A Fuzzy Approach to Aggregating Military Assessments

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ABSTRACT

Fuzzy set matrix operations in the form of a computer-aided decision tool are applied to the management problem of aggregating assessments upward through successive layers of a hierarchy. The particular problem addressed concerns the production of a worldwide assessment of military command and control at the global level based on an assessment of capabilities three hierarchical levels below. The program works directly with colors indicating the operational readiness state of the capability. Linguistic variables form a large portion of the data base. Extensive capability exists to link the global assessment with stored information on budgetary decisions identified by the software. The fuzzy set approach described is new in the defense community. The article provides an overview of the methodology and is not a detailed discussion.

KEYWORDS: *Fuzzy sets; fuzzy aggregation; decision support systems; military program assessment; automation of approximate reasoning*

INTRODUCTION

It is almost 20 years since Bellman and Zadeh published their watershed article entitled "Decision Making in a Fuzzy Environment" in *Journal of Management Science* [1]. Although it is difficult not to accompany the

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statement with a wry smile, the Pentagon truly has aspects of a fuzzy decision-making environment. Extremely serious and complex decisions must be made on information that contains a mixture of fact and inference. Moreover, the importance of informed military judgment must not be gainsaid despite the fact that it may contain strong subjective elements.

Problems arise when data and judgments from multiple sources must be combined to produce some kind of overall assessment. Automating such a procedure is beset with pitfalls because conventional approaches make precious little allowance for subjectivity in either the data or the judgment. The ultimate solution is probably some kind of expert system. However, short of that kind of investment, we have developed a decision support tool for personal computers with color monitors. The tool is based on fuzzy set logic operations that directly address the combination of data and judgment when each has a strong subjective element. Moreover, much of the data is expressed linguistically in terms of colors running from green through yellow to red.

A familiarity with fuzzy set theory is presumed in what follows; otherwise a thorough, albeit terse, introduction may be found in duBois and Prade [2]. On the other hand, because readers may be unfamiliar with either the OJCS or its associated decision-making environment, we first digress to introduce these two elements, in order to establish a perspective on the breadth and depth of the analysis reported here. Readers should bear in mind that this paper is an overview of a software tool designed to operate in a complicated decision environment. Also, although the program works on real world data, some small liberties have been taken in order to construct nonsensitive examples.

This application is without precedent in the defense analytical community. We are also unaware of any other such extensive computer solution to a like problem elsewhere. The closest may be a solution to the problem of establishing credit worthiness of bank customers which was done for the German banking system [3].

A WORD ABOUT THE OJCS

The Organization of the Joint Chiefs of Staff (OJCS) is an office within the structure of the Department of Defense. It is composed of the chiefs of each of the four major service elements (Army, Navy, Air Force, and Marines) plus a chairman. Their purview is high-level joint service problems arising from interfacing the various branches of the armed forces in various defined mission areas. In addition to the classical staff divisions of Personnel (J1), Intelligence (Defense Intelligence Agency [J2]), Operations (J3), and Logistics (J4), the OJCS has elements arising from their mission statement. One of these is Command, Control and Communications Division, which has again become J6 in the reorganization mandated by Congress in 1986. It is the C3 arm of the

OJCS with which we will be concerned. The OJCS deals with ten functional or territorial headquarters, each of which is headed by a Commander-in-Chief (CINC). In this paper we shall refer rather loosely to the ten commands as theatres or CINCs interchangeably.

For purposes of this paper, command and control (C2) by itself will be defined as those configurations of people, processes, and equipment through which the armed forces are directed. Add communications to command and control and you have C3. The whole of C3 is infrastructure, and it is notoriously difficult to evaluate; it really can be judged only through its effect on other things. Results can only be inferred by what C3 causes others to do and/or prevents them from doing. Since the OJCS deals at a national strategy level, often far removed from the final implementation of its decision, assessment of C3 is rendered even more difficult.

PENTAGON DECISION MAKING

Decision making in the Pentagon is driven largely by something called the Planning, Programming and Budgeting System (PPBS). It is a complex and confusing two-year cycle of goal identification and subsequent requirements generation that ends with budget specification. Its output forms the basis of procurement decisions. The whole process is marked by the appearance of various key documents with names like Joint Strategic Planning Document, Joint Program Assessment Memorandum, and Joint Strategic Capabilities Plan. The process of producing these documents is highly iterative and in a state of constant flux. It would be safe to identify it as an exercise in approximate reasoning, albeit not in any formal sense. The closest organizational theory might be management by objectives.

Among the more difficult items to track in the PPBS cycle are those military items related to infrastructure, since their ultimate justification depends upon the degree to which they facilitate the primary weapons of war. Perhaps the most difficult items to follow are those connected with C3. Classical operations research techniques for evaluation are generally defeated because of the combinatorics generated by all the possible combat outcomes that can result from varying the C3 infrastructure.

At some point in the PPBS cycle the need arises to translate national goals for the military into objectives for C3 support. That translation eventually results in a listing of capabilities associated with the C3 support of defense. These capabilities must then be evaluated theatre by theatre. The task then evolves into the problem of aggregating the evaluations so as to give a picture at the national level of the degree to which C3 supports the national defense goals.

