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OCCASION: A WORKSHOP ON DEALING WITH UNCERTAINTY

VENUE: U.S.NAVAL POSTGRADUATE SCHOOL
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TITLE: C3 MANAGERIAL DECISION AIDS FOR DEALING WITH UNCERTAINTY...VARIOUS APPROACHS

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**short form: OJCS,C3SEA

ABSTRACT: In Part I the context of military planning is examined from the standpoint of uncertainty. There is a special focus on the uncertainty surrounding the subject of C3. It is argued that military planning is a fuzzy process. Tools being developed in the OJCS to cope with the subject of tactical C3 are introduced. In Part II, case histories of two decision aids which deal directly with uncertainty are presented.

(1-1)

ABOUT THIS PAPER:

As this contribution is intended for a workshop presentation, it deals as much with unsolved problems as with solutions. This dichotomy is reflected in parts I and II. In part I considerable space is devoted to the context of the assessment of military systems with particular emphasis on command and control (C2). Together with communications, all three are known as C3. [A short definition of C3 is the people, processes and equipment through which military operations are controlled and commanded.] My purpose is to portary a sense of the uncertainty which, perforce, pervades any peactime military evaluation. Included in part I is a discussion of the special problems of assessing C2/C3. Part I contains no answers, only the context for an investigation. For a workshop the latter may be as important as the proposals for solutions. In part II, case histories of two methodological solutions to the problem of dealing with uncertainty are presented. Selected vugraph material from the verbal presentation are inlcuded herein.

PART I: UNCERTAINTY IN MILITARY ASSESSMENT

BACKGROUND

Local Influences

In 1970 a watershed article by Bellman and Zadeh appeared in the Journal of Management Science entitled "Decision Making in a Fuzzy Environment". [Bellman and Zadeh 1970] After some very brief considerations of my situation, I came to the conclusion that I need look no further than my immediate surroundings for a fuzzy decision environment. It happenend, incidently, that my position at the time was with the Office of the Chief of Staff of the Army in the Pentagon. Despite the apparent incongruity between the popular conception of the Pentagon as a place where only crisp decision making takes place, it is in fact a place where people must cope with uncertainty on a daily basis. The peace time decision maker in the Pentagon does not deal with circumstances on a particular battlefield. He deals rather with what might happen on some battlefield in a war he hopes will never be fought. Understanding that the Pentagon was, and remains, a fuzzy environment served not only to introduce me to fuzzy set theory, but as importantly, to orient my perceptions as to the true nature of the surroudings.

Prior to reading the Bellman and Zadeh article I probably adhered to the classical approach to the elimination of uncertainty. This is the trio of hard work, closer observation, and above all, more data. When the world about you is fuzzy, then only hard work remains from the foregoing trio. More fine grain examination only exacerbates the fuzziness. In fact, theoretical arguements exist in the fuzzy set literature which gainsay the importance of more data. In fact, fuzzy set theory predicts that only reformulation of the problem can further reduce fuzziness once some limit has been reached. [Asai 1977]

As I examined my environement further, I observed that it was not only fuzzy, but that is also was wont to operate on subjective judgements. This was particularly true of "military judgement" for which many unnecessary and defensive apologies continue to be made. In fact subjective judgement appeared to be a standard method of coping with uncertainty. It appears to be a legitimate way of coping with a number of common difficulties in environments such as the Pentagon. For example, all the following create a climate of uncertainty:

o A firm requirement to predict what sems to be the free future and plan accordingly.

o Performing legitimate forecasting in the presence of subjective, biased, or indeed erroneous information.

o Incorporating political aspects of a problem.

o Producing a plan whose inputs are a marriage of scientific certainty and guesstimated exptrapolation and missing information.

(I would hasten to add that we do not consider the term subjective synonomous with politically motivated action.)

Coping with Ucertainty in Assessment

The option of no decision due to uncertainty is not available. How then to deal with this climate of extreme uncertainty? At this juncture three divergent paths are open.

o One can try to remove the subjectivity; and otherwise ameliorate the uncertainty in the inputs. (The result could be called factoids. [Datamation 1986]) The "objectivized" data is then subject to a variety of tools, many of which may be subjective. This is the path most often followed. Common examples include programs which are based on weighting constituent characteristics, or goal programming.

o One can also try to operate precisely on the subjective inputs and imprecise data. This path is less often followed. Examples include elaborate linear programs based on Delphi input, and multi-attribute utility theory approaches.

o One can also try to operate scientifically, but not necessarily precisely, on subjective inputs. This path seems least often followed. Examples include some expert systems, fuzzy sets, and evidence theory.

In fuzzy sets I found a suitable tool for exploiting the third path. A good portion of this paper will recount the case history of a major attempt to deal with uncertainty using fuzzy sets. In particular, a computer code to aggregate (roll-up) information, based on the operational status of units expressed as color labels, will be treated. Other case histories will be sketched including one which uses a form of imprecisely specified multi-attribute utility theory.

Because any approach taken must be directly available to Pentagon action officers and analysts, any solution to dealing with uncertainty must be directly available on a local area computer network and employ techniques which are transparent to the user and avoid the need for precise and highly granular data.

THE SPECIAL PROBLEM OF EVALUATING MILLITARY C3

The Context

The triad of command and control plus communications (and sometimes intelligence and/or computers) presents a specialized challenge to dealing with uncertainty. C3 represents infra-structure. The command control portion (C2) especially can only really be judged by what is causes other elements to do, or by what it prevents from happening. Thus, estimating the effect of future C3 programs entails forecasting the uncertain performance of the weapons and people controlled, and their employment against a projected (and therefore uncertain) foe.

Against this fabric of uncertainty, the evaluation of C3 must take place. The analyst must decide whether the proposed C2/C3 schemes with their own degree of uncertain performance, will not only guide the forces, but also work either to limit, or to enhance, the uncertainty of the battlefield. The estimation process therefore does not take place in the abstract. Thus, we can understand the functioning of a communications network perfectly, and still he highly uncertain as to the degree to which it supports the main objectives; be they keeping the peace or waging the war. In this estimation process one also confronts the problem of deciding both what is probable, and also what is possible.

