1 0 1	0.768	0.98	1
4	1 1 1 1 0 1 1	0.762	1	1
5	1 1 1 1 1 1 1	0.758	1	1
6	1 1 0 1 1 1 1	0.758	1	1
7	1 0 1 1 0 0 1	0.757	0.83	1
8	1 1 0 1 0 0 1	0.750	0.75	1
9	1 1 1 0 0 0 1	0.749	0.98	0.73
10	1 0 1 1 1 0 1	0.748	0.83	1

2.7 REMARKS

A methodology for effectiveness analysis of an evolving system has been presented. It requires the explicit specification of candidate technologies and the consideration of the utilities of the various groups involved in developing the system. The context in which the methodology was formulated is that of a demonstration aimed at showing the progress achieved in developing the system as well as the capabilities of the latter. The methodology provides the decisionmaker with a powerful tool that can be applied systematically to quantifying the progress made in developing a system, the expectation of the various participant groups, and finally the global effectiveness of the system at each point in time.

3. RESULTS II: ASSESSMENT OF TIMELINESS IN COMMAND AND CONTROL*

3.1 INTRODUCTION: THE CONCEPT OF TIMELINESS

Time plays a fundamental role in most Command, Control and Communication (C^3) systems. Improvements in weapon system technology, higher capacity and speed in the transmission of data, combined with an increasing complexity of the battlefield, impose severe time constraints on both the hardware and the human decisionmakers. It is necessary then to develop methodologies for assessing C^3 systems that take into account time. Time has always been of crucial importance in combat; furthermore, it differs from any other attribute of a C^3 system. This uniqueness, combined with the growing concern of system designers, has motivated the study of time in C^3 systems explicitly.

*This section is based on the work of P. H. Cothier as documented in his MS Thesis and the paper referenced in Section 5. This work was supported in part under the Contract with the Space and Naval Warfare Systems Command and in part by the Army Research Institute under Contract No. MDA903-83-C-0196.

As Lawson [1981] relates, "in a typical discussion of Command and Control, it is taken as axiomatic that the information presented to the commander must be 'timely' as well as accurate, complete, etc.,... Little or nothing is said about how timely is timely enough; nor is any yardstick given by which to measure 'timeliness'. Rather, the clear implication is that all would be well if only communications and computers were 'faster'. In addition, this attention to rates (e.g. information processing rates, rate of fire, etc.,...) in which time only appears in the denominator, has led to a preoccupation with the performance characteristics of the component parts of a C^3 system. It does not provide any means of comparing the effect of an increase in one 'rate' with that of an increase in some other rate".

In this section, a methodology for assessing the effectiveness of C^3 systems by directly taking into account the issue of timeliness is presented. The methodological framework is the same one discussed in Section 1. The key idea is to relate the performance of a system to the mission it has to fulfill. One of the main advantages of this methodology in the case of the assessment of timeliness, is that it allows comparison of the effectiveness of different doctrines used with the same system. From the insights that the analysis yields, conclusions can be drawn not only for the design of C^3 systems, but also for their integration in the military doctrine.

The aspects that time can take in a warfare environment are numerous. The most important ones, whose subtleties the assessment methodology should be able to embed and to exhibit, follow.

System response time. It characterizes the time delay between the moment when the C^3 system receives a stimulus and the moment it can deliver a response. It is the sum of all the time delays at every level of the process.

Tempo of operations. In most military situations, rates are used to express the important quantities, e.g., rounds per minute, miles per hour. The term in common usage for the operating rate of a C^2 system is its "tempo". Lawson [1981] defines it as the number of actions per unit of time which the system is executing and states, further, that "the tempo tells us how complex an environment the system can handle (i.e., its bandwidth) while the response time tells us when it responds in time (i.e., the phase delay in the system)".

When a C^3 system initially receives a stimulus (e.g., a blip on an air defense radar), there is a great deal of uncertainty. The decisionmaker cannot take any action until this uncertainty is reduced below an acceptable threshold. Such a reduction takes time and effort. This presents the first trade-off: the more time is spent to reduce the uncertainty, the longer the response time, but the more adequate the response.

Two types of uncertainty can be distinguished: The first one, which can be called interscenario refers to what the commander is confronted with when he tries to identify what scenario is actually taking place (e.g., an enemy attack as opposed to a mere reconnaissance mission). The second one, which can be called intrascenario refers to the uncertainty within the scenario itself. The issue is to estimate the parameters of this scenario, such as the number of the enemy forces, their velocities or, the intensity of the attack.

For each type of stimulus, the decisionmaker has to choose among a set of options which one to implement as a response. Not to do anything (underreaction) is also an option. These options can be ranked according to two criteria: their desirability and the time required for implementation. A given option may take a longer time to be implemented but with a more desirable outcome. The decisionmaker must take into account these aspects, and an enhanced methodology for assessing timeliness should be able to express the notion of quality of option.

These notions depend on what is actually taking place, i.e., the scenario. The event that stimulates the C^3 system is only the partial perception by the system of a global scenario. Different scenarios can be perceived through identical events and the system is confronted with uncertainty. Once the scenario is identified with enough certainty, then an option must be selected. Some options are quite appropriate for certain scenarios while some others are completely irrelevant. It appears that any assessment of a C^3 system must consider the crucial role of the scenario: to each scenario corresponds an evaluation of the effectiveness of the system. Finally, these different measures can be merged into an overall measure of effectiveness for a given range of possible scenarios.

Timeliness is a concept that embeds all the above notions. Timeliness appears to be closely related to the notion of time interval, the so-called window of opportunity. There are basically two types of windows: one characterizes the system response capabilities, while the other expresses the requirements of the mission the system is expected to fulfill. Once the system has received a stimulus, no response can be delivered before some amount of time has elapsed. The lower bound is defined by the shortest response time possible. On the other side, there may be a latest response time after which no response can be implemented. The time interval between these two boundaries constitutes the window of opportunity for the system capabilities: (t^*, t^{**}).

Any response to the stimulus must come in time in order to be effective. There comes a moment when any response is preempted: this defines the upper boundary for the response time. A lower boundary can also be defined: for example a carrier may have to wait until a submarine enters the territorial seas before taking any course of action. The time interval between these two boundaries constitutes the window of opportunity for the mission requirements: (θ^*, θ^{**}).

When the two windows are superimposed, different configurations can be sketched for the residual window of opportunity (Figure 17).

