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C³I ANALYSIS TOOLS FOR DEVELOPMENT PLANNING
VOLUME I

P. A. VAIL
G. H. WEISSMAN
J. G. WOHL

ALPHATECH Inc
2 Burlington Executive Center
111 Middlesex Turnpike
Burlington, MA 01803

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"This technical report has been reviewed and is approved for publication."

JAMES D. TAYLOR, Lt Col,USAF
Project Manager

FOR THE COMMANDER

CHARLES J. LABLONDE, Colonel, USAF
Assistant Deputy for Development Plans

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PERSONAL AUTHOR(S)
?.A. Vail, G.H. Weissman, J.G. Wohl

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Subjective transfer function modeling method was developed for use in Command, Control Communications and Intelligence (C^3) systems planning and evaluation. Model is based on algrebraic relationship for each node of a tree structure which describes decision process in command and control systems for strategic and ballistic missile defense. Trees were found to be easy to construct, however, quantitative measures were difficult to define. Prototype program was developed for the Apple MacIntosh computer. Program does not cover all mission areas, but can be used for limited sensitivity analysis. Program was not found suitable for ranking proposed programs in order of importance.

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1. EXECUTIVE SUMMARY

Background

As part of an effort to improve Development Planning in Electronic Systems Division, Deputy for Development Plans, ALPHATECH was asked to study the Vanguard process and to focus on Vanguard mission and program analysis. A C^3I workshop held in early FY85 as part of this project concluded that the standard Vanguard analytic model (AFSCP 80-3) was not appropriate for C^3 missions and that other models and techniques should be investigated. Subsequent review of existing analytic models found that none of the then available models were both applicable and practical for use by Vanguard analysts.

We considered several approaches for constructing new models that could provide an applicable framework for connecting Measures of Effectiveness (MOEs) in a mission with Measures of Performance (MOPs) for C^3 systems, and a practical procedure that would not cost as much to implement as would conventional computer modeling techniques. The Subjective Transfer Function (STF) modeling method was chosen as the most promising approach for further testing.

STF is a quantitative technique developed at RAND Corporation. It uses a causal tree structure to trace the flow of information through the levels of a command and control system. A specific measure is defined for each factor in the tree. Relationships among the factors at each branch are derived through questionnaires administered to groups of experts who have operational experience with the system being modeled. The relationship at each node, i.e., how different levels of each input factor combine to provide a level of output, is expressed as a subjectively derived, numerical function. The functions for the entire tree can be concatenated into an overall quantitative expression which connects system capabilities, which are input at the bottom of the tree, with mission effectiveness, output at the top of the tree.

Results

We designed an experimental test of STF based on the previous successful RAND experiences. The Strategic C^2 Vanguard mission area was chosen for the test, and ALPHATECH analysts made several visits to both NORAD and SAC Headquarters to design the Strategic C^2 tree and subsequently to collect quantitative data. During the course of the test we adapted the STF method to fit the problem and spent much time devising tree nodes and measures and redefining the STF method. We also put considerable effort into development of automated tools to generate questionnaires and reduce data, and into installing the computational results in a user friendly tool for analysts. Due to limited availability of Air Force personnel, we completed only part of the test; nevertheless we were able to identify both benefits and limitations of the STF approach to modeling C^2 systems.

This was an initial experiment; much more was learned about STF as we proceeded. Much of our early design and tool development was not used in our scaled down test of STF. More experience with STF and its application to Vanguard, more intimate knowledge of the mission, and more time are needed if the Air Force wishes to convert our concept demonstration of STF into a Vanguard support tool for production use. We do not think that STF can be used by Vanguard analysts without technical assistance from STF-experienced consultants; we feel that the STF approach increases rather than obviates the need for familiarity with the mission, and we found that STF implementation cost is higher than we had hoped.

Causal Trees

The tree we developed, with its associated measures, is a useful model of the Strategic C^2 System. We found that respondents at the operating commands were quickly able to understand the ideas behind the STF approach. Our efforts to identify and quantify C^2 requirements paralleled similar efforts by NORAD/SpaceCmd to document Strategic mission requirements.

Data Collection

In some instances the novelty of using STF and the difficulties of applying the method to an evolving C^2 mission left us with less useful data than we had anticipated. Nonetheless, we were successful in collecting most of the data for NORAD systems. We did not collect data about SAC systems. An additional visit to the commands, as recommended in RAND's approach to STF, would have been useful to refine the tree structure and to administer sample test questionnaires prior to the final data collection effort.

Functional Relationships

The functions derived from the data appear to be reasonable representations of the relationships among causal factors and their outputs. However, we feel that respondents may not have clearly understood all the new concepts that we introduced in the course of administering the questionnaires; hence, the relationships may be incomplete and the data inaccurate.

The Expert Problem

Normally in applying STF, respondents to the questionnaires are chosen to be experts operationally experienced in their portion of the mission. The experts assume, as part of the "context" of the questionnaires, reasonable values for factors that are not specified and manipulated by design in STF. We found, however, that there was no obvious context for the still-evolving strategic mission, and there were no experts for such contextual factors as future requirements or standard scenarios. We had to generate much of the context ourselves, tabulating requirements and scenarios in detail, in order to make data collection possible.

The Scope of Implementing STF

Implementation of STF reorganizes but does not avoid the fundamental jobs of portraying the C^2 System as a coherent whole, understanding and writing down requirements, tying them together into an integrated plan and relating them to individual systems and technologies that might be acquired.

Conclusions

1. The STF causal tree model is a good framework for the operating commands and ESD to use when talking about future operational requirements and their relationship to system capabilities. For this reason alone it is worth pursuing.

2. Checklists are a useful way of collecting uniform data about acquisition programs. Checklist data can also easily be manipulated with automated data processing tools. Vanguard analysts should consider checklists as part of the Vanguard data call even if STF is not implemented further.

3. The STF method of collecting quantitative data about causal factors from experts is well suited for static factors that are well known to operational personnel. However, rapidly evolving missions with undefined future requirements that use advanced technologies (e.g., SDI, cruise missile defense) have no experts and do not lend themselves to easy analysis via STF.

For such missions a group or team comprised of current operations personnel, system planning personnel and technologists must be formed to provide the required expertise. In addition, other approaches to collecting quantitative data about relationships in a causal model may be better suited to ESD's needs. Nevertheless, even rough quantitative data collected via STF provides useful insights into the potential use and limits of system capabilities and the sometimes complementary relationships among those capabilities.

4. The analytic results from our initial test of STF were not rigorous enough to provide quantitative support for decisions about the relative value of acquisition programs.

5. The software tool developed on a personal computer demonstrates that simple but powerful ideas can be embedded in portable, easy-to-use software that the Vanguard analyst can use directly.

6. Although developing an STF model requires commitment of considerable resources in the form of ESD, MAJCOM and technical consultant time, it still involves less of an investment than does a computer based analytic model.

2. INTRODUCTION

This section briefly describes ALPHATECH's project for ESD/XR and the activities that led up to our experimental test of the Subjective Transfer Function method applied to Vanguard analysis, Task 4 of that project. A more complete discussion of Tasks 1-3 is provided in TR-226-2: "C^3I Analysis Tools for Development Planning, Cumulative Report, Tasks 1-3" (Jan 31, 1985). In the following, an exposition of the STF approach to modeling C^2 systems is provided. We also outline our parallel effort to investigate planning decision aids carried out by installing the analytic results of our experiment on a personal computer.