Before embarking upon the actual aggregation process, which forms the substance of this report, it was necessary to do considerable initial analysis of the

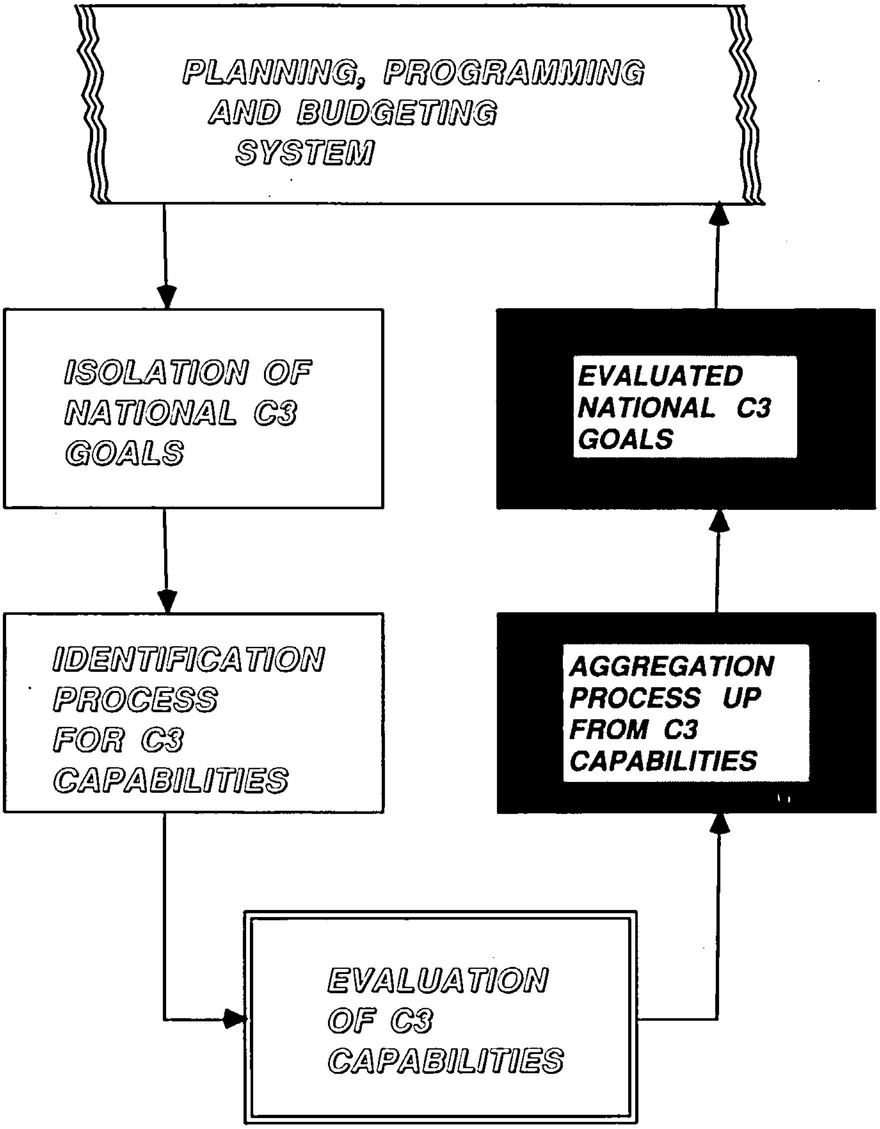

Figure 1. Decision Cycle Analyzed. (Stippled blocks are the decision functions for which the fuzzy set based software was written.)

in-place decision processes. Figure 1 may be helpful in understanding the whole process. Thus, we had to

- Isolate the C3 performance assessment process from the PPBS cycle
- Understand a totally manual process
- Split off the process of identifying needed military C3 capabilities (starting

from PPBS goals) from the subsequent assessment of those goals—which is based on the same capabilities!

- Perform an end-to-end analysis to eliminate needless steps
- Program the aggregation steps using fuzzy sets algorithms

We may summarize the decision universe as we found it, once isolated from the PPBS:

- The process was a manual collection of ill-defined heuristics, which were used in a nonuniform fashion to produce an assortment of high-level judgments that could not be supported at the detail level.
- The data were a heterogeneous admixture of fact and opinion in a variety of formats.

With the foregoing preamble complete, we turn to a more detailed problem statement.

FORMAL PROBLEM DEFINITION

In some respects the entire OJCS is quintessentially a C3 organization. However, quite apart from that aspect, the C3 branch is concerned with the mechanics of the C3 process as it applies to multiservice endeavors. Among its requirements is one which mandates a periodic update at a global/national level on the state of affairs within the various C3 support areas. As we have said, automating the assessment procedures associated with this update is the subject of this contribution. Simply stated, the assessment is to be a report card on the question: How well does C3 support the national defense for four different states of armed conflict? These states run from peacetime, through the kind of tension associated with something like a hijacking, all the way to nuclear conflict. Two budgetary horizons are involved as well. We will argue that this decision making which accompanies the C3 assessment at the national level may be an archetype of approximate reasoning.

Displayed in Figure 2 are the four hierarchical levels associated with the assessment procedure. Broad arrows indicate the direction of aggregation. The horizontal arrow (step 2) is discussed later. There are eight such structures: one for each of the four conflict states combined with the two budgetary horizons.

Each set of hierarchical levels has the following components:

- At the lowest level are the capabilities of equipment and procedures and organizational units that satisfy military requirements for C3 support. They are grouped into sets of varying length that support further hierarchical level substructure.
- At the next level up, sets of these capabilities contribute to various missions in one of four C3 functional areas: monitoring, deciding, executing, and sometimes reconstitution (of forces) shown schematically by the vertical bars for each mission.