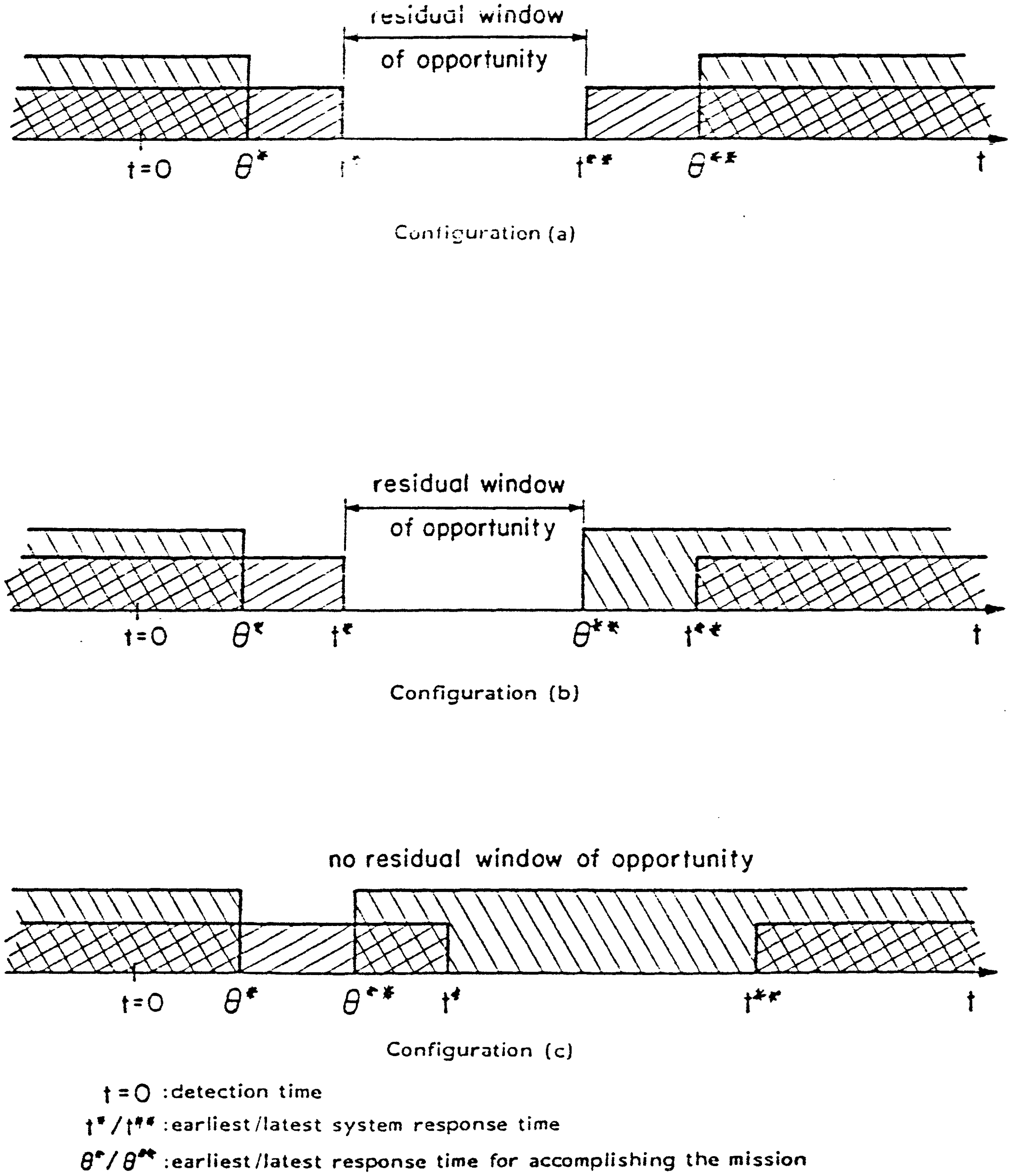


Figure 17. Different Configurations for the Windows of Opportunity

However, a measure based only on the window of opportunity is not satisfactory. While, it appears that timeliness is intrinsically related to the notion of a time interval, a time interval is not sufficient to convey the concept of timeliness; one must also consider the way this time is employed, which depends on the actual time rather than the time interval. Thus timeliness refers to the quality of time management within a given window of opportunity. In that sense, it appears that a measure of effectiveness based upon this time management can be an effective measure of timeliness. Therefore, in assessing the timeliness of a C^3 system, one should consider not only the C^3 system, but also the doctrine that is used, as well as the options from which the decisionmaker can choose; the time available and its management depend on the consideration of systems, doctrine and options. The better the effectiveness of the combination, the more timely the C^3 system.

3.2 ASSESSMENT OF TIMELINESS

The issues discussed in the introduction will be illustrated by applying the methodology to a hypothetical, but realistic, fire support system (Cothier, 1984). While, for realism, an Army scenario was used, the models and the methodology are directly applicable to a Marine scenario.

One can isolate three main elements in the fire support system at the battalion level: the forward observer, the battalion fire direction center and the field artillery cannon battery. The system can include several forward observers and several batteries connected to the same central battalion computer.

The Forward Observer (FO) is the part of the system that receives the initial stimulus by detecting an enemy threat. The FO is equipped with vehicle position determining equipment and a laser rangefinder. The FO is also equipped with the Digital Message Device (DMD). The FO uses the DMD to communicate estimates of the position and velocity of the target and requests for fire to the battalion computer.

The Battalion Fire Direction Center (BN FDC) is provided with a central computer. Digital communication over any standard Army communication means (radio or wire) provides for input of data into the computer center and for the return of the results. Forward observers and firing batteries are provided with remote terminal equipment to obtain data from the central computer.

The Battery Display Unit (BDU) is the cannon battery's link with the C^3 system. The BDU assists execution of fire plans by receiving and printing firing data for each target that the battery will fire.

While this is the basic configuration, additional equipment is maintained in parallel to augment the basic system.

- o Voice communication links can be added in parallel with the digital links, for instance between the battalion fire direction center and the cannon battery. Voice communication is slower, more vulnerable, but still very useful, if the digital link fails.

- o If the fire support system computer become fails at the battalion level, the battery has the capability to do the firing computations locally. This alternative is slower, though.

A representation of the system that will be analyzed is shown in Figure 18. Seven links are shown. Nodes are not subject to failure; only links are. A voice link is in parallel with the digital link between the battalion fire direction center and battery B.