BACKGROUND OF PROJECT

Previous Tasks

In Task 1, we provided a formal representation of the Vanguard process using the IDEF representation language. This task familiarized us with Vanguard, providing ESD/XR with a representation of Vanguard at ESD which was useful for training and introducing other communities to Vanguard.

Under Task 2, ALPHATECH hosted a workshop which reviewed the current Vanguard process and identified shortcomings, including a lack of applicable quantitative models and problems with the existing analytic model used by Vanguard analysts. One particular problem is that the requirements for acquisition programs are set by the operational community and expressed in terms of operational measures. The capabilities developed by acquisition programs are often expressed by the development community in terms of system performance. There appear to be no relationships, currently acceptable to both communities, that map system performance measures into operational measures. Furthermore, under the current Vanguard process, the Vanguard analyst is asked to express all deficiencies and all program contributions in terms of a single measure, percent of task accomplishment, that does not allow for either the effects of task interrelationships or the non-linear contributions of tasks to mission effectiveness.

It would be useful for the analyst to have a better way of translating system capability inputs into mission effectiveness outputs, i.e., a transfer function. Such a transfer function might be derived from a computational model that incorporated detailed algorithms capturing the relationships among C^3I capabilities, weapon system capabilities, and mission effectiveness.

In Task 3, we surveyed available computational models, implemented as computer programs, to see if any of them were appropriate for the Vanguard analysts' needs. It was found that most models focus on weapon system performance and do not incorporate C^3I system performance. Those that do incorporate C^3I are impractical in that they require too many resources to operate, or are inappropriate because they do not cover enough of the C^3I systems of interest. In the long term, the use of complex computational models might be a worthwhile objective for C^3I Vanguard analysts; but in the near term, simpler models are necessary.

Goals

There were several major goals of the Task 4 plan. First, to develop a model relating system capability to mission effectiveness which was practical for use by Vanguard analysts. We, and our ESD sponsors, wanted to adapt an existing approach; but as we found in Task 3, existing computer models were not the solution.

Second, to test the implementation of the model selected for one Vanguard C^2 mission. For ESD's purposes, a practical demonstration is better than a theoretical investigation. Part of this goal included installing the model in an automated decision aid for analysts.

Third, to evaluate the opportunity for using the model in Vanguard on a larger scale. As a consequence of this last goal, we implemented STF with general purpose tools and tried a few excursions to test alternative ways of making STF work.

Choice of STF

STF: Subjective Transfer Function method was one of the methodologies discussed at the workshop, and received a very favorable hearing (Rand publication R-3021-AF, July, 1984). This method allows the analyst to structure a mission area as a hierarchy of factors and outcomes, and to investigate the relationship between these on the basis of (subjective) expert judgment. Because of the use of expert judgment as a surrogate for more formal analytic relationships, this method promised to provide a means for modeling a very broad mission area, incorporating many diverse factors, with substantially less investment in time, and personnel resources than is required by other modeling methods. Because of the hierarchical nature of the model, this method promised to relate measures of performance, at lower levels of the hierarchy, to measures of effectiveness at higher levels. Thus it seemed an appealing alternative to more conventional computer modeling techniques such as simulation.

THE SUBJECTIVE TRANSFER FUNCTION APPROACH

Overview

The STF method was developed at RAND Corporation to capture the essentials of a transfer function, relating factors to outcomes, by using the structured judgments of experts as surrogates for a computational model. STF allows the experts consulted to express mission effectiveness and task performance in terms of the quantitative variables that they deem appropriate; the method is not restricted to a percent task accomplishment as its only measure. STF can capture both the nonlinearity of performance contribution and the relationship among performance parameters on several tasks. STF could also be a first step toward the subsequent development of more objective computational models if such models are deemed appropriate.

Causal Trees

A test of the STF method requires the construction of a hierarchy (tree) of appropriate quantitative measures, such as effectiveness, performance, and capability. Quantitative information must then be gathered by means of carefully designed data collection procedures for each level of the tree; operational personnel should be consulted whenever possible. From this data, STF models are derived for each level of the tree and then concatenated into a single model, the subjective transfer function, relating capabilities at the bottom to mission effectiveness at the top. This model, in the form of a set of interacting algebraic formulas, becomes the analyst's tool to evaluate programs and identify deficiencies and technology opportunities. For example, Fig. 1 shows a single node of the tree that was constructed for the strategic defense mission.

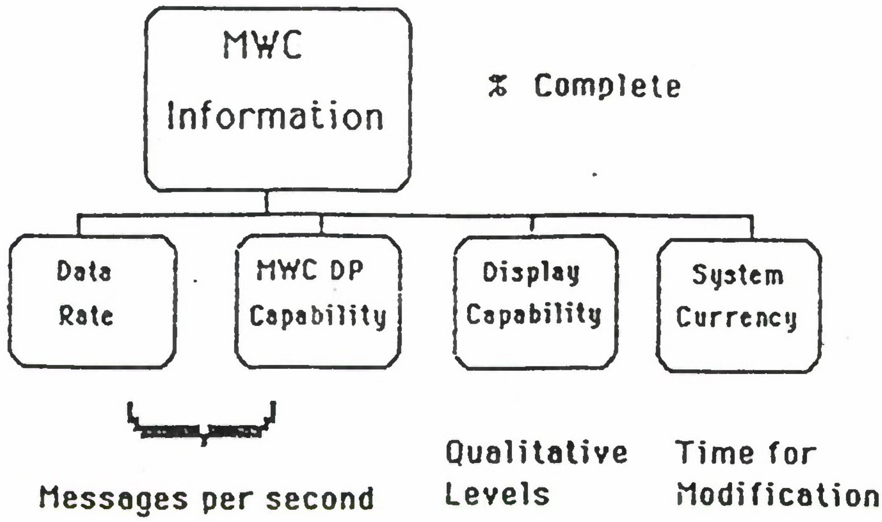


Figure 1. Node for Questionnaire 1111

The preceding figure and the related measures were derived in discussion with Missile Warning Center (MWC) personnel. The figure indicates that the factors of interest to ESD which affect the completeness of MWC information are those shown: data rate (from the sensors to the MWC systems), data processing capability, display capability and system currency (or flexibility). Other factors also affect this outcome, but these other factors are not of interest to ESD since they do not relate to C^3I systems. During data collection we asked the respondent experts to keep these other factors in mind at a reasonable level, but to focus on the difference that different levels of our particular factors make to the outcome, completeness of MWC information.

Measures

Factors that are used to describe C^2 systems must be measurable. For operator experts to answer questions about these factors, the measures have to be clearly known to the operators, not obscure or abstract entities that they have no feeling for. Objectively determined, quantitative measures are preferred, but subjective measures, with qualitative levels, may be used where appropriate. In Fig. 1, display capability was described with qualitative levels.

Data Collection

Having determined the factors of interest, the appropriate measures and a reasonable range of levels for each measure (for Messages per Second we chose .1, 1, 10 and 100), the next step is to design and administer a questionnaire eliciting subjective estimates of the outcome for various combinations of input factor levels. Appendix D shows the questionnaire that was administered for the node shown in Fig. 1.

The questionnaire is administered to a group of experts, in this case to experienced MWC personnel. The questionnaire session begins with a thorough discussion of the outcome, the factors and the measures. Following this, selected questions are discussed by the group; the object of this discussion is not to decide what the "right" answer is, but to ensure that all respondents are operating in the same background context. Finally, the questionnaire is completed by each respondent without consulting the others.