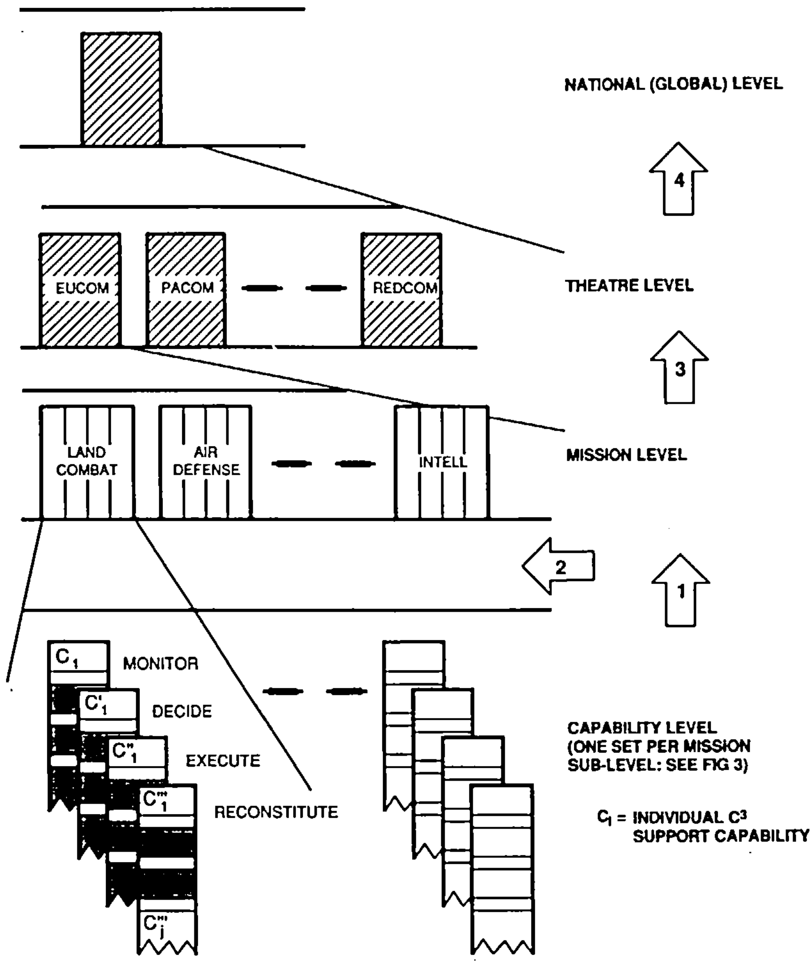

Figure 2. Basic Four-Level Hierarchical Structure (Capabilities → Missions → Theatres → Global) (This illustration is one of a total of eight such level diagrams: one for each of four warfighting environments combined with two budgetary horizons. Arrows show direction of the aggregation.)

- In turn, at the third level up, sets of missions contribute to the support and definition for theatres of operation. As already stated, some of these theatres are defined geographically, for example, Europe (EUCOM), while others are defined functionally, for example, REDCOM (Readiness Command). Each of the theatres has a CINC from whose staff ultimately come the input assessment data.
- Finally, performance over the 10 theatres or CINCs worldwide produces a

global assessment of the degree to which C3 supports the ability of the armed forces to defend the nation.

Note again that the mission level is indicated by schematic vertical bars. Each bar is further subdivided into sublevels of intensity that can be associated with a conflict. For example, the lowest intensity could be an enemy that is only making threats. Eventually one passes to actual contact, and then to more lethal weapons. The number of conflict intensity sublevels may run from three or four to six.

Because the presence of level substructure, the aggregation process from mission to theatre level is not at all straightforward. First the mission functions must be combined. We have dictated that all mission subfunctions for a particular mission share the same conflict intensity substructure. This facilitates the lateral combination—arrow 2 in Figure 2. However, the conflict intensity sublevels for the theatre are, in general, *not* the same as those for the mission. In going from mission to theatre, sublevels of a mission may be "chunked" together in the aggregation process leading to a single theatre conflict intensity sublevel. Thus, it may take two or three intensity sublevels of a mission to provide the aggregated support to one conflict intensity sublevel of a theatre. See Figure 3 for a detail of the mission sublevel structure where five sublevels have been arbitrarily displayed.

As one proceeds up the hierarchy, the reasoning becomes more and more approximate. Whereas judgments at the lowest level may still be close to measurable achievements like the ability to sense movement more than 30 km beyond a front, much more subjective elements enter higher up. Thus, at the second or mission level, the geography plays a major role. For example, the Pacific Command (PACOM) deals with vast open spaces of water, while EUCOM operates over a continental land mass. Although these two theatres may include the same mission in their aggregated definition, the way in which in the mission is perceived can be quite different. One such case could be air defense. By the time the third or theatre level is reached, such external decision components as risk assessment and political estimates enter directly.