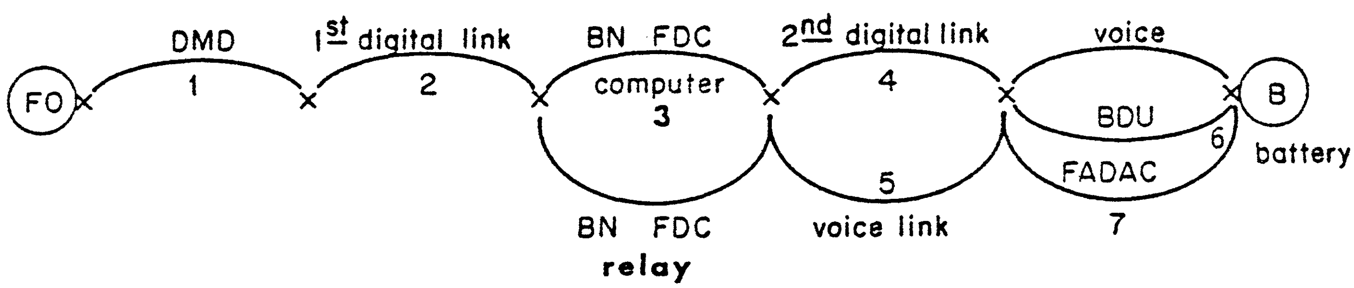


Figure 18. Fire Support System Structure

If the BN FDC computer does not work, the target estimates from the FO can be sent to battery B through voice communication (the BN FDC acts as a simple relay). The battery crew can then compute the firing data manually.

- In the case where the firing data are computed at the BN FDC level and transmitted by voice communication to battery B, neither the BDU nor the manual technique have to be used. The voice communication of the firing data reaches directly the firing platform of the battery.

In order to assess properly the effectiveness of this system it is necessary to specify the context in which it operates as well as the scenario.

The context and scenario that will be considered are shown in Figure 19. Some vital point of the blue forces (i.e., headquarters) is situated at the end of a valley. A road along this valley leads to these headquarters. The topography of the area is perfectly known by the blue forces, and the road is the only access to the blue camp. A fire support battalion including one forward observer FO, one battalion fire direction center BN FDC and two batteries B_1 and B_2, have been positioned to protect this access. This battalion is equipped with the fire support system (Fig. 19). The batteries cannot see the road; they shoot according to the firing directions that are computed on the basis of the observer's estimates.

An enemy tank (threat) appears in the area of detection of the forward observer. It is moving on the road towards the blue forces with hostile intentions. The <u>mission</u> of the fire support battalion is to prevent the attack on the blue headquarters by destroying or incapacitating the threat.

It is assumed that the threat cannot attack the fire support battalion directly; the only countermeasure that will be considered is the jamming of the communications by the enemy. It is also assumed that the threat will pursue its attack, even after it is fired upon. It will try to carry out its own offensive mission, as if it encountered no reaction from the blue forces.

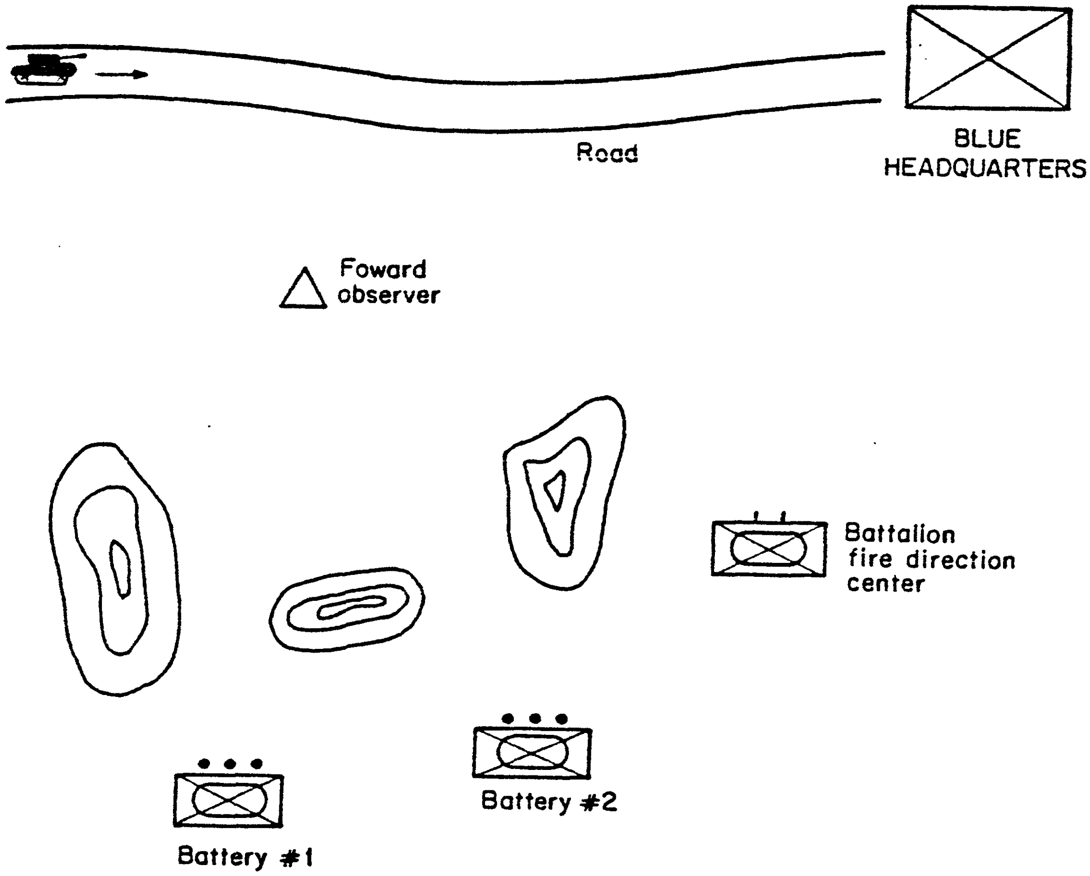


Figure 19. Context for Operations

3.2.1 Definition of Attributes

The window of opportunity for the system response capabilities is defined by the ordered pair of attributes (t^{**}, Δt), where t^{**} is the latest time at which the target can be destroyed, and Δt is the width of the window.

In order to characterize the ability of the system to destroy or incapacitate the target, the third attribute is the overall kill probability (OKP). Choosing such a quantity as an attribute raises a very interesting point in the system effectiveness analysis methodology. Indeed, the OKP can be considered as an attribute (an MOP) since it is a function of the system characteristics (hardware and procedure), but it is also a measure (MOE) in itself since it evaluates the destructive capabilities of the system. Such a duality can be used advantageously, because the mission requirements can be expressed fairly simply in terms of such a measure/attribute.

On the system side, the third attribute OKP is computed on the basis of the system primitives and the first two attributes t^{**} and Δt. On the mission side, the fire support battalion is required to prevent the attack on the headquarters with a desired level of confidence. Since the commander is only concerned with the outcome of the fire support, the mission requirements are simply expressed as conditions on the third attribute OKP. The first two attributes which describe the window of opportunity are not taken into account at that level.