Quantitative Relationships

Analysis of the completed questionnaires, using statistical techniques similar to curve fitting, allows the derivation of an algebraic relationship, the transfer function, between the factors and the outcome. Often this relationship has a simple additive, multiplicative or averaging form. The method does not claim to explain how different factor levels "cause" a particular level of outcome. What the method does claim is that, for any combination of factor levels, within the range covered by the questionnaire, the transfer function gives a good approximation to the subjective estimate of the outcome level that the respondents would have given, if they had been asked that particular combination.

The following points should be noted:

- This method allows the analyst to focus on the factors of interest and to investigate the relationships between those factors; other factors, equally valid, can be left to the background. This means, however, that the relationship between those background factors and the factors under investigation is unknown. In particular, for man-machine systems, it leaves unanswered the question, to what extent is the outcome the result of the given levels of the given factors (the capabilities of the systems the operators are working with), and to what extent is the outcome the result of the operators compensating (with informal, perhaps ad hoc procedures) for the shortcomings of the systems with which they work.

- This method allows the analyst to investigate relationships between factors that would ordinarily be thought incommensurable. This is particularly a problem in C^2 systems involving complex man-machine interactions.

- STF is not for everything. In particular, if adequate quantitative analysis of a problem already exists, then STF will not improve on this existing analysis. We feel that this is the case with communications systems, adequate analysis of connectivity already exists, so nothing would be gained by applying STF to analyzing communications systems.

- Building a model with this method involves the concatenation of subtrees into a larger tree. For example, the outcome of the preceding tree, Completeness of MWC Information, is a factor in the tree in Fig. 2.

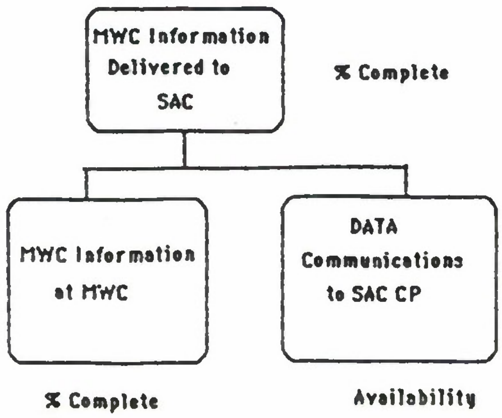


Figure 2. Node for questionnaire 111

Because the questionnaires for the different trees may be administered to different groups of experts, it is vitally important that the definitions of the factors and the measures be understood consistently by all groups.

A PLANNING DECISION AID FOR VANGUARD ANALYSTS

Goals

Practical use by ESD staff analysts is an important quality for any tool that purports to help out in the C^3I Development Planning job. As part of our Task 4 plan we set out to demonstrate that results of STF analysis could be packaged for use by Vanguard analysts. Our objectives were:

- to show examples of program analysis and program comparison: the tool should provide a measure of the contribution to baseline capability for each program or program combination under consideration.
- to show how technology guidance can derive from Vanguard analysis: the tool should indicate, through sensitivity analysis, the capabilities that most impact the overall mission value.
- to demonstrate easy user interface concepts: the tool should be small and portable and directly usable by the Vanguard analyst with minimal effort; hopefully, it should be reasonably interesting to work with.

3. EXPERIMENTAL TEST OF STF APPLICABILITY

CHOICE OF VANGUARD STRATEGIC C^2 MISSION

Several simple facts led to the decision to test STF with the Strategic Defense C^2 mission.

- Analysts at ALPHATECH were familiar with the mission. We realized that this would be helpful; in fact, we discovered that familiarity with the mission area is crucial to the analyst pursuing the investigation.

- ESD had good contacts at the commands. This was even more important than we had expected.

- There were not as many strategic programs as in some other mission areas, so the job did not appear overwhelming. In fact we ended up looking at only a few programs. Also, this was a mission area in which all the programs under consideration contributed ultimately to a common goal, which provided a means of comparison of these programs.

We focused on information flow from the MWC to the NORAD CP to SAC and to the NCA, and on programs serving this flow. Practical limits to the resources available for analysis and data collection left us with a reduced tree and only a few programs that it could cover. The program comparison and analysis was therefore only a demonstration, not a full scale test of how STF could be used for Vanguard. Appendix A shows the complete tree originally devised, and the reduced tree. In particular, the demonstration analysis includes most of the the NORAD Command Center programs, but excludes those from SAC. It excludes communications systems for reasons discussed above: we can draw better quantitative results from existing analytic studies, so we felt that applying STF was inappropriate. We excluded sensors and Air Defense systems because they belong to a different mission. We also excluded mobile systems because they made no contribution to our scenario, in which post-attack Force Management was not covered. Similarly we excluded SPADOC systems because SPADOC does not feed Strategic Defense at SAC.

SETTING UP STF

Initial Visits

We began our data gathering with initial visits to SAC and NORAD. In these interviews we were concerned with structuring the hierarchy, determining appropriate measures for each of the nodes in the tree, and determining appropriate levels of the measures. Generally we found that agreement could be reached fairly quickly on the elements of the hierarchy, and their relative structure, but the question of measures was far more difficult.

Later developments in the project convinced us that further data gathering is very necessary, prior to administering the questionnaires, for the following reasons:

- These initial trips tended to focus on current mission area requirements, with future requirements less well discussed.
- Not all the factors that were initially discussed were actually relevant at the questionnaire stage.
- Many of the factors were very sensitive to the specific scenario being used as context.

Trees

As expected, in the tree we developed in discussions with MAJCOM personnel, the SAC Strategic Offense Mission has three major components: Force Warning, the survival options available; Force Direction, the offensive response; and Force Management, fine-tuning, retargetting, and R^3. These three branches are not simply a task breakdown of the C^2 mission; they represent specific information that the C^2 mission provides to the Strategic Offense mission.

We found that there were three major NORAD information products provided to SAC: Missile Warning Data, the stream of processed and summary data that is provided from the Missile Warning Center (MWC); CINCNORAD's Attack Assessment, provided at * minutes after each event warning, and NORAD's Attack Characterization, again a stream of data from the NORAD CP. Each of these products feeds the next, as well as feeding SAC. The relationships between these can be pictured as in Fig. 3.

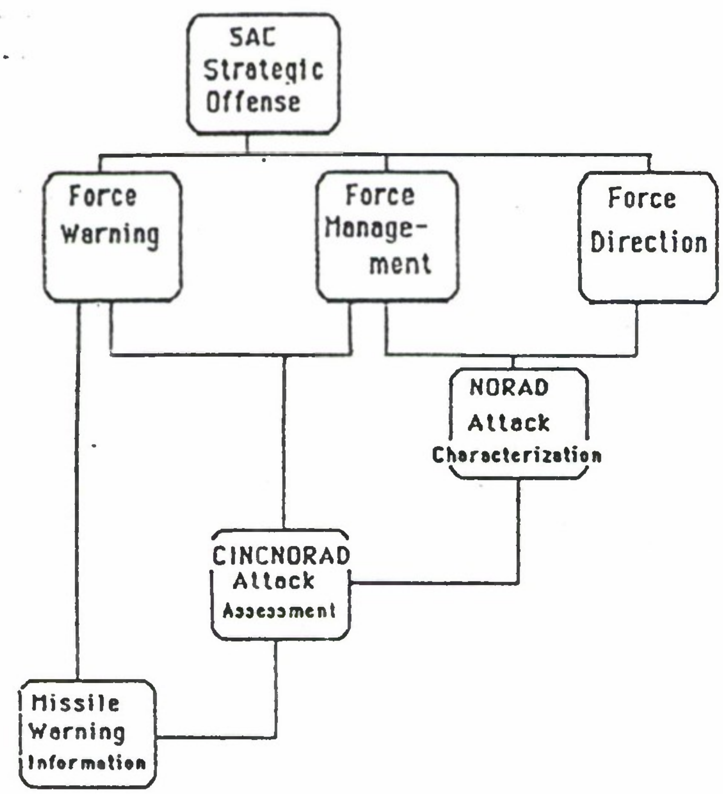


Figure 3. Flow of Information, NORAD to SAC

Formulating Measures

As mentioned above, it was difficult to define appropriate measures for many nodes of the tree. The task was complicated because we were trying not only to model the existing mission, but also to gain insights into systems that would best suit future mission requirements. We had anticipated a need to define and discuss alternative future technologies. We also discovered that operational personnel were not necessarily familiar with future mission requirements, and found it necessary to involve planning personnel from the relevant offices to define and discuss possible future mission requirements. The STF method stresses the need to deal with operational personnel; however, we found it necessary to deal with technologies and requirements outside of the day-to-day experience of these personnel.