THE IDENTIFICATION OF A FUZZY PROCESS

The decision to use fuzzy set and approximate reasoning paradigms was driven by the nature of the input to the aggregation process at the capability level, which is the lowest lying of the four levels in Figure 2. This input is a characterization of the degree to which a C3 capability is judged operationally ready to support a military mission or an element in a mission. An example of this type of capability might be the ability of a sensor system to "look" more than 100 km, or the ability of a processing center to prepare and transmit detailed military orders within, say, 10 minutes of tasking. Many attempts have

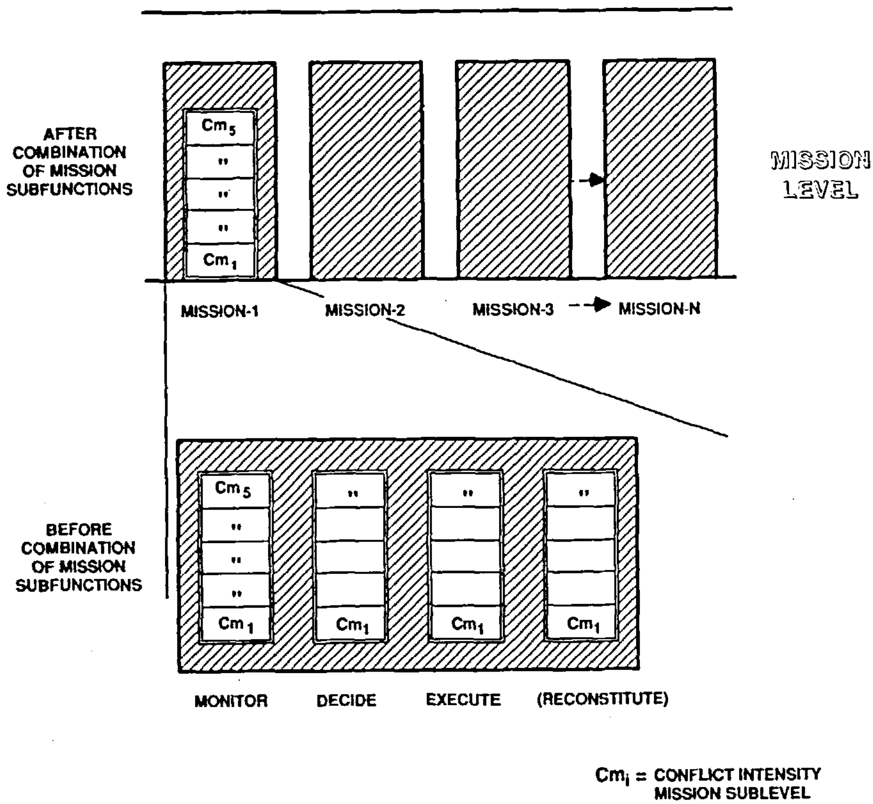

Figure 3. Detail of Mission Substructure Showing Conflict Intensity Sublevels.

been made to quantify such abilities, usually in terms of numbers related to the physical processes associated with equipment used in the field for C3, such as telephones, computers, and networks. The resultant data are then considered to have been objectively gathered. Subsequent processing is usually subjective.

We have identified an alternative paradigm based on fuzzy sets. If fuzzy sets are introduced, then we can gather subjective input data but process them according to well-defined mathematical operations. With a view to the future, we were also aware that a fuzzy treatment would permit goals and constraints to be treated in the same decision space. This could be very useful for building a tool to aid in approximate reasoning, as decision makers were observed to regularly mix goals and constraints in their arguments. We elected, therefore, to base a computer code on fuzzy set logic.

FUZZY DATA GATHERING

Possibilities

Another approach to data collection about capabilities, and one that does not depend on numerical measurement, is possible. Such an approach is the one on which the decision aid described in this paper is based. This approach directly utilizes the theatre commander's military judgment of the degree to which the C3 capability under discussion supports his mission. This is a subjective evaluation of considerable merit that may be conventionally expressed by color. Generally, green is good capability, and red is bad. We treat the colors as linguistic variables in a fuzzy set. We then solicit as input the possibility that the defined capability is one of seven colors in the spectrum, operationally defined as follows:

Color Label	Operational Definition
Super Green	The capability is so good it enhances other capabilities.
Green	The capability meets all requirements.
Yellow/Green	Less than full operability.
Yellow	Limited operability.
Red/Yellow	Minimal operability.
Red	The capability fails to meet the requirement.
Super Red	Capability is so lacking that other capabilities are hindered.

Then, for each national defense posture, for each theatre or CINC, and for each mission and subfunction within the mission by conflict intensity level, the possibility that a C3 capability will support the mission is obtained according to the defined color scheme. Point membership function values are used internally for each color-capability combination. However, since our users seem more comfortable with the range of numbers 0 to 100, we use percent possibility as input. Such a response might then generate the following sample possibility distributions, where dashes indicate no response (zero percent possibility).

Capability	SG	GR	Y/G	Yel	R/Y	Red	SR
Ability to Look 30 km	—	—	40	60	75	40	—
Send Message in 5 Min	—	80	30	—	—	—	—

Since these are possibility distributions, their internal representation need not sum to unity according to the governing fuzzy set rules.

These possibility distributions form one cornerstone of our program data base. Associated with all capabilities that are not green is a reference to some deficiency and perhaps to some corrective action. [Eventually the program should also relate to the cost of the corrective action(s)—an associated approximate reasoning problem in itself which we tend to call the portfolio construction problem.]

Linguistic Variables

Having decided upon a color possibility distribution, the next step is to solicit the degree to which the next hierarchical level up depends upon the stated capability. Linguistic variables are again used. The user is asked to form a set of dependencies—linguistic variables with corresponding membership function values. Such a set may look like the following:

(NO-DEPENDENCE|0.1, SOME-CONNECTION|0.25,
MODERATE-IMPORTANCE|0.4, HIGHLY-IMPORTANT|0.7,
ESSENTIAL|0.85)

Not that the variable "essential" is not equal to unity nor is "no dependence" equal to zero. The values assigned in this example may be thought of as hedging of a sort. Future versions of the software will be designed to infer the membership values from elicited responses, as we currently find that the users are able to "game" the software through artful choices of membership value assignments for the linguistically chosen variables. This choice is intuitively based since the mechanisms of the aggregation (covered later) are unknown (or "transparent") to the user. The user seems to be able to detect patterns in the answers resulting from dominance of either dependency values or color possibility distributions.