3.2.2 Definition of Primitives

Each node and link of the system is assumed to have a probability of failure, independently of the countermeasures of the enemy. Only the technical characteristics of the system are considered. This refers to the concept of reliability. The system is operating in a hostile environment. The communication links are subject to jamming from the enemy. Therefore, each node and link has a probability of failure due to enemy countermeasures. This refers to the concept of survivability. Although the two concepts of reliability and survivability are distinct (the two sets of probabilities of failure can be considered as independent), they are merged in the present analysis to reduce the dimensionality of the problem. A single probability vector $\underline{p}$ is considered for the set of nodes and links of the system: it embeds considerations both of reliability and survivability.

One of the simplest way to illustrate the influence of the event that is actually taking place is, for instance, to choose the speed w of the threat as a system primitive. This way a whole range of slightly different versions of the same scenario can be investigated by varying w.

It is assumed that the only uncertainty comes from the target estimates by the forward observer (intrascenario uncertainty). An appropriate system primitive can be, for example, the angle β that separates the two sightings (distance measurements) of the observer. Intuitively, the larger the angle β the more accurate the speed estimate but the longer the response time.

Perturbing the system primitives $\underline{p}$, β and w defines the system locus in the attribute space (t^{**}, Δt, OKP).

The issue of the quality of option can be addressed by considering two batteries instead of a single one. Then coordinated fire as opposed to uncoordinated can be studied.

3.2.3 Geometric Analysis

The geometric relations for this scenario are shown in Figure 20.

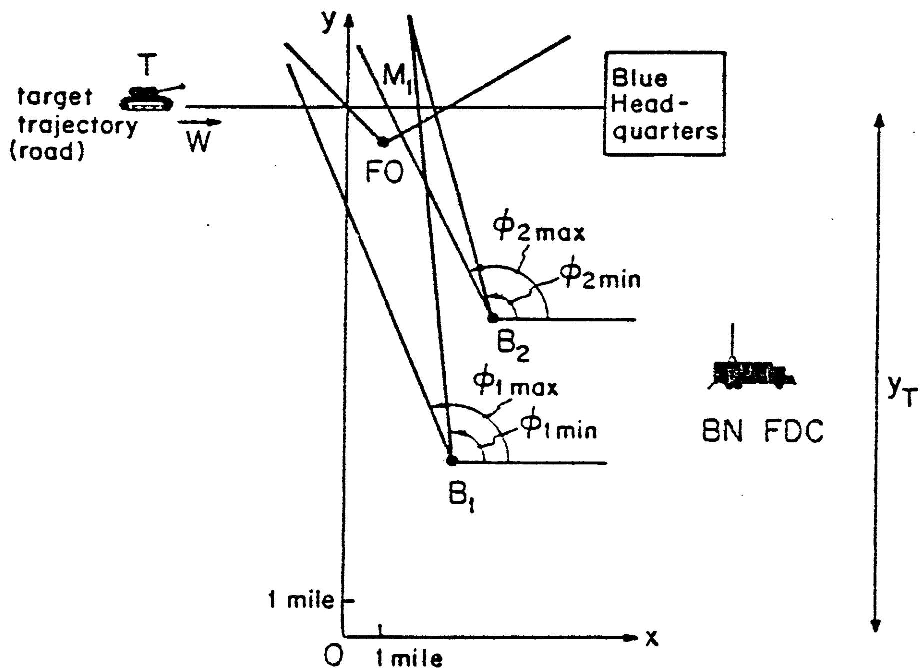


Figure 20. Geometric Relations of the Situation

Figure 21 shows the chronological sequence of the response process. The impact time, t_{impact} is given by:

$$t_{impact} = t_{obs} + \sum_{i=1}^{3} \Delta\tau_i \qquad (96)$$

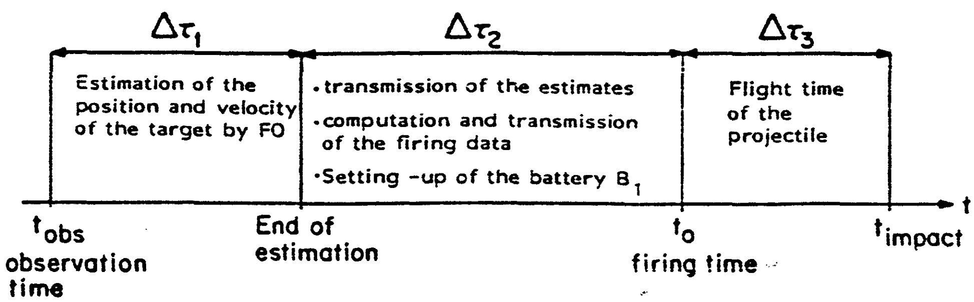


Figure 21. Time Profile of the System Response

$\Delta\tau_1$ is computed from the geometric properties of Figure 21. It is a function of the speed w, the angle β and the observation time (Cothier, 1984):

$$\Delta\tau_1 = \Delta\tau_1(w, \beta, t_{obs}) \qquad (97)$$

A sensitivity analysis shows that it is legitimate to consider $\Delta\tau_3$ as a constant for this topography and characteristics of the weapon system. In the present analysis, this constant is:

$$\Delta\tau_3 = 36 \text{ seconds} \qquad (98)$$

Let $t^* = \min \{t_{impact}\}$. For a given angle β and a given target velocity w, the earliest impact time corresponds to the earliest possible observation time, i.e., $t_{obs} = 0$ (detection time), and to the minimal time delay $\Delta\tau_{2_{min}}$ between the end of the estimation and the actual firing of the battery. Thus:

$$t^{*} = \Delta\tau_{1}(w,\beta,0) + \Delta\tau_{2_{min}} + \Delta\tau_{3} \tag{99}$$

Let M_1 be the point on the trajectory where the threat leaves the area covered by battery B_1 (see Fig. 20). For battery B_1 to be able to destroy the threat, the impact time must not occur after the threat has passed M_1, that is after time t^{**}. This creates an upper constraint on the system capabilities:

$$t^{**} = \max \{t_{impact}\} \tag{100}$$

Again, from geometric considerations,

$$t^{**} = \frac{K}{w} \tag{101}$$

where K is a constant depending on the geometry of the situation. The quantity t^{**} characterizes the limit of the system capabilities when considering the latest response time possible to the initial stimulus.

Therefore, there are both a lower and an upper limit on the system capabilities as far as its response time to the stimulus is concerned. This time interval is the system window of opportunity: the system can deliver a response to the stimulus at any time t_{impact} lying between t^{*} and t^{**} (for $t^{*} < t^{**}$). The window of opportunity is completely characterized by the ordered pair $(t^{**}, \Delta t)$, where $\Delta t = t^{**} - t^{*}$.