To my way of thinking both the actual functioning of C2 systems in which human decision enters, and the peactime evaulation of such systems, are paradigms of approximate reasoning. They are, as well, quintessentially, fuzzy processes. This paper will now focus on the peacetime managerial process of evaluating C2/C3 systems. The difficult question of how C2/C3 systems behave when employed in an active defense situation is subsumed in the prior evaluation.

A Distinction

Before moving to a closer examination of uncertainty in the evaluation of C2/C3, and the case histories, the focus of this paper needs to be narrowed still further. The basis of the narrowing is a distinction between strategic and tactical C2/C3. Loosely speaking, we may assume that:

o Strategic systems involve the global reach of the armed forces, and what is more they have come to be identified rather exclusively with the forces that deliver nuclear weapons.

o Tactical systems involve more localized combat against a variety of threat postulations. Whereas the strategic forces are pre-configured for a rather specific role against a defined threat, the tactical forces represent rather more a collection of resources which can be rapidly molded into the configuration needed to oppose a generalized threat.

Figure 1 summarizes the posited role of tactical C3.

[FIGURE 1 GOES HERE]

Strategic C3 System Uncertainties

Analysis of strategic C3 systems, which forms the basis of that input to the evaluation cycle, is quite scientific and precise compared with analysis of tactical C3 systems. In order to understand this, one may think of a spectrum in which we move from manning the equipment to equipping the men. The C3 systems associated with the former are strategic. They tend to be equipment oriented, while the latter are associated with tactics and so involve a considerable amount of real time human decision making.

- SETS BOUNDARY CONDITIONS FOR COMBAT
- A SOURCE OF COMBAT OBJECTIVES AND DIRECTION
- CHANNEL FOR PROVIDING RESOURCES AND RESUPPLY
- ARGUABLY THE SOURCE OF THE SELF-ORGANIZATION PRINCIPLE FOR COPING WITH CHAOS IN COMBAT

Figure 1: Summary of Tactical C3 Roles

While there is uncertainty in projecting the performance of strategic systems, one is dealing chiefly with the probability that concatenations of systems will perform as promised. This entails modelling equipment performance, natural phenomena, and the consequence of certain military decisions, e.g. nuclear detonations. We are pretty good at this kind of analysis. Although the C3 would function in real time, the C2 is analyzed in "virtual time" by exhaustive procedures that test all contingencies. Then, if it is ever needed, the C3 process would be simplified as follows.

World-wide sensing systems would report and be centrally evaluated so as to produce a recommendation to the President. Upon his decision, the function of the strategic C3 systems becomes that of guaranteeing delivery of his decision to the fighting forces. Because of time constraints, the forces then exercise one of many options which they have previously been directed to use. Analysis thus reduces to only one of the triad, namely communications reliability. The real uncertainty lies in the intelligence estimates on which the strategic scenarios are based. Worst case scenarios are popular. Since they generally cost too much, the finally identification of uncertainty in the strategic evaluation case maps over into the uncertainty of risk assessment.

Tactical C3 System Uncertainties

By their very design tactical C3 systems are intended to be generic resources. From these resources, a commander's staff will build a temporary configuration to meet the current requirements. Thus, the specific role any C3 system may play in a combat scenario lies somewhere within a large envelope of possibilities. Tactical systems do have specific functional niches: for example, mobile subscriber systems, satellite HF terminals, However, how specific C3 systems will relate to other pieces of tactical gear can be uncertain. In choosing these examples I have deliberately biased the problem toward evaluation of joint tactical operations involving the land/air battle. It is a far less straigtforward problem than say, tactical shipboard C3.

Unlike strategic communications, where there is a demonstrable one to one correspondence between outcome and system performance, no such assurance attaches to tactical communications gear. In fact, tactical C3 analysis is often replaced by communications path analysis in analogy to the strategic case. One can progress from pure communications systems, through nearly automated sensor systems, and various display and decision aiding C2 systems such as are found aboard ships, to C2 systems having a considerable human element. At each step the uncertainty in evaluation increases.

In place of statements about the degree to which outcomes are influenced, one finds shibboleths. Three of the most common are "timeliness", "accuracy", and "quantity" of the data transmitted. Thousands of messages are transmitted for a handful of combat outcomes. In the face of uncertainty the designer strives to transmit everything. While timely and accurate data may be useful, quantity can be positively counter productive. Resilience of C3 systems to the disruption caused by electronic warfare is a better measure than any of the previous three. In a sense jamming introduces third order uncertainty into the analysis. Restating the chain of uncertainty which relates the evaluation of tactical C3, we have following worst case sequence.

C2/C3 systems of uncertain performance influence...

the performance of combat in uncertain ways...

against an uncertain foe..

The Basic Source of Uncertainty in C2/C3 Analysis

The raw material of the C2 process are future event chains. Their creation and control is the objective of C2. Communications are an element in the process. How then to assess uncertainty in systems designed to control (and sometimes create) uncertainty?

The simplest method is simply to eliminate uncertainty by fiat. One assumes the uncertainty away either in whole or in part. Thus, we decide that C2 systems will perform as indicated; that they will influence combat as advertized; and that the combat will take place according to a prescripted (and therefore certain) scenario. Only the degree of success is in doubt. The arguement goes bottom up, and follows the line of the fable that:

"for want of a nail the shoe was lost",

"for want of a shoe the horse was lost",

.....

"...the kingdom was lost"

The problem with the foregoing is that the projection may be irrelevant. The usual question is "did the message get through", which is success of sorts. However, for evaluation purposes, the question is rather "did the message have any bearing on the outcome?"

At the other extreme is the response which concatenates all the worst case scenarios that the mind of the analyst can dream up. This leads invariably to huge and expensive investments in C2/C3. Since the worst case sequencing resulted in systems which may have prevented something from happening, how is that outcome to be judged. Congress incidently may then assume that since nothing did happen, that nothing would have happened! The hapless decision maker then cuts back his worst case sequencing. At that point he enters the murky waters of risk analysis. In fact evaluation becomes nearly the same as risk assessment.