Of the measures that appeared the most useful, the hardest to explain was the concept of completeness of information. We also used delay, rates and qualitative measures of the man-machine interface. Appendix B gives the definitions we used and Appendix C contains a separate discussion of the concept of Completeness of Information.

Scenarios

In the design of our experiment we tried to be scenario independent, but in some contexts we found that we had to tie questionnaires to concrete examples to provide a common basis for discussion. We devised a low load scenario evolving to a high load scenario as background and for use when such discussions became necessary. The low load scenario was meant to be ambiguous; additional information from several sources would be needed to assess the situation with confidence. This would stress the Integration and

Assessment (fusion) activities in the NORAD Command Post. The high load portion of the scenario, on the other hand, was chosen to stress the event processing activities of the Missile Warning Center.

However, we eventually discovered (at SAC) that the employment of strategic offensive forces was quite dependent upon nuances of the scenario and for our particular example CINCNORAD's Assessment, though normally an important input, was not a significant factor. Because requirements and decisions in this mission are so sensitive to scenario, and because system performance is also scenario dependent (i.e., interactions with threat, environment and other sources of stress) we determined that a more elaborate scheme than the one we tried is needed for including scenario effects in STF.

Collecting Acquisition Program Data

Inputs at the bottom of the tree describe the capabilities of systems that are produced by acquisition programs. In the Vanguard application of STF we measure program contribution and value to the mission by these system capabilities.

For most capabilities the contribution of a program (or a collection of programs) can immediately be estimated from basic information about the system(s) that are being acquired and deployed. However, some system capabilities are defined by operationally oriented measures of performance. Such operationally oriented measures include: clarity of display, user friendliness, data base query capability, sophistication of fusion data processing, and data processing capacity.

These capability measures depend on several system attributes, which the STF methodolgy combines into single measure. In this experiment we did not collect quantitative data on the transfer function describing how the operational capability depends on the attributes. Instead, we chose a simple weighted sum of attributes as a surrogate transfer function.

The forms for recording system attribute data are shown in the charts in Appendix E. Weights for different attribute levels are included on the forms.

For each set of systems and for each operationally oriented measure a form is filled out indicating the attributes that the system(s) include. The selected weights are then added and multiplied by an appropriate scaling factor to give a rough value of the measure. More elaborate transfer functions can be constructed with the same attribute data.

ADAPTING STF

Initial Questionnaire Design

We developed an automated tool for generating questionnaires in anticipation of many nodes of data collection and to determine if STF could easily be implemented on a larger scale. We discovered that for many of the nodes, a complete full-factorial questionnaire (asking all possible combinations of levels of factors) would run to several hundred questions and was not practically possible. Our initial questionnaire design concentrated on asking more questions of combinations of all factors together, at the expense of asking few two-way combinations of factors. We felt that this would give us the best statistical fit of model to data. Unfortunately this masked the two-way interactions in which we were also interested.

For our second round of visits we adopted a technique called Central Composite design. This is an efficient technique for choosing a minimum number of questions posing combinations of all factors; it allowed us to ask a complete set of two-way combinations of factors, and did indeed give us better insights into interactions between factors.

We believe that future STF efforts should utilize general purpose tools, such as we developed, for generating questionnaires, recording responses, and doing data reduction. This means that the "housekeeping" involved in an STF effort can be greatly reduced.

What cannot be reduced, and we stress this, is work with the respondents. The originators of this method (Rand publication R-3021-AF) state that three visits are necessary: a first to develop the trees and measures, a second to validate the tree and administer a small dry run of the questionnaire, and a final visit to administer the full questionnaire. Originally we questioned the necessity of the second visit. We now not only agree that the second visit is necessary, but we feel an additional visit, prior to these three, may be necessary to locate the "experts." Because future mission requirements and future system capabilities must be judged, it is not necessarily true that operational personnel doing the job today are the best respondents. We found that personnel with operational experience who also had recent experience in the planning field were most helpful. (This prior visit would also provide an opportunity to explain and "sell" STF.)

SETTING UP THE ANALYST'S DECISION AID

We chose the MacIntosh personal computer as the PC for implementation of the prototype decision aid because it offered easy access to interface options such as: windows, mouse, dialog, pushbuttons, menus, graphics, and the like. We made a deliberate attempt to sample several different interface techniques to show ESD the kind of things they should ask for and expect in future data processing tools. As a prototype, we expect that the decision aid will not have operational use and will provide concepts for, but not be, an operational baseline for subsequent applications.

4. RESULTS

This section summarizes the results of the experimental test of the STF method applied to Vanguard analysis. The test was successful, but we did not cover as much ground as we had wished. We learned a lot about the relationships among operational requirements, system capabilities and program evaluation. In addition, as was planned, we did implement and install a C^2 model on a personal computer. Some of what we learned is applicable to Vanguard analysis, some applies more broadly to Development Planning and System Acquisition.

THE CAUSAL TREES

We believe that the causal tree developed in this project has value even apart from the software tool in which it is embedded. It offers an alternative and complementary view of the mission area from that mandated in AFSCP 80-3 and used in Vanguard today.

Since the trees delineate the system capabilities that operators themselves find important in their work, the trees can be used by Vanguard analysts as a first step in program evaluation. In particular, they show what capabilities need to be present together to accomplish a particular function. Similarly they should be helpful to analysts doing Technology Planning and System Development.

DATA COLLECTION EFFORT

We encountered several difficulties in data collection. We have already mentioned the difficulties in defining measures; these were sometimes difficult to explain. Clearly, from the responses on the questionnaires, we can see that our understanding of some of these measures was not the same as the respondents'. For example, the relationship between completeness of information and time: Is completeness something that must increase with time (as you get more information processed)? Or is it something that can be expected to decrease (because the amount of information you need increases relative to what you have — or — because the amount of information that is available in "the real world" is greater than you can process)? Another difficulty, already mentioned, was the problem of asking operational personnel, whose experience and overwhelming concern is with the current mission requirements, to make judgments about future mission requirements. Because we underestimated the amount of preparation needed we sometimes found ourselves redesigning questionnaires and refining definitions and scenarios on the spot. Lastly, there were practical difficulties involved in locating appropriate personnel and getting them together in the same place at the same time for the amount of time we needed — typically at least half a day, sometimes an entire day. For no questionnaire did we have more than three respondents.