The single shot kill probability $SSKP(t_{impact})$ associated with the impact time is easily computed by taking into account the uncertainty in the speed estimate, and the kill radius of the munition. For fixed values of w and t_{obs} the shape of the variations of SSPK with t is given in Fig.

22; the latter also shows an important trade-off. As β increases, the width of the window of opportunity decreases because it takes a longer time for the FO to make his estimation. But at the same time, a large β yields a more accurate estimate of the speed of the target. Therefore the kill probability is increased. The upper limit t^{**} is unaffected by changes in β.

Also, as time goes by, the uncertainty on the exact position x_T of the threat increases and therefore SSKP decreases with time.

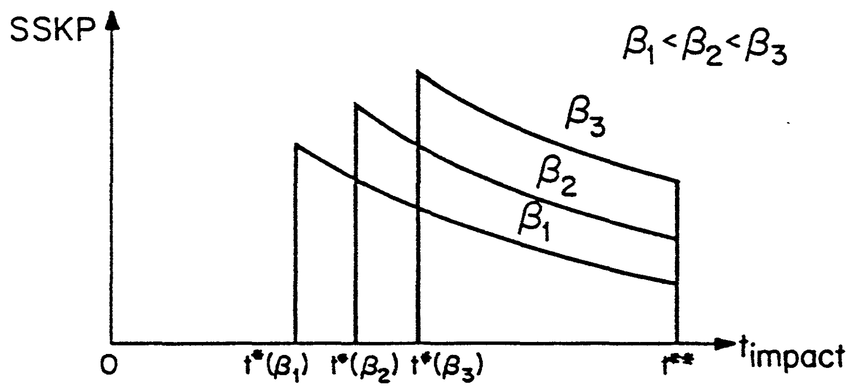


Figure 22. Single Shot Kill Probability as a Function of Impact Time

The seven element structure of the C^3 system has been presented in Fig. 18. The analysis reveals that out of the tem possible paths, six paths do not lead to the transmission of the information from FO to B_1. Four paths lead to a successful communication between FO and B_1. For each path i (i=1,...4), the following quantities are defined:

q(i): probability that the path #i is operational

u(i) = $\Delta\tau_{2_{min}}(i) + \Delta\tau_3$, i.e., u(i) is the minimum time delay between the estimates by the FO and the impact time.

v(i): minimum time delay necessary to recompute new firing data based on the initial estimates, to transmit them and to set up the battery accordingly. If the system recomputes the firing data immediately after each shot and fires in sequence, then v(i) represents the minimum time delay between two shots ("minimum reshooting time").

3.2.4 Doctrine

The management of the time available for the system response has been shown to be a key point in the assessment of timeliness. The notion needs now to be applied to the example.

The earliest response time to the stimulus is t^*. The system can use the remaining time within the window of opportunity to deliver other responses, e.g., to fire again, therefore increasing the overall kill probability. This can be done in many different ways. This analysis focuses on two of them, which are classical military doctrines, known as "LOOK-SHOOT-SHOOT-SHOOT..." and "LOOK-SHOOT-LOOK-SHOOT...".

The "LOOK-SHOOT-SHOOT-SHOOT..." Doctrine: The observer initially makes estimates of the speed and position of the threat, and then the battery keeps on shooting at the target, recomputing each new firing data on the basis of these initial estimates.

The observation time is $t_{obs} = 0$ for each shot since there is no updating of the estimates. The time delay between two shots in thus the reshooting time v. The battery fires as many shots as possible within the window of opportunity since there is no feedback from the observer.

The "LOOK-SHOOT-LOOK-SHOOT..." Doctrine: After each shot, if the threat is neither destroyed nor incapacitated, the observer makes new estimates of its speed and position, new firing data are computed on the basis of these updated estimates, the battery shoots according to these new firing data, and so on until the upper limit of the window of opportunity is reached.

3.2.5 Derivation of the System Attributes

The three system attributes (t_i^{**}, $\Delta\tau_i$, OKP_i) are derived first for each path i of the 10 possible paths. In a second step, an overall probabilistic description of these attributes is given. For any of the 6 paths that fail to transmit the information from the FO to B_1,

$$\Delta t_i = 0 \qquad \text{for} \quad i = 5,\ldots,10. \tag{102}$$

The Overall Kill Probability is equal to zero for any of the paths #5 to 10, but for paths #1 to 4, it varies according to what doctrine is chosen.

The first attribute, the upper bound t^{**}, is assumed to be non-probabilistic. There are several different paths with associated probabilities. The width of the window of opportunity and the overall kill probability depend on what path is used. The relevant attributes to consider are thus the <u>expected values</u> of these quantities.

$$E(\Delta t) = \sum_{i=1}^{4} q(i) \,.\, \Delta t_i$$

$$E(OKP) = \sum_{i=1}^{4} q(i) \,.\, OKP_i \tag{103}$$

From now on, only the expected values $E(\Delta t)$ and $E(OKP)$ will be considered. To simplify the notation however, they will be denoted by Δt and OKP, despite their probabilistic nature.

3.2.6 System Locus

The dependence of the system attributes on the system primitives is shown in Figure 23. It is interesting to note that OKP does not only depend on the primitives w, β and p, but is also computed from the two other attributes t^{**} and Δt (i.e., the window of opportunity) on the basis of the doctrine used. In other words, the primitives are mapped twice in the third attribute OKP, at two different levels.

At each value of the primitive set (w,β,p) corresponds a point in the attribute space $(t^{**},\Delta t,OKP)$. Now consider all the allowable values that the primitives may take:

$$w_{min} < w < w_{max}$$
$$\beta_{min} < \beta < \beta_{max} \qquad (103)$$
$$p_{min} < p < p_{max}$$

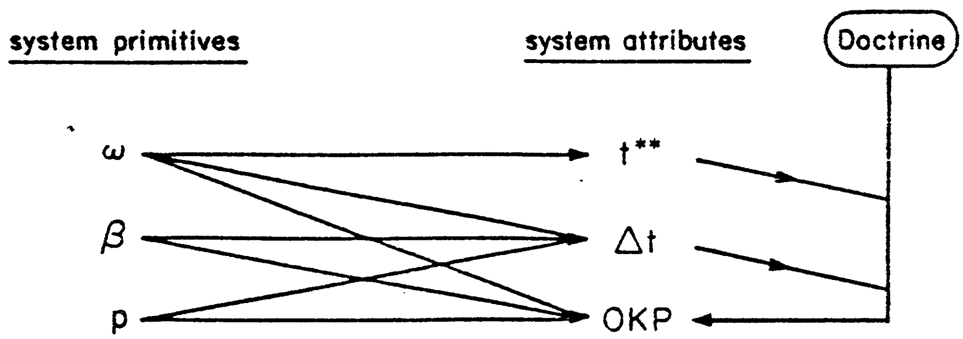


Figure 23. Mapping of the System Primitives into the System Attributes

If the primitives are allowed to vary over their admissible ranges, then the variations define a locus in the attribute space. This is the <u>system locus</u> L_s.