The case histories and methods shortly to be reported choose a middle ground. They are based on the desire to make the most of informed military judgement. That judgement is to be bolstered by techniques which directly address the fundamental uncertainties, nay chaos, of combat. The appoach is two tiered: a suite of computer based methodologies for purposes of strategic and tactical C3 system analysis in plausible scenarios; and a suite of analysis programs for assessing aspects of C2 which use both real and simulated data. Figure 2 summarizes the special assessment problems of tactical C2.

[FIGURE 2 GOES HERE]

- C2 IS A SECOND ORDER EFFECT WHICH COMPOUNDS UNCERTAINTY
- C3 HAS A PARADOXICAL ROLE TO BOTH ELIMINATE AND ENHANCE UNCERTAINTY IN COMBAT
- C2 HAS THE UNCERTAINTY OF ENORMOUS COMPLEXITY AND COMBINATORICS
- THERE IS NO THEORY OF COMBAT OR C2
- C3 ASSESSMENT INCLUDES THE ADDITONAL BURDEN OF RISK ASSESSMENT
- THE ESSENCE OF C2 IS CONTROL OF FUTURE EVENT CHAINS

Figure 2: Some Special Assessment Problems of C3

Avenues to Assessment of C3

It is necessary first to review the generalized options open to the analyst and decision maker faced with the task of assessment. They may be categorized as follows:

- o Computer Simulation and Interactive War Games
- o Field Tests/Engineering Tests/Training Exercises
- o Analytical Solutions
- o Expert Judgement

The trouble with the first two is rooted in a classic design of experiments problem. Because C2 changes outcomes, considerable statistics have to be accumulated for any configuration. When one adds the fact that combat usual'y destroys elements of the C3 infrastructure, the universe of outcomes is even larger. In theory one then repeats the process for each C2/C3 configuration. Practically speaking, this is usually impossible. Some nominal configuration, for which no damage to C3 is permitted, is usually analyzed.

For an analysis of the influence of message traffic we have developed a tool called C3EVAL in which one module models a system of command nodes. [Robinson, et al 1986] A separate module models combat. Both modules are straightforward in themselves but can generate very complex interactions. The model is useful for first order assessment of major changes in organizational structure. Coupling between combat outcomes and message traffic can be surpisingly weak according to this model. Rather, the overall effect of the higher headquarter seems to be the following: to set and adjust boundary conditions for combat; to supply resources; and to occasionally make area resources available locally, e.g. air strikes.

Under development within another branch of OJC3 [J6] is another major high level model called

JAWS for Joint Analytical War Gaming System. It has C2 built into it. It is being written in C and will be object oriented code. Both the foregoing design choices are greatly facilitating development of a simulation in which the interaction of combat, planning and C3 can be modelled.

Turning to the third option we find that the trouble is this. There is no accepted theory of combat, let alone C2. Everything is largely empirical. Fragmentary theory elements such as Lanchester Equations are stretched to the limit in simulations. In another semi-analytical solution one finds that the designers dispense with C3 entirely and instead, collect thousands of "factors" about consumption, estimated attrition, rates of advance, etc, etc. These are then put into some kind of computer program which does bookkeeping on the factors for a totally prescripted scenario. Periods covered can run to weeks. Such an approach might be trustworthy for trench warfare, but little else. It is yet another example of worst case analysis. Communications theory does, however, permit analytical solutions. Unfortunately, linking communications survival to combat outcomes encounters the difficulty in the preceding paragraph.

For theatre level analysis of C3 our approach has been two pronged: first, develop missing analysis tools for C2; second, cope with expert judgement where it seemed the only reliable input. Our challenge was then the need to use expert/subjective judgement in an analytical fashion, and to deal analytically with envelopes of uncertainty.

The rest of this contribution will outline steps we have taken to develop tools to expand anaylsis horizons, and to deal with subjective information. Everything which is listed falls under the general umbrella of the 'electronic workbench', which is our term for the widespread use of a local area network of computer workstations by the action officers and the analysts. We close Part I with a list of currently [winter 1986/87] active tactical C2 analysis efforts which we sponsor. Figure 3 summarizes the foregoing discourse.

[FIGURE 3 GOES HERE]

Analysis Tools

o Analysis of tactical C2 connectivity and systems configurations using a tool of geographers and sociologists called q-analysis. [Dockery 1984] It is based on an analysis of simplicial complexes. It has been shown to be isomorphic to graph theory but more useful when the problem lacks intial structure. The concept of a structural 'backcloth' arises, over which generic traffic flows. The backcloth 'permits and allows, but does not require' transactions to occur. [Gould and Johnson 1986]

o Through the stochastic integration of Lanchester Equations, we are gaining an appreciation of the uncertainty masked by deterministic solutions. White noise is added to the usual Lanchester equations. Outcomes show considerable variability. Our working hypothesis is that C2 acts to control the noise of combat. [Cobb and Harrison 1986]

o Development of measures of effectiveness for C3 from Petri Net analysis. [Moore 1986]

o Exploration of the catastrophe theory manifolds as generators of a decision landscape. This work has proven to be a very rich source of results. [Woodcock 1986] Efforts to date have

- Statistically fitted a Cusp manifold to simulated combat data;
- Embedded C3 and combat conceptually in a Butterfly manifold;
- Found the Double Cusp manifold to be a source of extended Lanchester Equations;

- STRAIGHTFORWARD PARADIGMS RECURSIVELY APPLIED

- MODERN MATHEMATICS MADE TRANSPARENT VIA COMPUTER SCREENS

- INTRODUCTION OF THE ELECTRONIC WORKBENCH

- STUDY COMPLEX INTERACTIONS BETWEEN SIMPLE COMPONENTS

Figure 3: General Methodology Guidelines for Dealing with Uncertainty

- Explained C2 in low intensity conflict; and

- Discovered chaos in the coefficients of the time dependent Cusp equations when time is treated discretely. (Incidently, the last was an alternate abstract to this meeting.)

o Exploration of cellular automata as a model of C2/C3 and combat interactions. This work should address the large number of ordinary differential equations (ODE) needed to address certain combat modelling problems. (This work is just beginning.)

o Work in using more general non-linear, time dependent equations for combat which include diffusion and convection terms, and which also embed Lanchester Equations. Results show for the first time the spread of formations on the march, and attrition as forces close. Control of the integration may involve the use of fuzzy data. An extensive partial differential equation (PDE) formulation is involved. [Protopopescu et al 1987]

o The C3EVAL nodal model already alluded to.