The implication of the above is that we feel it unlikely that a Vanguard analyst could do an STF analysis of his mission area unaided. It requires considerable expertise in the operational aspects of the mission area as well as considerable expertise in STF, and a lot of preparation.

In addition to collecting mission data from the Major Commands, we needed to collect program data from ESD. Since the number of programs that our reduced mission area coverage could include was very limited, the latter was rather cursory. We reviewed the data calls and relied on our knowledge of the programs we felt we could realistically include in the demonstration to complete the program contribution sheets.

STF ANALYSIS

Reducing the questionnaire responses to transfer functions requires considerable effort. We used a general data reduction tool that uses statistical techniques similar to curve fitting. Had we been able to analyze the entire mission area we would have done far more questionnaires. We could not have accomplished it without this tool.

As it was, for at least one of our questionnaires the best transfer function we could devise has a larger chi-square measure than we would like. We feel that the questionnaire design in this case was poor.

Some of the interactions displayed by the quesionnaire data made obvious intuitive sense. The questionnaire covering fusion (information integration and assessment) showed a relationship between data processing capacity and display: the more data processing capacity, the more important to have sophisticated display available; the relationship is as shown in Fig. 4. As data processing capacity increases we see that increased levels of display make more of a difference to the outcome. The result is that the plots spread out in a fan shape; if there were no interaction the plots would be parallel.

In other cases, relationships that we expected did not appear. On the same questionnaire we expected a similar relationship between access to other data and display: we expected that the more non-MWC data was available, the more important display would be. This did not appear in the data; see Fig. 5.

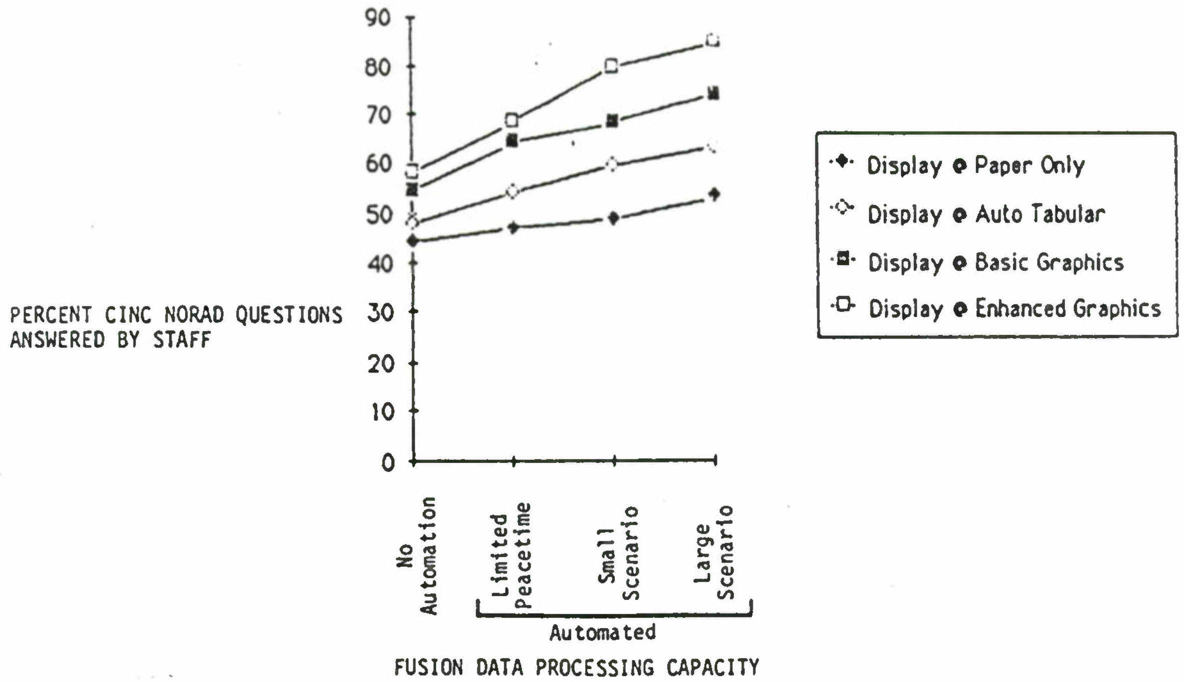


Figure 4. Interaction of Display with D.P. Capacity

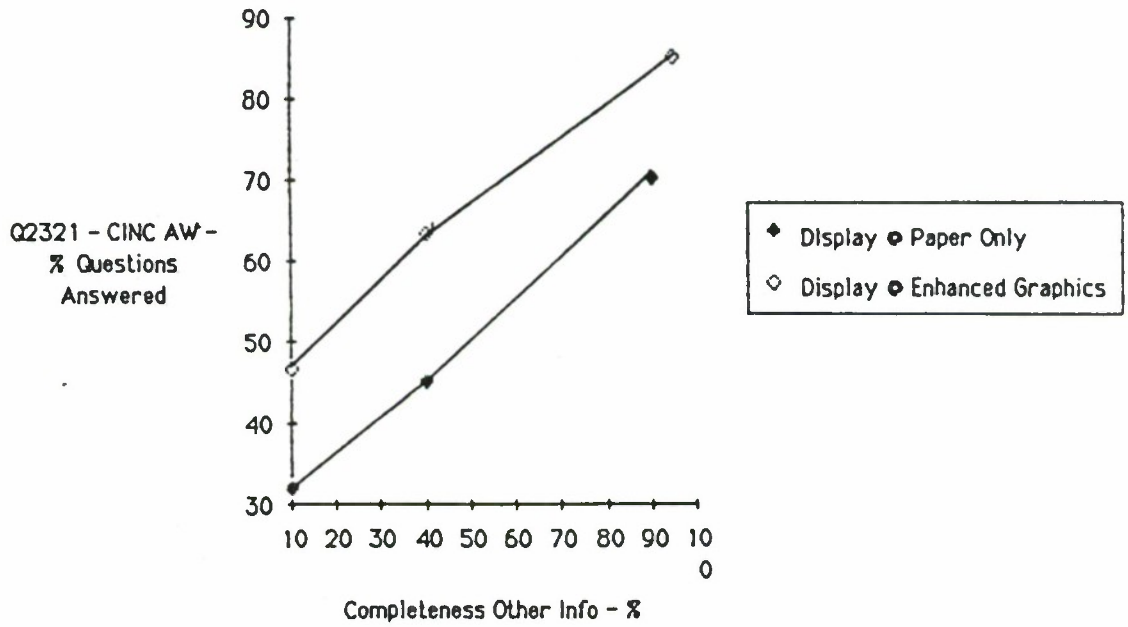


Figure 5. Lack of Interaction Between Display and Other Information

The plots are (nearly) parallel because the increase in display capability makes the same difference in the outcome, regardless of the level of completeness of other information. Perhaps there is little interaction between these factors. We suspect that we asked the wrong questions or that we asked them in the wrong way. In this instance we suspect that we did not make clear that other data was not something that would just somehow "be there;" i.e., that other data would also need to be displayed.

Usefulness of Results

We are convinced of the potential value of the STF method. It indeed provides an excellent way of getting an approximation of the nature of complex interactions between multiple factors affecting an outcome. The nature of the complete STF model is such that, if more precise analytic relationships become available, it is easy to substitute these for the transfer functions developed from the questionnaires.

We caution, however, that the results of this project will not lead directly to a Vanguard analyst's support tool. We were unable to cover an entire mission area with the time and effort available and we still feel the question of appropriate respondents for an evolving mission area remains open.