The final step in the input process is to link the first two hierarchical levels by having a user assign a dependency variable to a previously identified capability. Thus, with reference to the previous possibility distribution example, we might have for the Execute function of the Land Combat mission the following:

Capability	Dependency
Ability to Look 30 km	Moderate Importance
Send Message in 5 Minutes	Essential

The result of a manual aggregation (or rollup as it is often called) of these two capabilities with respect to the mission would be Green. The reason is as follows. The capability to Send Message in 5 Minutes is Essential, and the possibility that it is Green is 80%. The alternative is only of Moderate Importance and has a diffuse possibility distribution peaked at Red/Yellow.

On the other hand, the dependency linkage for the Monitor function of the same Land Combat mission might look like the following:

Capability	Dependency
Ability to Look 30 km	Highly Important
Send Message in 5 Minutes	Moderate Importance

In these circumstances the rollup to the mission level would produce a Red/ Yellow or Yellow label depending upon total context. The process continues for all levels of combat intensity of Land Combat. Then the next mission is considered, for example, Intelligence. Curiously enough, colors can even retreat to a greener hue at higher sublevels of combat intensity despite the strong dependency on the preceding sublevel.

We speak metaphorically in referring to our interpretation of the degree to which a color is green. However, provision exists for a visual expression of this with color graphics if hue is taken as the measure of greenishness or greenish tint (admixture). The retreat to a greener color means basically that the higher levels of aggregation are being essentially decoupled from their dependence on lower-lying levels that would drive us toward red. In a sense the program deliberately "forgets" things. This forgetting is the software analog of the decision maker who cannot proceed if he or she is enmeshed in detail.

Everything said about moving to a greener hue could, of course, be said about moving to a more reddish hue. Figure 4 provides a schematic view of the color aggregation process.

Fuzzy Aggregation

The challenge of producing an automated decision aid that would roll up hundreds of such capabilities sets into dozens of mission areas was to duplicate the results of the manual process in a sufficient number of cases to inspire confidence in the tool.

Having determined the color for the various C3 mission support functions [Monitor, Decide, Execute, and Reconstitute (the forces)] from the underlying operational capabilities, the next task is to roll across the support functions to determine the overall color of the C3 support to the mission itself. (This is the horizontal arrow of step 2 in Figure 2). This is done in much the same manner. Again the user is asked to define a set of linguistic variables that link the overall mission accomplishment to the four functional C3 support areas. Such a set might look like the following:

(LOW-IMPORTANCE|0.5, AVERAGE|0.65, GREAT-IMPORTANCE|0.85)

The result might be like that found in the display following in which we have supplied a plausible color label for the Decide function for the Land Combat

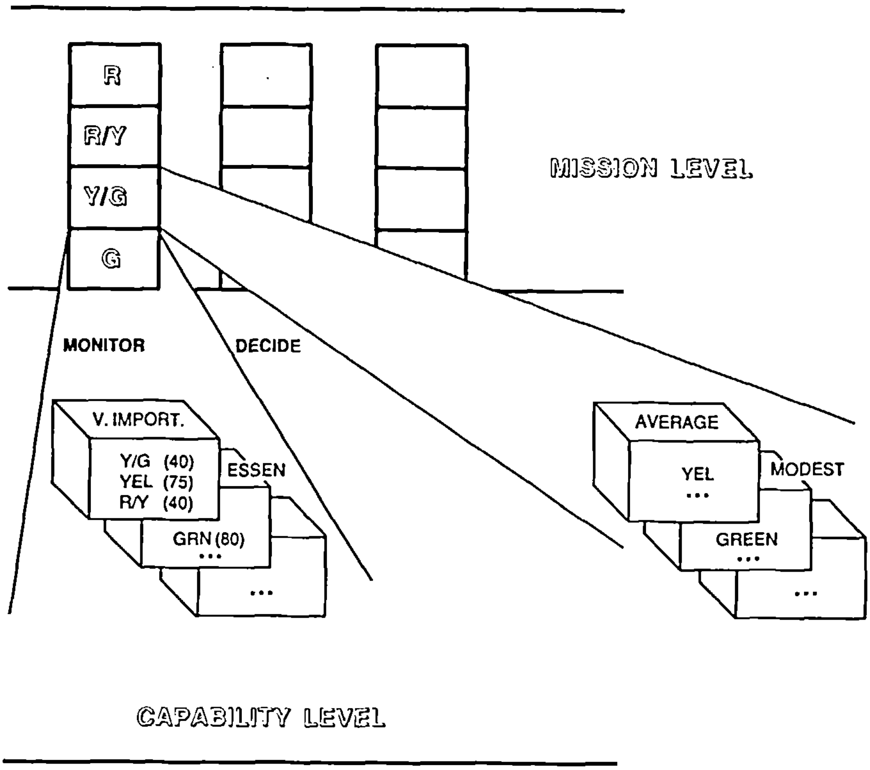

Figure 4. Schematic Illustration of C3 Capabilities Rolling Up into Mission Sublevels by Color and Dependency

mission. Thus, the whole mission might relate to three of the key subfunctions as follows:

C3 Function	Color	Dependency
Monitor	Red/Yellow	Great Importance
Decide	Yellow	Average Importance
Execute	Green	Great Importance

Here we have a problem. Is the result Green or Red/Yellow? To some degree it depends upon whether the user is an optimist or a pessimist. Doing the rollup manually, the user would probably opt for the Red/Yellow color, particularly since there is a possibility that the result could be Red or Yellow for the Monitor function. On the other hand, the Execute function is definitely Green and has equal weight. The software would have computed the conservative case (Red/Yellow) without additional instructions. At present we have no fuzzy consensus operation built in for instances like these. In any case, this process continues until all the various mission functions within all the missions in a theatre have been combined.