3.2.7 Mission Locus and Measure of Effectiveness

The analysis of the mission is much simpler since the mission requirements can be expressed directly at the attribute level, although it would be preferable to find the mission locus in the attribute space by perturbing the mission primitives. More precisely, the mission requirements reduce to a single condition on the third attribute OKP that translates the level of confidence that is desired by the commander for achieving the fire support mission objectives. If λ is the level of confidence, where $0 < \lambda < 1$, then the mission locus is the region in the attribute space (t^{**}, Δt, OKP) that verifies the inequality:

$$1 \geq OKP \geq \lambda \tag{105}$$

For the present analysis, a simple measure of effectiveness (MOE) has been chosen. Let $v(L_s)$ be the volume of the system locus. Let $v(L_s \cap L_r)$ be the volume of the intersection of the system and mission loci. Then the measure of effectiveness E is given by the ratio of these two volumes (Figure 24):

$$E = \frac{v(L_s \cap L_r)}{v(L_s)} \tag{106}$$

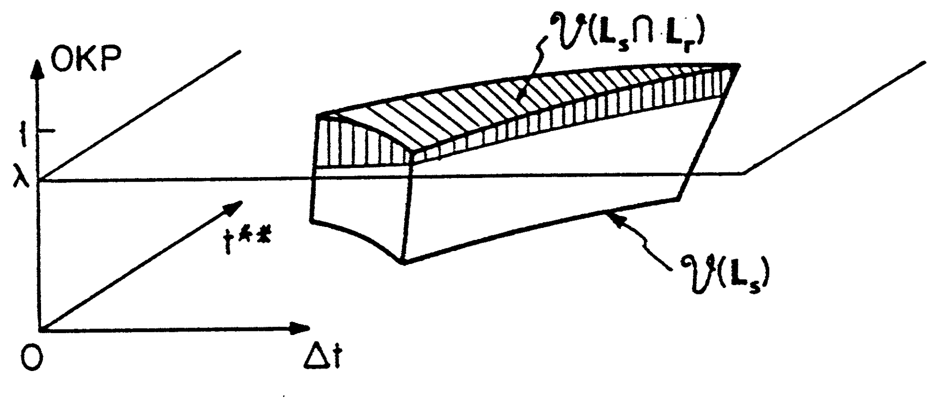


Figure 24. Measure of Effectivenes

3.3 COMPARISON OF DOCTRINES AND OPTIONS BASED UPON THE ASSESSMENT OF THEIR TIMELINESS

3.3.1 The One-Battery Case: Comparison of Two Doctrines

Figures 25 and 26 show the system locus and its intersection (shaded region) with the mission locus for both doctrines. The ratio of the shaded volume over the total volume of the system locus is larger for doctrine 1 than for doctrine 2:

$$E_1 = E(1 \text{ battery, doctrine } 1) \sim .55$$

$$E_2 = E(1 \text{ battery, doctrine } 2) \sim .50$$

When the threat moves rapidly, the window of opportunity is small: it is better to make a good measurement of its speed once and then fire in sequence without taking time to make new estimates, rather than to make an estimate, shoot, make a new measurement, and so on. Therefore, the "LOOK-SHOOT-SHOOT" doctrine has an overall effectiveness which is larger than that of the "LOOK-SHOOT-LOOK" doctrine. Its timeliness is thus better.

3.3.2 The Two Battery Case

When the two batteries B_1 and B_2 are considered, it appears from Fig. 5 that their areas of coverage overlap. Therefore the threat moves first on a part of the road that is covered by one battery (B_1), then on a part that is covered by two batteries (B_1 + B_2), then again on a part that is covered by only one battery (B_2). Intuitively, the probability of kill varies with time, suddenly increasing then decreasing. Assuming a "LOOK-SHOOT-SHOOT-SHOOT..." doctrine, two different options for the fire support commander will be considered:

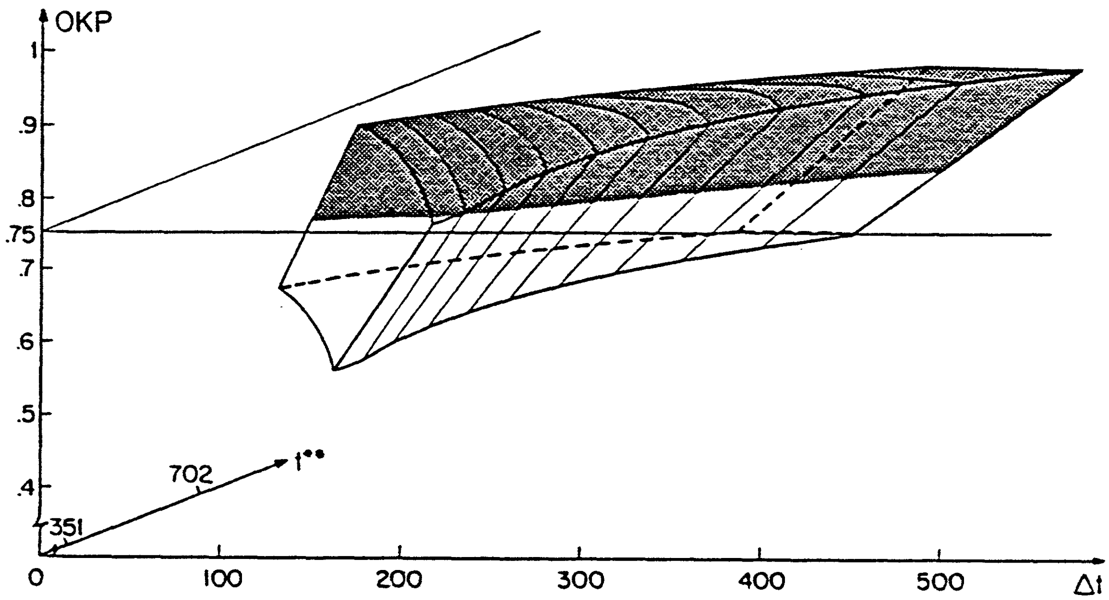


Figure 25. Doctrine 1 (LOOK-SHOOT-SHOOT) System and Mission Loci

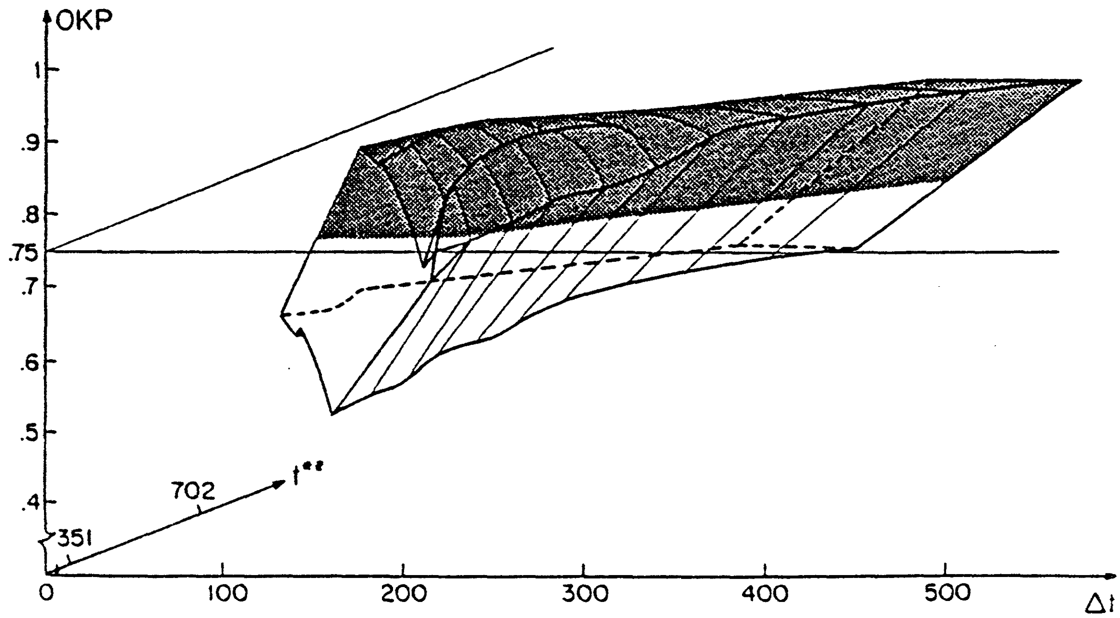


Figure 26. Doctrine 2 (LOOK-SHOOT-LOOK) System and Mission Loci

Option 1: the two batteries shot at the threat independently, each one using the maximum of its own window of opportunity. There is no coordination between the two batteries.

Option 2: Battery B_1 starts firing only when the threat enters the area covered by both batteries. In other words the commander decides not to fire immediately with B_1, but to wait until coordinated fire can be achieved, i.e., both batteries B_1 and B_2 shooting so that their projectiles hit the target trajectory at the same impact time. The global window of opportunity of the system is thus reduced to that of battery B_2. The time interval during which B_1 holds its fire can be used to keep the observer's estimate updated.

Figures 27 and 128 show the system locus and its intersection (shaded region) with the mission locus for both Options 1 and 2. The evaluation of the effectiveness of the system for both options, measured by the ratio of the shaded volume over the total volume of the system locus yields, the following results. Let E_3 be the MOE when Option 1 is used and E_4 when Option 2 is used.

Then

$$E_3 \sim E_4 \sim .6$$

Therefore, both options result in approximately the same value for the effectiveness of the system. The notion of the quality of option is appropriate here. In Option 2 fewer shots are fired than in Option 1. Therefore, coordination reduces costs for the same kill probability. Besides, in Option 2, while the battery B_1 is waiting, the threat does not know it is tracked and will not request any increase in the countermeasures (e.g., enemy jamming), nor start shooting at the blue force positions. In Option 1, this may happen as soon as B_1 starts firing, before B_2 has the opportunity to shoot. The survivability of the overall system is thus higher in Option 2 than in Option 1. Considering the closeness in the

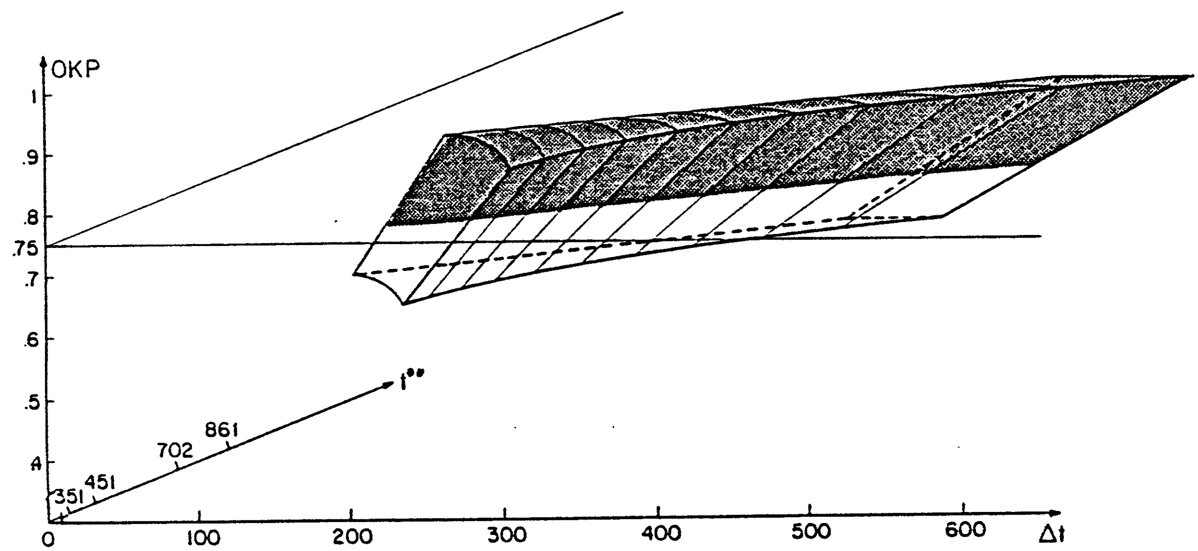


Figure 27. Option 1 (immediate fire without coordination) System and Mission Loci