TOOL DEVELOPMENT

In Task 3 of the project we surveyed available computer models of C^2 systems. We determined that few were applicable to the problem Vanguard addresses and that none of these was practical. Often, these applicable models were not practical because they lacked a model environment. The relationship between a model and its environment is shown in Fig. 6.

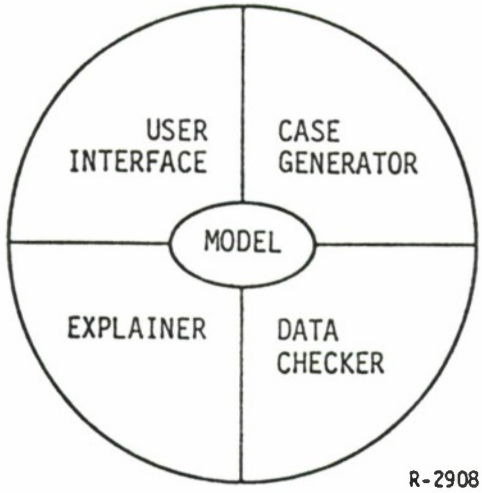


Figure 6. Model and Environment

A model environment includes a user interface, a case generator, a data checker and an explainer. A user interface makes it easy to use the other parts of the environment, as well as running the model itself. A case generator makes it easy to change selected variables of the model and to create new data sets. A data checker ensures that the data prepared by the case generator fits the requirements of the model, and if not, indicates why not. Finally, an explainer both interprets the model results and explains how they were developed.

Our prototype, the Vanguard Analysts Support Tool (VAST) incorporates much of the necessary model environment. Figures 7 through 12 show screens which VAST uses to interface with the analyst. The interface is graphic where possible, and relies on the use of windows, buttons, and the mouse, as well as default choices, to reduce analyst effort to a minimum. Figure 7 shows the opening screen; from this screen the analyst selects an item from one of the menus. If he wishes to create a new data set, he is shown the screen in Fig. 8. The upper window allows the analyst to name the data set and the