Figure 4 summarizes the foregoing in terms of the special uncertainties addressed by each.

[FIGURE 4 GOES HERE]

Decision Aid Approach

o **Construction and use of the Performance Assessment Review (PAR) roll-up program.

o **Introduction, use and extensions of Imprecisely Specified Multi-Attribute Utility Theory (ISMAUT). [Scherer 1986]

o Development of the Modular Command and Control Evaluation Structure (MCES), which is an approach to C3 architecture comparison using a robust but simple information processsing paradigm. With the aid of heuristics, it steps the user through successively

- Q-ANALYSIS FOR UNCERTAIN STRUCTURE
- STOCHASTIC L.E. FOR RANDOM EFFECTS
- PETRI NETS FOR UNCERTAIN MOES
  AND
  FUZZY SETS FOR OPERATIONS ON MOES
- CATASTROPHE THEORY FOR PRODUCING A LANDSCAPE CONTAINING ALL THE UNCERTAINTIES
- CELLULAR AUTOMATA FOR THE UNCERTAINTY OF TOO MANY ODEs
- NON-LINEAR PDEs FOR THE UNCERTAINTY OF MOVEMENT IN TIME AND SPACE
- C3EVAL MODEL FOR THE UNCERTAIN CONNECTION BETWEEN MESSAGES AND COMBAT OUTCOMES

Figure 4: Summary of Analysis Efforts Linked to the Kind of Tactical C3 Uncertainty Which They Address

deeper layers of detailed analysis for each function in the information processing paradigm. [Sweet 1986]

o Investigations into the application of expert systems software to the problem of introducing and tracking C3 requirements as they pass through the Planning, Programming and Budgeting System (PPBS) cycle.

o Introduction of a suite of highly interactive multi-goal/attribute computer programs. [Tilman and Hwang 1986]

**Case Histories follow.

Figure 5 summarizes the foregoing in terms of the special uncertainties addressed by each.

[FIGURE 5 GOES HERE]

Before taking up the case histories, a word about the fundamental difference between the first two entries on the preceding list is in order. The first of these, the PAR roll up, adopts a strictly bottom up approach. The programming operates such that it 'forgets' the details of the constituent processes once a roll up is complete. It remembers only key elements in the process. These we call simply, 'the drivers'.

The second of the two, which is ISMAUT, is a strict top down approach to a decision aid. Its goal is the construction of dominance digraphs from an input matrix of alternatives and utility attributes. Its programming operates such that it 'remembers' all details of the interaction between, and within, all levels. At all times the algorithms seek to trade-off all available information, and all designated hierarchial clusters of information.

Distinctions are also observed in the way the two deal with uncertain data. The PAR program

- PERFORMANCE ASSESSMENT USING FUZZY SET LOGIC EMBEDDED IN A COMPUTER PROGRAM FOR UNCERTAINTY IN LINGUISTIC ASSESSMENTS

- ISMAUT FOR UNCERTAINTY IN SPECIFYING UTILITIES

- EXPERT SYSTEMS FOR THE UNCERTAINTY IN WORKING BACKWARD FROM GOALS

- MULTI-GOAL & -ATTRIBUTE PROGRAMS FOR UNCERTAINTY IN CONFLICTING BOUNDARY CONDITIONS

Figure 5: Decision Aiding Tools Linked to the Kind of Tactical C3 Uncertainty Which They Address

needs little in the way of numerical data, working instead with linguistic variables. For ISMAUT, on the other hand, we need numerical information but only in the minimum form of a rank ordering.

PART II: CASE HISTORIES

PROBLEM STATEMENT

The problem at hand is to present a portrait to the Joint Chiefs on the world wide status of the degree to which C3 support the global defense mission of the US government. In order that improvements can be directed where shortfalls have been uncovered, some linkage to programmatic dollars must be made. We should avoid a negative focus on the deficiences in the capability of C3 to provide support. Results of the foregoing assessment process guide decision makers in allocating constrained budgets for C3 infrastructure.

THE PERFORMANCE ASSESSMENT (PAR) ROLL-UP PROGRAM

The Specific Challenge

Base a global C3 evaluation scheme on information about C3 capabilities to support missions. Use the information on capability as a kind of hinge so that we can look at capability statements as pointing in two directions.

(1) Capabilities can be tied to specific expenditures for equipment, or changes in personnel or organizational processes.

(2) Estimates of the operational status of a particular mission can be inferred from the operational status of the requisite capabilities.

Automate the evaluation process to account for items (1) and (2) above which, heretofore, had been manual.

We can examine the second point further. If we knew how well C3 supported the missions, for which a theatre commander is responsible, and also the degree to which he depended upon them, then we could presumably decide just how well theatre operations were supported by C3 assets. One more level of aggregation, based on like estimates, would infer global performance from theatre level performance.

Details of the PAR Process

C3 capabilities are phrased in terms of the ability to do something usually associated with C3, e.g. "look more than 30 kms" or "process more than 100 messages per interval" or "react within 5 minutes with a decision". Inability to meet such requirements are translated into equipment deficiences or organizational difficulties, e.g. a radar which is not powerful enough, or a command staff with the wrong mix of people. Two judgements can be made about these capabilities.

- o What is the operational state of the capabilities in a given mission and theatre context.
- o To what degree does the next hierarchial level depend on each of the constituent elements at the preceding level.

Usually, the aggregation process occurs within the context of a theatre of operation until that level is reached. Moreover, four separate hiearchies, depending on the type of military conflict anticipated, are involved: Peace-crisis, conventional warfare, and two states of nuclear war. Each war posture is further evaluated for the current budget year and for the FYDP (or five year defense projection)! Some numbers are also instructive.

- o Five to seven capabilities on average are involved for each mission
- o Seven to ten missions on average support the theatre
- o There are ten theatres** world wide.

**Theatre is used herein as shorthand for the ten unified and specified commands which cover the world both functionally and territorially. Each has a CINC (command-in-chief).