The next level of rollup occurs when all the missions that are carried out by a theatre commander have been evaluated for a color label. The next level up links the missions with the theatre. The drill is the same. Consider a fictitious theatre called WESTCOM. We need the dependency links between it and the various missions. Something like the following might result.

Mission	Color	Dependency
Land Combat	Red/Yellow	Essential
Air Defense	Green/Yellow	Very Important
Logistics	Yellow	Essential
Naval Air	Green	Moderate

Despite the preponderance of favorable colors, the rollup would produce Red/Yellow.

One step remains: aggregation from theatre/CINC to global level. At this point significant external factors enter in. Chief among these are risk assessment and political realities. Both may reintroduce the possibility of additional colors for theatre readiness. Moreover, they may also influence the degree of dependency of the global picture on different theatres.

While we tolerate it, we do not recommend use of the code to automatically roll up to theatre level. We actually prohibit the final level of aggregation assessment without reconfirmation of all color possibility values being used. We would note parenthetically that there is a reason that we do not recommend automatic rollup more than one step at a time. It is because fuzzy data get used up, or washed out as it were, when too many fuzzy operations are concatenated. Remember that each rollup corresponds to a decision, which ought to reduce the level of fuzziness. Instead, our rollup process increases fuzziness. The process of washout can be quite swift, sometimes occurring in three to five concatenated operations. We were guided in our work by a comparison between automatic predictions and those resulting with manual intervention and reconfirmation of the data.

Fuzzy Computational Details

It suffices to sketch one level of aggregation in order to understand the manner in which all aggregation was accomplished. For each basic capability that was identified as supporting a conflict intensity sublevel of a mission function, a matrix was defined. The row labels were the dependencies, and the column labels, the seven colors. The matrix is constructed internally and not displayed to the user. Entries are possibility distribution point values showing the possibility that a capability is the indicated dependency-color combination. Thus, we might have the notional matrix in Table 1. No special significance should be attached to the fact that only two rows are nonzero. The matrix can be nonzero at any point. It is simply that our users usually filled in only one row, more rarely two. At times it was difficult to prevent them from entering only a single point value somewhere in the matrix.

A separate matrix is constructed by the software from the color-dependency combinations solicited from the user for each conflict intensity sublevel of the mission function supported by the indicated capability. Similar matrices can be constructed for the other capabilities supporting the designated mission function. The initial version of the program then performs a fuzzy disjunction (union) using the MAX operation on the matrices appropriate to a selected conflict intensity sublevel of a mission function. Computationally, this corresponds to selecting the maximum value for each row-column entry (ij). Thus, where

$$N = C_1 U C_2 U \cdots C_p,$$

$$n_{ij} = \text{MAX}\ [c_{ij_k} : k = 1, p]$$

But N is only an intermediate matrix result, since the row labels are themselves a fuzzy set. Kaufmann [4] calls this a conditioned fuzzy matrix. 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 as follows. We have for each element in the resultant row matrix M_f for the selected mission function for a given conflict intensity sublevel (where D is the row matrix of dependency labels),

$$m_{f_k} = \text{MAX}_j\ [\text{MIN}\ [d_{1j}, n_{jk}]] \qquad k \in [\text{color set}]$$

One last step remains. A projection operator is applied to M_f to get the largest value entry. The resultant color is the label associated with that entry. In practice, ties were common. To break the ties, a screen prompt asked the user to declare whether she or he was a pessimist or optimist. If a pessimist, the color label closest to red was chosen; if an optimist, the label closest to green.

At this stage in the computation, the program has rolled up one set of capabilities that support a conflict intensity sublevel for a single function of one

Table 1. Matrix for Capability C1

	SG	GR	GY	YE	YR	RD	SR
Essential	------------------------			0	------------------------		
V. Important	0	0	0	.30	.85	.45	0
Average	0	.90	.80	0	0	0	0
Modest	------------------------			0	------------------------		
Not Important	------------------------			0	------------------------		

mission in a theatre for one war posture and one of the two budgetary horizons. Some numbers are instructive at this point. For a total iteration there are

4 to 7 capabilities for each of 4 to 6 conflict intensity sublevels of 3 to 4 mission functions for each of 7 to 10 missions for each of 10 theatres for each of 4 war postures for each of 2 budgetary horizons

We estimate that this results in some 1000,000 possible combinations, which is in itself a powerful argument for using approximate reasoning technique to avoid combinatorial explosion.