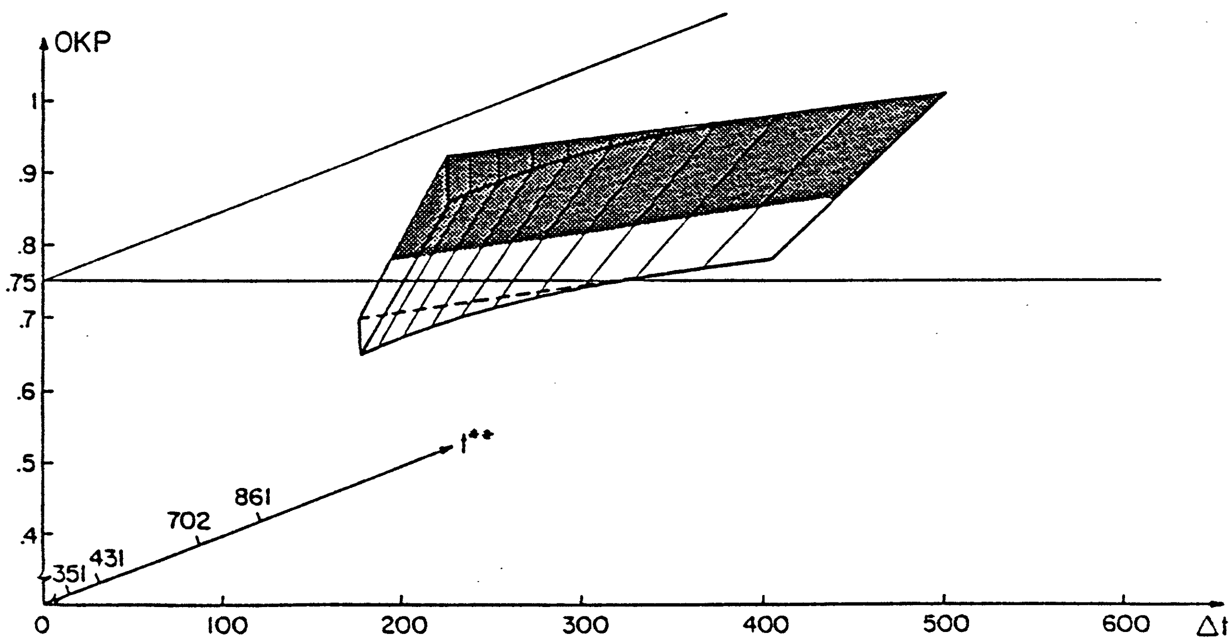


Figure 28. Option 2 (wait and coordinate) System and Mission Loci

value of the effectiveness measure, one can thus conclude that Option 2 (wait and coordinate) is of better quality than Option 1 (immediate uncoordinated fire).

It is important to note that the quality of Option 2, coordinated fire, is better than that of Option 1, although its window of opportunity is much narrower. In fact, the time available is better managed: it is more effective to wait in order to implement a better option. This example shows that the quality of an option and the size of the window of opportunity are two independent characteristics.

3.4 REMARKS

This paper addresses the need for a measure of timeliness as described by Lawson [1981]. Without such a measure, any assessment of a command and control system is incomplete because the information is axiomatically assumed to be "timely", i.e., the issue of timeliness is not addressed. In this paper, the temporal characteristics of the system are treated on the same level as the other performance characteristics. More precisely, time is not taken into account only as a denominator in the definition of rates, but as a fundamental factor with its own special characteristics. The proposed methodology allows the evaluation of a measure of effectiveness embedding all the time-related notions: response time, tempo of operations, uncertainty, quality of options, scenario, and window of opportunity. The elusive concept of timeliness that rests upon these notions can thus be captured and modeled quantitatively.

In developing the methodology, approcahes to important issues on the influence of time in command and control have been introduced. First of all, partial measures of effectiveness allow the quantitative comparison of different doctrines. Some doctrines are shown to make better use of the available time than others and effectiveness analysis can aid in the selection of doctrines appropriate to a given situation. Without such a tool, the comparison can only be carried out through simulations or tests; these are, however, much more expensive assessment methods (Zraket, 1980).

A second point has been illustrated by considering the relationship between different aspects of the system components. While the speed of processing and transmission of data can be improved, the effectiveness of the system may not change if, for instance, the reliability and survivability of the system's components are not also improved. Faster does not necessrily mean better; it can even mean worse, if the increase in speed is gained at the expense of the system's survivability. The proposed methodology allows a decisionmaker to relate a change in one part of the system to a change in another part. The strength of system effectiveness analysis is the ability to carry the assessment on an overall basis: the variations in the features of a given system are not considered separately, but jointly. This yields useful perspectives for future design of C^3 systems. The influence of any modification either in the components, or the organization, or the doctrine, can be evaluated using the proposed measure of effectiveness of the system. Lawson [1981] pointed out the consequences of insufficient attention to timeliness: the system designers' effort is focused primarily on the performance characteristics of the system components (e.g., bit rate or capacity). This methodology shows promise as a tool in the computer-aided design of such systems.

A third point refers to the window of opportunity. A wider window does not mean a more timely system. Timeliness is a more subtle concept and this is the reason why a measure based on the relative window widths is not meaningful. The quality of the management of the time available, i.e., the window of opportunity, is at least as important as the width of the window. Therefore, the size of the window of opportunity is not a sufficient determinant of a system's timeliness. The set of possible options, and their respective quality as responses to the initial stimulus, must also be considered. Desirable responses may be implemented within a narrow window, whereas a wider window may allow undesirable ones to be considered. The feature of the methodology presented in this paper is that it stresses the importance of the quality of options and embeds this, as well as the window widths, in the measure of effectiveness.

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5. DOCUMENTATION

A. Papers in Conference Proceedings

A1. J. G. Karam and A. H. Levis, "Effectiveness Assessment of the METANET Demonstration," Proc. 7th MIT/ONR Workshop on C^3 Systems, LIDS-R-1437, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, December 1984.

A2. P. H. Cothier and A. H. Levis, "Assessment of Timeliness in Command and Control, to appear in "Proc. 8th MIT/ONR Workshop on C^3 Systems, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, December 1985.

A3. J. G. Karam and A. H. Levis, "Effectiveness Analysis of Evolving Systems," to appear in Proc. 8th MIT/ONR Workshop on C^3 Systems, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, December 1985.

Note: Paper A.2 has been submitted to an archival journal for publication; paper A.3 is being revised for submission to an archival journal.

B. Theses

1. Cothier, P. H., "Assessment of Timeliness in Command and Control," MS Thesis, LIDS-TH-1391, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, August 1984.

2. Karam J. G., "Effectiveness Analysis of Evolving Systems," MS Thesis, LIDS-TH-1431, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, January 1985.

C. Presentations/Briefings

Presentations on research results have been given annually at the MIT/ONR Workshop on C^3 Systems. Progress reports were given at the NAVELEX Technology Meetings in Arlington, Virginia (1984) and in St. Petersburg, Florida (1985). Dr. Levis gave an invited lecture (seminar) at the Naval Postgraduate School on measures of effectiveness. He also participated in the Workshop on measures of effectiveness organized by MORS at the Naval Postgraduate School and served as a member of the group on mathematical models and methodologies for MOEs (January, 1985).