The number of combinations, including further sub-structure not yet discussed, approaches 100,000.

We summarize as follows.

(Sets of C3 capabilities aggregate to

Mission support capabilities.

(Sets of C3 mission capabilities) aggregate to

Theatre support capabilities.

(Sets of theatre capabilities) aggregate to

Global support capabililites.

In figure 6 the aggregation process is shown graphically.

(FIGURE 6 GOES HERE).

Actually the process is bit more complex. At both the mission and theatre level, there is sub-structure in the form of sub-levels which correspond to the intensity of the conflict supported. These range from four to six. Additionally the theatre aggregation sub-levels may include more than one mission sub-level! Finally, the mission sub-levels have some horizontal sub-structure as well. The C3 capabilities support is more narrowly focused onto support for three (and sometimes four) C3 sub-functions of the missions. These are called functions and were respectively:

MONITOR *DECIDE* *EXECUTE* *(RECONSTITUTE)*

This introduces an intermediate need to 'roll-across' at the mission level before aggregating to the theatre level. (It also provides the opportunity of maintaining the distinction as well.) Sometimes Super-Missions, equivalent in level to theatre, are also created by aggregating

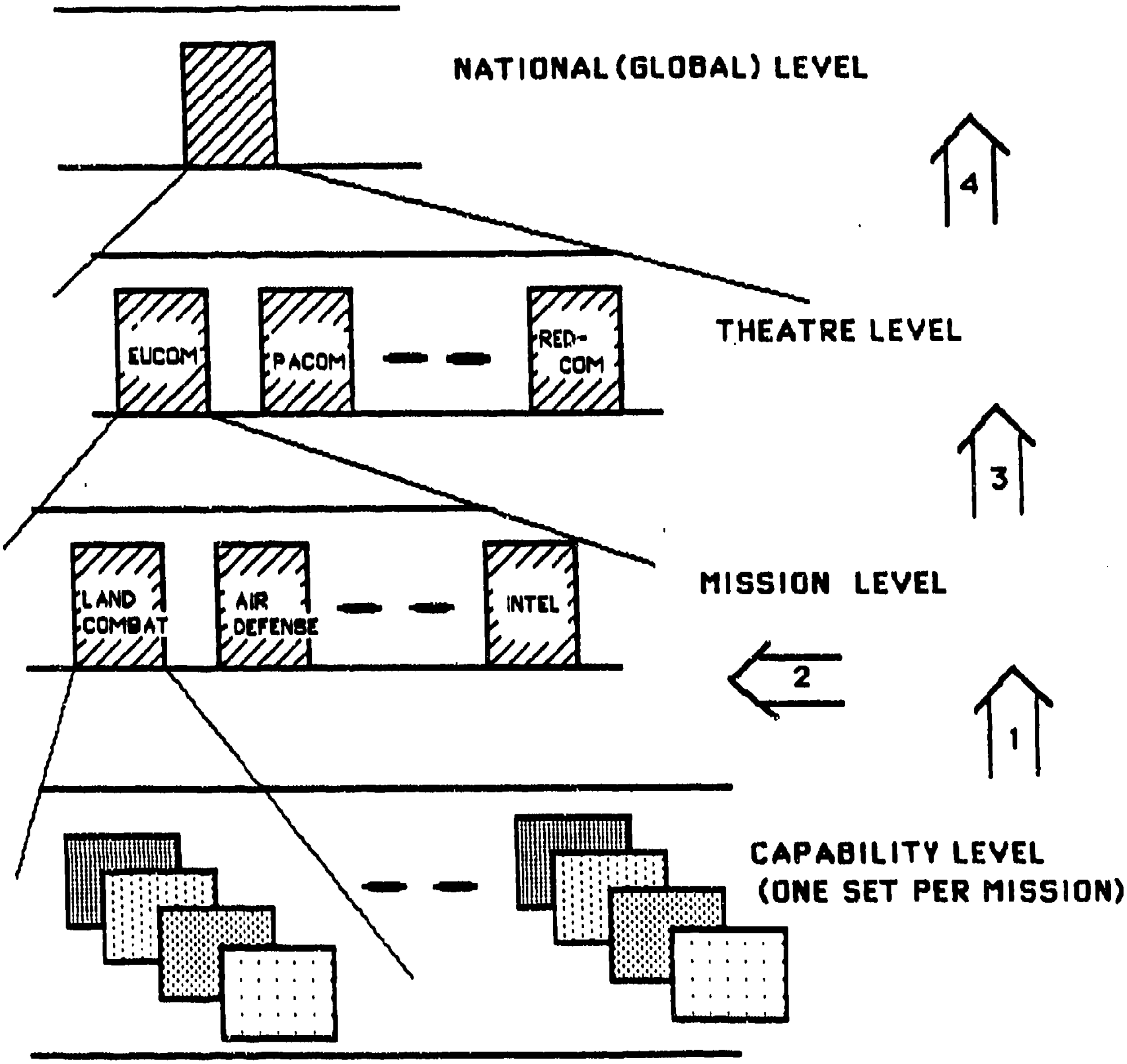

Figure 6: Basic Four Level Hierarchial Structure
[Capabilities -->Missions-->Theatres-->Global]

combinations of missions over all theatres. See figure 7 for a summary.

[FIGURE 7 GOES HERE]

A Fuzzy Roll-up Program

The search for a proper mathematical framework upon which to base a automated decision support package began with the basic input. That data was judgemental in nature and expressed linguistically. Operational readiness statements about the C3 capabilities were often found to be expressed according to color labels. A GREEN capability was operational without qualification. A RED one was out of commission. YELLOW, and the various combinations of intermediate colors, were all somewhere in between. (Two additional limit colors, called SUPER-GREEN and SUPER-RED, were also added.) Moreover, the linkage between levels was usually stated in terms of some degree of dependency like ESSENTIAL, or IMPORTANT, or NOT VERY IMPORTANT.

A computer program was evolved which used the linguistic information directly in the following manner. From the set of color labels for operational readiness of a capability to support a mission function, a possibility distribution was constructed. In the display following is an example of such a distribution expressed as a percentage.