The next step is to complete all three (four) mission subfunctions for all mission conflict intensity sublevels. In order to achieve rollup across the functions at the same hierarchy level, a matrix is constructed for each mission sublevel using the row matrix M_f just discussed as input. The columns are again the colors, and the rows are the new dependencies appropriate to the relation being aggregated. The process may be either manual or automatic. If automatic, all the entries from any row matrix M_f form a row in a new matrix M_f similar to that introduced for the capabilities but with (usually) different row labels. Unless filled in by hand, the new matrix M_f has zeros in all rows but one.

$$m_{f_{ij}} = \begin{cases} m_{f_k} & i = \text{selected dependency, with } j \text{ and } k \in \text{ [color set]} \\ 0 & i \neq \text{selected dependency, with } j \text{ and } k \in \text{ [color set]} \end{cases}$$

The process then proceeds as before by rolling across M_f for each sublevel of the mission for each mission. The end result for each mission is another row matrix. These then become the building blocks for rollup to theatre level. These repeated sequences of disjunctive operations on the same data, which are part of the automatic aggregation, are responsible for the washout phenonmena already mentioned.

FIELD EXPERIENCE WITH THE PROGRAM CODE

Testing and Fielding

The program was written to satisfy what is called an "urgent mission requirement." Translated, this meant that development and field test went hand in hand because of the extremely short time frame from conception to implementation, about 3 months. The program went out to all 10 CINCs/theatres worldwide for use by local staff. In all instances a team of coworkers, who were actually charged with conduct of the Performance Assessment Report (as opposed to the methodological aspects described in this contribution), accompanied the developing code. They worked directly with local staff officers in the field to build the data base and to produce aggregations through theatre level that were agreeable to the local staff.

Back in Washington, additional work in aggregation was performed by a local contractor using the data base gathered in the field. The final level of aggregation from the theatre level to the national assessment level was done both manually and automatically, but in both instances with a new set of input data. Our basic confidence comes from users who agree that the program is producing results in accord with their basic understanding of how the aggregation process should work. At times the program results have initially been rejected but after further consideration the user has agreed with them.

User Response to the Code

The original program code had two sets of users: those who were internal to OJCS, and those external. Most external users tolerated the code as an intrusion on their normal activities. Internally, OJCS users and their contractor liked the program. They were troubled only in passing about references to fuzzy sets, as the mathematics was totally transparent. Some considerable explanation did attach to the idea of possibility as opposed to probability. Field users never picked more than one possible dependency choice. Moreover, many specified only one color as being possible but hedged their bets at the 70% level. Thus, much of our basic input data were crisper than we had anticipated. It was probably this fact alone that permitted the extensive automated concatenation of fuzzy operations.

ADDITIONAL PROGRAM FEATURES

Basic Information About the Code

The program is currently written in Basic. (It is being rewritten in Pascal.) The choice was dictated by the fact that a rapid prototype, based on existing subroutines to generate screen displays, was available. Practical considerations such as the availability of the compiler for desk-top computers were also a factor. During sessions the user is guided through the software by a sequence of nested menu screens. A highly schematic functional view of the program is presented in Figure 5.

Displays are in the form of bar graphs for each rollup level. The bars are segmented by intensity conflict sublevels and portray the appropriate color for each segment. A user's manual is also available [5].

Use of the Optional Disjunctives

In fuzzy set theory there exist hierarchies of connectives that may themselves be used to model the decision process. In our software, one program screen does

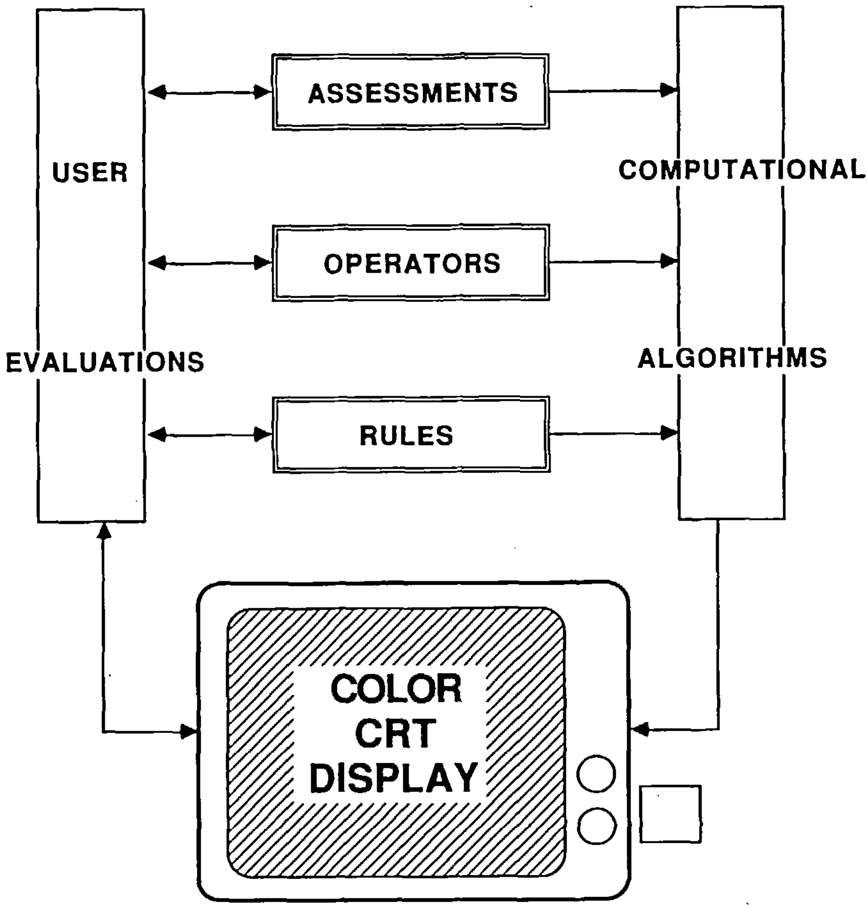

Figure 5. Overall Functional Schematic of Aggregation Program Software.

offer a limited choice of fuzzy disjunctions since only disjunctives were used in this version. In a sense the options model the strength of various aggregation combinations.