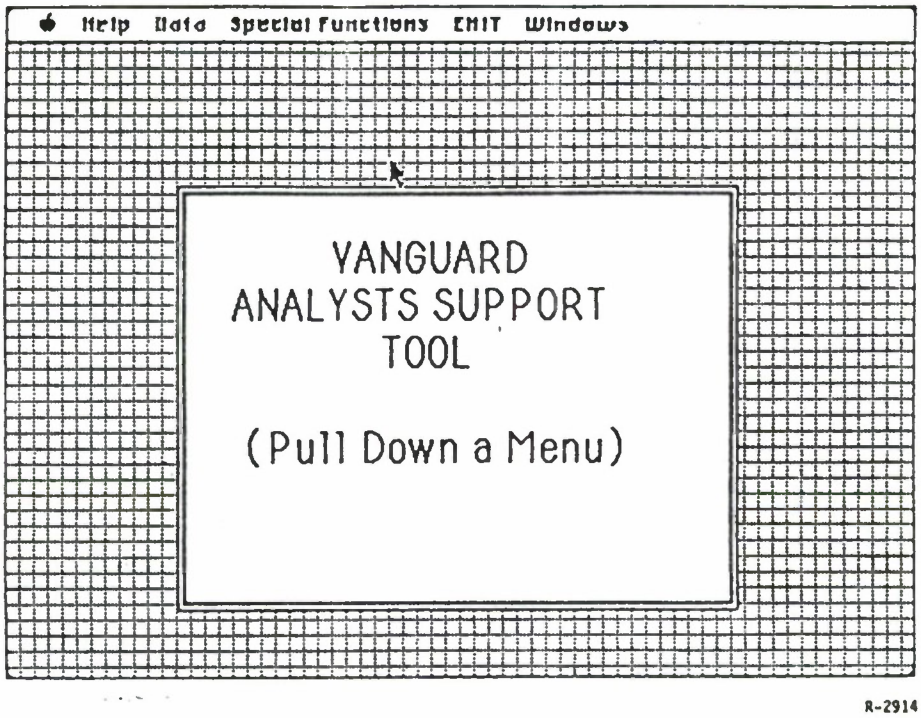


Figure 7. Opening Screen

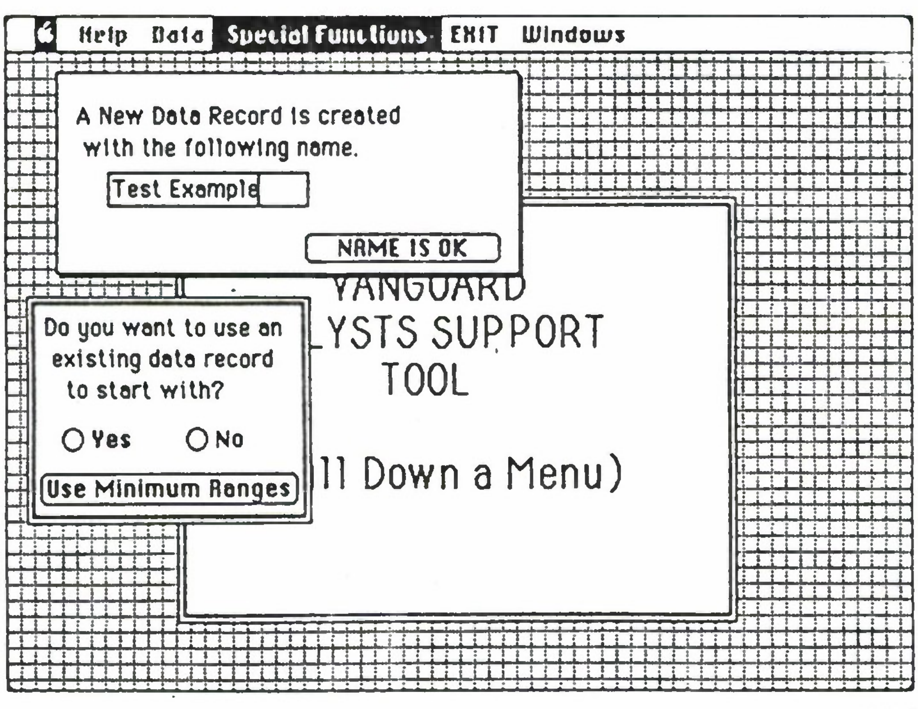


Figure 8. Creating a New Data Set

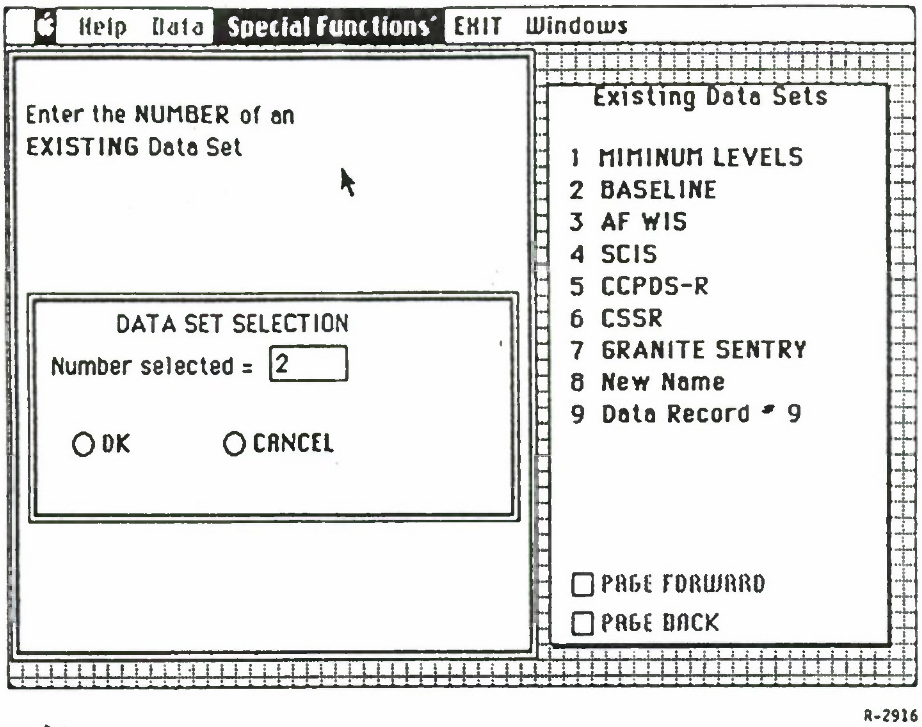


Figure 9. Basing the New Data Set on an Existing Data Set

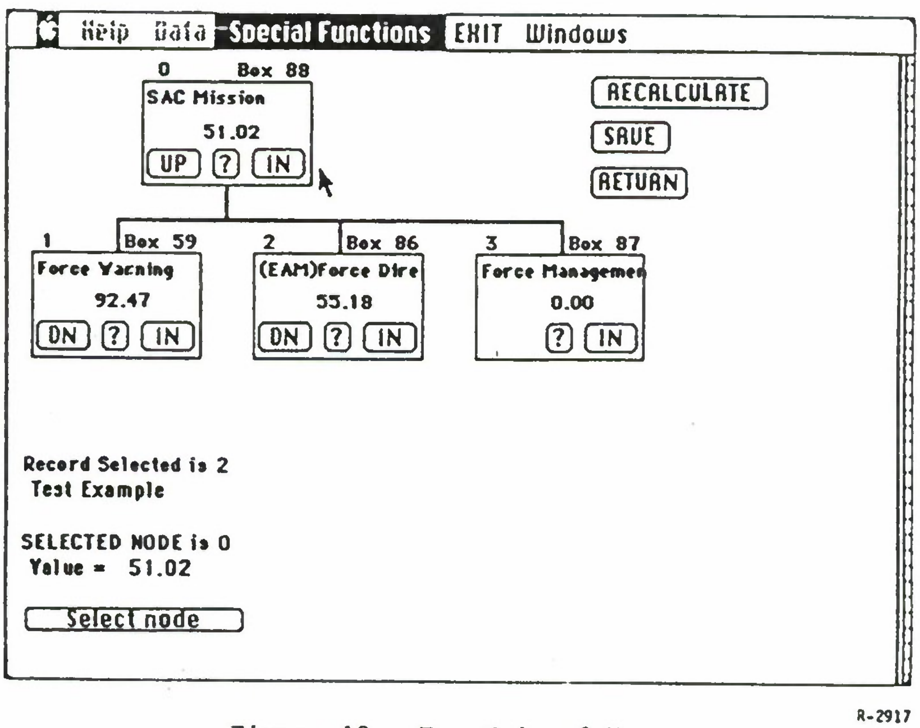


Figure 10. Top Node of Tree

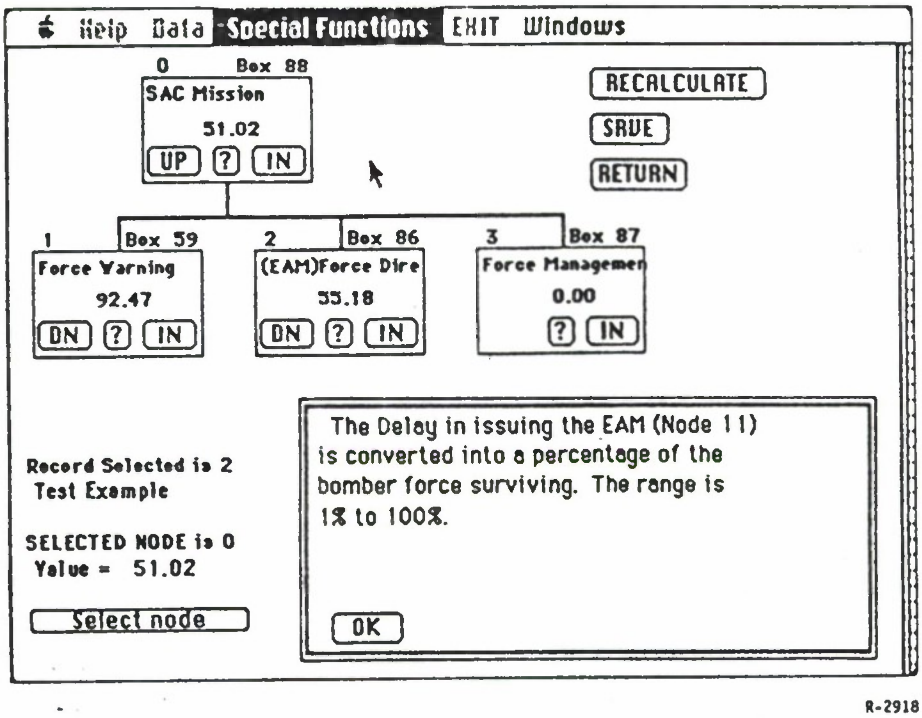


Figure 11. Information Screen

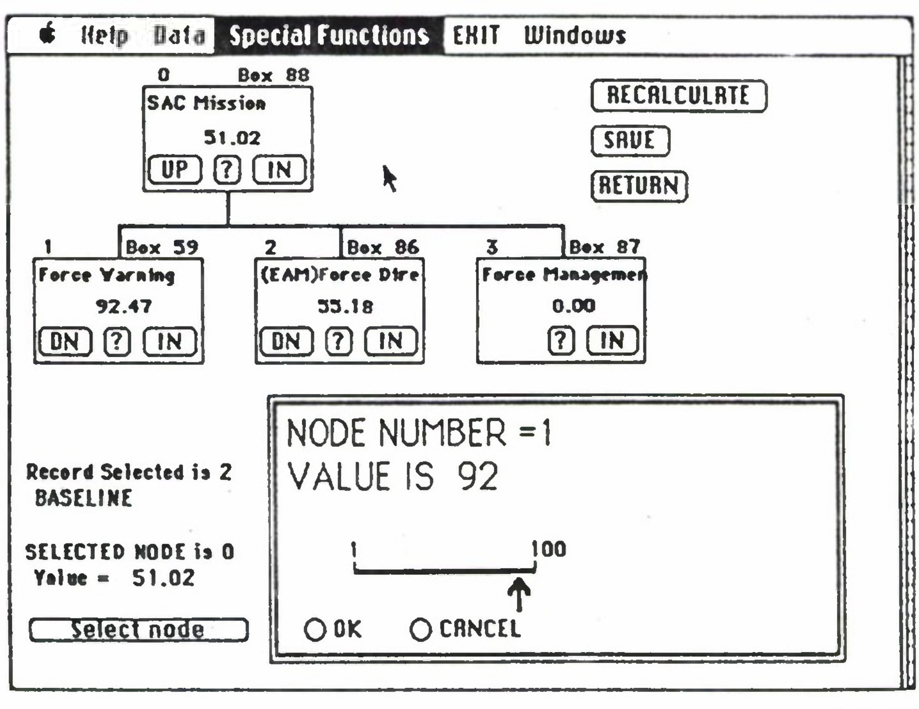


Figure 12. Data Entry Screen

lower window allows him to base his new data set on an existing data set. Figure 9 shows the screen for selecting the existing data set. Having selected a data set, Fig. 10 shows the top level of the tree for this data set. The UP (up) and DN (down) buttons allow the analyst to view other levels of the tree. The ? (information) button provides information about each node and the IN (enter) button allows the analyst to change the value at any node. The RECALCULATE button initiates a recalculation of all values; when completed the screen appears with new values as calculated. Figure 11 shows the result of selecting ? for node 1 and Fig. 12 shows the result of selecting IN for node 1. Note that in place of an explicit data checker, we restrict the choice of values for each node to a valid range.