CAPABILITY	SG	GR	Y/G	YEL	R/Y	RED	SR
ABILITY TO LOOK 30 KM	--	--	--	30	85	45	--
SEND MESSAGE IN 5 MINUTES	--	75	45	--	--	--	--

For each capability, the computer program, through a series of menu driven screens, solicited these possiblity distributions. Data was collected in the field at meetings between teams from the OJCS, C3SE office and local C3 support staff at each CINC Hq. The aggregation program was then run by the data collection team to show the local staff the aggregated results. CINC data was merged in Washington.

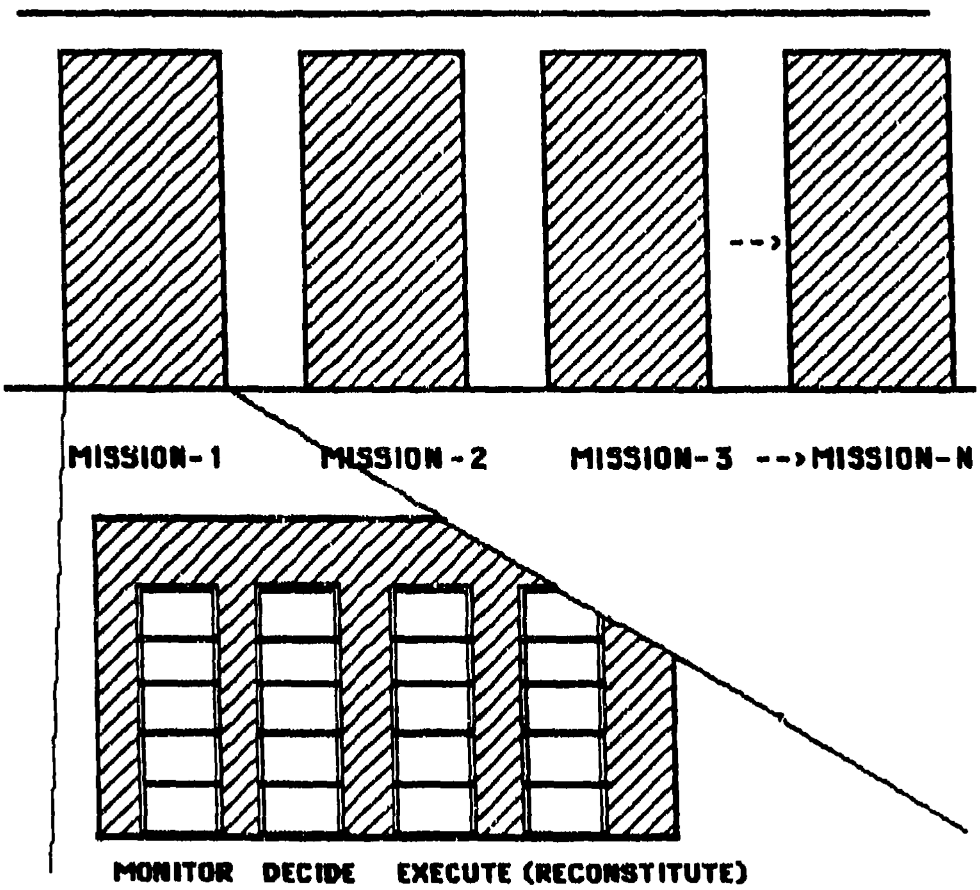

Figure 7: Detail of Mission Sub-Structure Showing Conflict Intensity Sub-Levels

Between each level, (and within the mission level), a fuzzy set set of dependencies was also constructed. Although the program works with any set of dependencies and associated fuzzy membership functions, a single set of dependencies (for each level) was used in the first field test. Thus, the dependency of the various sub-functions of a mission on the supporting C3 capabilities might be expressed as

(ESSENTIAL|0.85, VERY IMPORTANT|0.75, AVERAGE|0.6, MODEST|0.3, NONE|0.1).

For each capability a matrix is constructed whose rows are the dependency labels and whose columns are the color labels. Entries are the possibility distribution point values. Thus, we might have the following. Note that no special significance should be attached to the rows of zeros. In general the matrix may be non-zero anywhere.

MATRIX FOR CAPABILITY C1

	SG	GR	G/Y	YEL	Y/R	RED	SR
ESSENTIAL		-----------0------------					
V.IMPORTANT	0	0	0	.30	.85	.45	0
AVERAGE	0	.90	.80	0	0	0	0
MODEST		-----------0------------					
NONE		-----------0------------					

(In practice no more than one row was usually ever filled in.)

A set of capabilities was then combined using the fuzzy AND/OR operation between the matrices for each capability. Computationally this corresponded to selecting the maximum value for each row-column entry. Thus, where $N = C_1 \cup C_2 \cup \ldots C_N$,

$$n_{ij} = \mathrm{MAX}[c_{ijk} : k = 1, N].$$

But N is only an intermediate matrix result since the row labels are themselves a fuzzy set. Kaufmann calls this a conditioned fuzzy matrix. [Kaufmann 1975]. In order to get the final result the fuzzy set corresponding to the row labels must be combined with N. Formally, the operation is represented for each element in the resultant row matrix M_i for the mission sub-level is as follows, where D is the row matrix of dependency labels,

$$m_{ik} = \mathrm{MAX}_i[\mathrm{MIN}[d_{ij}, n_{jk}]] \qquad k \ [\text{color set}]$$

One last step remains. A projection operator is applied to M to get the largest value row entry. The resultant color is the label associated with that entry. In practice, ties were common. To break ties, the screen prompt asked the user whether he was a PESSIMIST or an OPTIMIST. If the former, the color label closest to RED was chosen; and contrarywise for the latter. Figure 8 summarizes the foregoing.