Using only disjunctions produced a one-dimensional view of the decision maker that worked surprisingly well. The choices of connective were taken from duBois and Prade [6], who discuss a very rich variety of fuzzy operators. The screen options are all weaker disjunctions; their use also serves as a kind of rough sensitivity analysis. If the color does not change as the choice of connective is varied, we count the result as robust.

One connective in particular is interesting because it contains a variable γ (gamma) that sweeps over the range of several other disjunctions and is called a compensatory operator. It is ultimately due to Hammacher [7]. For two membership point values x, y we have

$$f(x, y)=\frac{x+y-xy-(1-\gamma)xy}{\gamma+(1-\gamma)(1-xy)}$$

The definition is recursive; thus for three point values,

$$f(x, y, z)=f[f(x, y), z]=f[x, f(y, z)], \textit{ etc.}$$

Gamma may take values from zero to infinity. Users are permitted to input their own value for γ, which gives them some sense of control. What they do not know, however, unless they read the user's manual very closely is this: Gamma introduces the maximum variation between 0 and 1; most of the remainder of the variation occurs between 1 and 2. Most users input large values up to 100, the current limit. Our tacit assumption is that approximate reasoning is nonlinear anyway in dealing with numerical estimates. In understanding the role of this compensated operator and its range of values, we have taken a leaf from the counting system in Pidgin English; "one-fella, two-fella, many-fella". It seems adequate for them and for us as well.

Linking to Program Deficiencies

Whenever a capability is judged to be some color other than green, a reason is sought. The cause is usually in the form of some kind of perceived deficiency in current processes or equipment. To remove the deficiency requires some action, which often takes the form of a budgetary line item program. One feature of the code is that it keeps track of which deficiencies have some bearing on the national assessment. Only those capabilities that are vital to the support of essential missions usually survive the aggregation process, although there can be surprises. Users may challenge the results by experimenting with the connectives or by altering the basic color-dependency input combinations. If they succeed in changing the color, they will obtain a new fuzzy audit trail which usually lead to a new set of budgetary line items.

RESULTS AND OBSERVATIONS

Fuzzy set theory is valuable as a modeling tool for automating approximate reasoning problems. It can be said to have done the following for us:

- Reduced the data requirements to two types: an estimate of the capability expressed as the possibility that it was a certain color and the dependency of the higher aggregation levels on that capability
- Communicated to the user in terminology he or she readily used and understood, such as colors
- Replicated a heuristic decision-making process using only a very limited

data set and a bare minimum of fuzzy operations, compared with the manual process.

Viewed in terms of its effect on the management of the effectiveness evaluation process, the use of an automated program had some interesting consequences. It did at least the following:

- Centralized, and returned to the military staff in the Pentagon, the fundamental judgmental aspects of the warfighting capability aggregation process
- Permitted data gathered from diverse sources to be standardized
- Provided the same paradigm for all CINCs used for aggregation if they so chose; and even if they did not, permitted the OJCS decision makers to replicate their results using a standard paradigm
- "Quantized" the budgetary process being driven by the aggregation process

The last entry deserves some amplification. By "quantized" we mean that there was no longer a linear relation between dollars added to the budget and color change as in the usual case. Instead, all contributions to the color (other than green) that the program had identified as "drivers" had to be ameliorated before any change could occur. Thus, by conventional budget wisdom, it is not possible to have 80% of the program total green and 20% red and still roll up to red. Likewise it is improbable at best that with 80% of the programs red and only 20% green the rollup would be green. Yet that is exactly what this exercise in automated approximate reasoning produced.

The document this methodology helped produce is actually being used as decision input for the JCS. It is not a toy program. The observations reported here are taken from field use by military staff decision makers. The most general conclusion that we wish to draw concerns the kind of data used. It seems that the closer the methodology comes to using the actual field data, the better the result. This lesson is often forgotten when the data are linguistic.

FUTURE DEVELOPMENT

Experimentation with More Complex Combinations of Connectives

The original program used only disjunctive operations corresponding to fuzzy AND/OR. The user could vary the strength of the connectives as outlined above. However, conjunctives corresponding to fuzzy AND and combinations such as [(AND, AND, AND) OR (AND, AND)] were not permitted. We had surprising luck with disjunctions alone. We had not expected such success. People who had previously done the process manually indicated that they usually talked in terms like A AND B AND SOME OF C. It may be that introduction of the dependencies took care of this effect to a first order.

It has become apparent that when the program is used in an interactive mode in which the user is seeking a particular aggregated color change, a richer menu of connectives might produce the desired result. This will require the addition of automatic features that shuffle through the combinations, and also a facility to permit the user to specify more complex combinations. The addition of expert system features has also been suggested.

Introduction of Goal-Directed Artificial Intelligence Techniques

The addition of AI techniques represents only a small modification. Buried in this problem is a much more significant application of AI to approximate reasoning. We sketch it in closing. While the program code discussed here performed the aggregation upward from information on capabilities through intervening levels to a national assessment, the equally important downward path through the same hierarchy from national goals to identification of the needed capabilities was not automated. (See Figure 1.) There remains a laborious initial step to identify the lowest-lying capabilities. While national goals change slowly, the goals of the CINCs and the missions planners that support them change more rapidly as they seek to respond to national goals in a changing environment. For this application we are exploring the application of backward chaining over the four hierarchical levels.

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