[FIGURE 8 GOES HERE]

At this stage the program has rolled up one set of capabilities that support but one conflict intensity sub-level of a single function of one mission in a theatre for one war posture, and one of the two bugetary horizons. The next step is to complete all three (four) mission sub-functions for all mission sub-levels. In order to achieve the roll across aggregation, a matrix is constructed for each sub-level using the row matricies M_i discussed above. The process may be either manual, or automatic. If the latter, a word of caution is in order. There

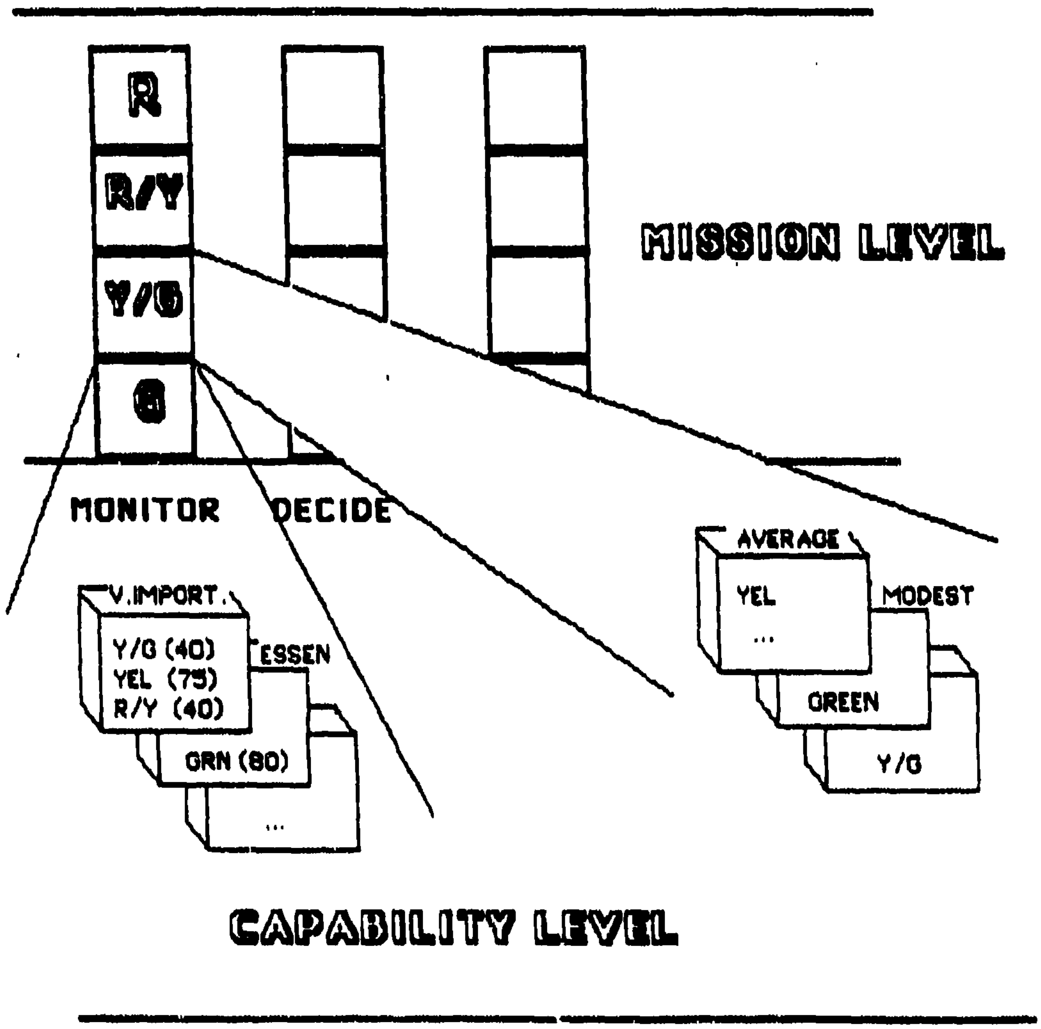

Figure 8: Schematic Illustration of C3
Capabilities Rolling Up Into
Mission Sub-Levels

is a limit to the number of fuzzy operations which can be concatenated before the result is meaningless. You might say that the orginal input data is 'used up' in a fuzzy program. The reason is that after we aggregate to a color we have made a decision which reduces the initial fuzziness. Working with the initial results, we opted to let the process continue automatically. Although no new color information was input, a new and explicit set of dependencies of the mission on its sub-functions was always required as input.

The internal algorithms rolling across the functions are the same as those doing the intial roll up, and are the self-same used to roll up from mission to theatre level. (In the latter case, multiple sub-levels of a mission usually roll up to a single theatre sub-level.) In initial trials the automatic feature was used with a new set of theatre-mission dependencies. Further roll up to global level required new input as to the possibility that the aggregate color was something else; plus a still further set of theatre-global dependencies was needed. Significant new information also enters in at the theatre level in the form of risk assessment. For instance coping with a support mission that has deficiences in its C3 support when weighed againt all other missions. Likewise risk assessment is involved in making global trade-offs among the CINCs.

Features of the Fuzzy PAR Roll-up Program

In its final form the computer program permitted some limited options and dialogue. Although only disjunctions were permitted, a menu of disjunctions taken from a paper by duBois and Prade were available. [duBois and Prade 1984] These worked to weaken the disjunction. Further, some limited statistics about entries in the data base were possible.

In terms of dialogue the user can ask to have a color changed. The program responds by asking whether he wishes to change any of the dependencies or possibility distributions. If not, there is no change. It is also possible to isolate which capabilities drove a result which is not green. Moreover, since each capability which is not green, is linked in the data base to a deficiency and line item program, it is possible to list those deficiences which must be changed to improve the operational readiness, and hence the color.

The program has also had a profound impact on budget perceptions. Previous computerizations, and all manual aggregations, involve a 'bean counting' exercise for which the amelioration of any deficiency always results in improved readiness. With the fuzzy program it is quite possible to have a situation in which the following occurs. A roll-up is green even though 80% of its input is red. Conversely, a roll-up is red even though 80% of its input is green. It all depends on the chain of causality. This can never happen with conventional linear approaches. The fuzzy program effectively *quantizes* the budget process. Almost all programs causing a resultant color must be fixed, or the user must manually intervene, before the readiness color changes. This leads to a concept of line item program portfolios containing suites of C3 items requiring change rather than individual item changes.

Verification of the Results

The automated roll-up was compared with manual results from current and previous years. In all but one case it matched the earlier outcomes using the simplest of the disjunctive operators. Hand computations were done to check the mechanics of the program. Results of the aggregation have been accepted by the users.

Management Implications of Using the Fuzzy Per Program

There were several interesting changes introduced into the management of the aggregation process.

o Gaming of input to reflect wishes, as opposed to actual needs, was substantially reduced since the automated program treated all computations equally.

o Merging of results from all CINCs was easier since all were directed to provide the same kind of input to the same program.

o Dependence on a local contractor, who had heretofore done both data collection and manual roll-up, was reduced to data collection and input. The military managerial decisions associated with the aggregation were again brought back to the OJCS.

o The computer program now permited one officer to manipulate the entire data base affording a previously unknown degree of consistency.

o The data base is available in a form permitting further statistical investigation.

o So called 'what-if' excursions, in which capabilities are enhanced, is now easy to do where, heretofore, the aggregation was a one shot process which could not be repeated.

Future Development of the PAR Program

The program now in BASIC is being rewritten in PASCAL and will be tied to a Wang computer data base using the relational data base language PACE. Expert system techniques will be added to make the program more interactive in determining how to change colors. Moreover, a portion of the PAR process by which national goals are eventually interpreted in terms of C3 capabilities, which had not been previously automated, will be the subject of an attempt to use goal directed artificial intelligence techniques.

Summary

A computer program, embodying fuzzy set computational algorithms, aggregates subjective input data in linguistic form over four hierarchial levels to aid in the production of a national assessment of C3 support.

ISMAUT

Background

The somewhat Biblical acronym, standing for 'Imprecisely Specified Multi-Attribute Utility Theory', represents another approach to Performance Assessment. ISMAUT is actually complementary to the fuzzy set based methodology just described. It begins with the identification of line item programs that can be used to fix perceived C3 deficiencies. The problem at hand is then the rank ordering of the various programs. The challenge in using ISMAUT is to select and quantify those utilities which will assess the degree to which the individual line item programs will enhace the national C3 support posture.

ISMAUT is a product of a group at the University of Virginia Systems Science Department and represents a generalization of an existing multi-attribute paradigms. As output, it produces dominance digraphs showing 'bands' of alternatives, all of which dominate lower ranking alternatives.

In the case of ISMAUT we began with an existing tool. No development was required, but some tailoring was in order. In a sense, the contractor was tasked to give the tool a 'miliary paint job' by which we mean adapt it for general use in the Pentagon decision making environment.

Use of ISMAUT

ISMAUT is a model suitable for a group decision making environment although it can as well be used by an individual. In a conversational mode the model solicits information on sets of alternatives, and set of attributes which the alternatives share. The information is input to a matrix whose rows are the alternative programs, and whose columns are the attributes. Once the rows and columns are identified, the following information is required.

o Any pairwise preferences among the set of alternative programs.

o Any trade-off weights between the attributes where the description of the weighting may be imprecise such as A1 > A2 or A3.

o Utility scores for each attribute on each alternative at the lowest level of disaggregation where description of the scoring may be imprecise such as U1 > U2 or somewhat less imprecise such as U2 = 2*U3.

A key feature of the model is that any of the foregoing inputs may be modified interactively by the user as the decision process proceeds.

Typically the user/decision maker's primary input is pairwise comparison of alternatives, and also changes in trade-off weights for attributes. The choice and intial configuration of the utilities is typically a staff function. The same is true of the trade-off weights. Thus, ISMAUT is a managment tool which provides a meeting ground between decision maker and supporting staff and which employs the strong points of each. The input tableau is summarized in figure 9.

[FIGURE 9 GOES HERE]

At each iteration ISMAUT constructs and solves a large number of linear programming equations (thousands). Before each iteration a consistency check is made for all current input data and choices of ordering. Practically speaking the consistency check exercises a powerful discipline on the user. Unlike the fuzzy PAR methodology which 'forgets', ISMAUT quite clearly 'remembers' all input. When we attempted to apply ISMAUT directly to the performance assessment process, there was very little dominance of any kind. All options fit into the same band. Further attempts at specification ran afoul of the consistency check. Increasing the number of attributes to upwards of 30 or so did not help either. The conclusion we reached was

PROBLEM ATTRIBUTES

PROBLEM ALTERNATIVES	COST	RELIAB'TY	IMPORTANCE	COLOR	ETC.
PROGRAM1					
PROGRAM2	(IMPRECISELY				
PROGRAM3	SPECIFIED				
PROGRAM4	UTILITIES)				
.					
.					
.					
.					
.					

DECISION MAKERS DOMAIN (ALTERNATIVES)	STAFF'S DOMAIN (ATTRIBUTES)
	(UTILITIES COUPLE STAFF & DECISION MAKER)

Figure 9: (Upper) Input Matrix Set Up for ISMAUT
(Lower) Participants Inter-Relationship Thru Input Matrix

that the basic input to performance assessment was so uncertain as to be consistent with virtually any hypothesis if one does not prune information. Greater specificity only made the situation worse, which is something characteristic of fuzzy decision processes. Although we were able to apply ISMAUT to a number of test cases, the intial PAR data proved too inconsistent to get meaningful results.

ISMAUT is capable of creating multi-level attribute hierarchy by aggregating lowest level attributes into lumped attributes which themselves may be even further aggregated. Trade-off weights between the super attributes may also be input. Without significantly consistent results we could not apply the attribute aggregation feature to the problem. Inconsistency also ruled out use of the so called inverse decision making feature which takes preferred alternatives as input. It then outputs the trade-off weights necessary to achieve that result.

Future Work with ISMAUT

From knowledge gained by reworking the data base gathered for the fuzzy approach to the PAR, and from a knowledge of what were the drivers of the assessment process, we are again working with ISMAUT. The challenge is now to construct portfolios of programs. Future work by the developers of ISMAUT will permit input of the degree to which alternatives satisfy additional criteria imposed on the utilities posed in the form of positive and negative worth. Still more advanced work is contemplated in the form of functional specifications for implementation of expert system techniques for searching solutions for portfolios of alternatives which satisfy stated goals.

Summary

We have adopted a model for complementary use with the fuzzy assessment program which must work within a smaller envelope of uncertainty than the fuzzy assessment to construct packages of line item programs which will change C3 operational readiness at high levels.

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