The Analyst's Decision Aid, VAST, uses as a basic data structure a Data Set that represents a level of capability from groups of programs. We have included a Data Set that represents Minimal Levels, and a Baseline Data Set. It is our estimate that the baseline capability represents, roughly, the capabilities presently available in the NORAD MWC and CP systems. For each of the programs considered in the demonstration (SCIS, AFWIS, etc), there is a data set which represents the baseline plus the added capability from the program. We designed a contribution form which facilitates entry of data into the data set; for the qualitative capabilities we designed checklists of system attributes which will aid in estimating the level of capability that the program provides. In this initial effort it is not possible to compare combinations of programs.

We believe the software tool developed on the PC demonstrates that successful incorporation of STF concepts in a tool that the Vanguard analyst can use directly is feasible. The prototype took approximately four person-months to develop. We are still unsatisfied with the way in which program data is incorporated and suggest extensions for a second edition that would involve automating the checklists and programs contribution sheets. A next edition could take six person-months to develop. This is still modest as software costs go. This tool is an example of the simple, PC-oriented tools that we recommended in Task two.

VANGUARD PROGRAM EVALUATION

The program evaluation that the prototype software tool provides must be used very carefully if at all. Program comparisons are available but should be interpreted carefully. Given the data content of the tool, the prioritization of programs is not significant. The sensitivity analysis that the tool provides is a useful concept but again, is probably not significant due to the lack of rigorous data.

5. CONCLUSIONS

SUMMARY

The immediate problem we faced in applying STF to ESD's Vanguard mission area analysis was that of separating the process of Command and Control, leadership, if you prefer, from the evaluation of Command and Control systems. Our primary conclusion is that this can be done; our solution was to approach C^2 system as information systems whose purpose is decision support. Implicit in this approach is the assumption that the better the decision support available, the better the decision that is made. Beyond this, we did not attempt to analyze how decisions are made by commanders.

Thus we focused on information generation and transformation from the sensors through to SAC CP, and attempted to determine how capabilities of information systems affected the quality of the information available: timeliness, accuracy, completeness, relevance (priority), etc.

We conclude that STF can be an effective modeling tool for mission area analysis and program evaluation. It is not a panacea for Vanguard. STF needs to be done carefully, and with a lot of preparation. It is expensive.

Apart from STF, we feel the prototype software tool developed on the PC demonstrates that tools can be inexpensively developed that incorporate relatively simple yet powerful ideas, and that the analyst can use directly without a software expert as intermediary. As we stressed in our Task three report, the user friendly interface is highly important.

ABOUT STF APPLICABILITY

We leave open the question of whether STF should be applied to further Vanguard analysis, even though we are convinced of the basic merit of the method. We believe it is applicable to other analyses. The trees are a useful tool for requirements definition; they provide a common basis for discussion between operational personnel and planners as to what is important and what is related to what. The capability sensitivities and interactions are useful for technology planning: they tell technology planners what capabilities "go together" and where tradeoffs can be made.

A major limitation of the STF method is that it forces measures into one dimension. Operators might feel that MWC information, for example, should be measured both by completeness and by timeliness. As now defined, STF forces the analyst to choose one measure, or to invent some surrogate measure that somehow incorporates both completeness and timeliness. This surrogate measure may not be intuitively obvious to personnel who are being asked to make judgments about it.

In some cases the precision and accuracy that STF requires is not needed: for some program decisions qualitative relationships would be just as useful. But on the questionnaire the respondent is required to make a precise numeric judgment; he cannot respond with a range of values, or a qualitative judgment.

We have discussed elsewhere the lack of expertise in future technologies and evolving mission requirements.

ABOUT ANALYST DECISION AIDS

We still believe in analyst decision aids that are PC-based, useful and inexpensive to develop. The ideas and data content that inform these decision aids, however, may not be cheap.

ABOUT RESOURCE COSTS

The question arises: What resources would be required to do the Strategic C^2 Vanguard sub-mission area in another Vanguard cycle, given the preceding conclusions?

These are the assumptions that were made in arriving at the following estimates:

1. The size of the mission area hierarchy will not vary much from the tree devised for this effort: there will be about 90 nodes and 25 questionnaires.

2. The number of programs will continue to be about 30.

3. The data reduction software (to convert questionnaire results to transfer functions) is satisfactory. This software is written in Fortran to run on a VAX 11/750. It required eight person-weeks to write; it would probably require three person-days to convert it to run on another VAX system, somewhat more to run on some other system.

4. All BASIC programs should be rewritten in a more structured language on a common micro-computer:

STF10:	data entry for nodes	5 days
STF20:	print questionnaires using Central Composition design	5 days
STF30:	data entry for questionnaires	5 days
VAST:	Vanguard Analyst Support Tool	50 days

   (All the above estimates include time required for design and documentation.)

5. Three visits will be required for each of the major commands, SAC and NORAD. This assumes that a preliminary trip to familiarize the commands with STF will not be necessary, and that the required group of experts can be located, and their cooperation agreed to, either by telephone or by local cooperation. It also assumes that it may not be possible to make the first, second and third visits to SAC and to NORAD on the same trip, because of the difficulties of getting the required experts together. On the other hand it does assume that all the expert groups at one command can be interviewed on the same trip.

With the above assumptions, the following are estimates of person-days of effort required for each of the tasks shown.

0.	Preliminary: Software -- see above	65 days
1.	Structure trees and devise measures	
	- two people at 1/2 day per questionnaire*	25 days
	- from the major commands, three people at 1/2 day per questionnaire	38 days
2.	Check overall tree structure, node data entry and print questionnaires	5 days
3.	Follow-up visit	
	- two people at 1/4 day per questionnaire	12 days
	- from the major commands, three people at 1/4 day per questionnaire	18 days
4.	Preliminary analysis at 1/4 day per questionnaire	6 days
5.	Fix any problems	5 days
6.	Final visit	
	- two people at 3 questionnaires per day	10 days
	- from the major commands, three people at 3 questionnaires per day	15 days
7.	Data entry of results	2 days
8.	Data reduction at 1/2 day per questionnaire	12 days
9.	Get results into VAST and check	10 days
10.	Analyze programs at 1/2 day each (This assumes some familiarity with the programs.)	15 days
11.	Write reports, prepare briefings	10 days

*The estimate of four hours per questionnaire is an average, some would take less, others more. For the follow-up and final visits the estimate of two hours per questionnaire assumes that not all questionnaires would need to be discussed: many would be similar to one another.

Other charges:

1.	A micro-computer	$4,000
2.	12 round-trips to the West at $500	$6,000
3.	Other travel at $100 per day	$4,800
4.	VAX time at 1 hour per questionnaire	$7,500

ABOUT REVISION OF THE MODEL IN SUBSEQUENT YEARS

The following estimates assume that the higher levels of the tree represent organizational arrangements which are not likely to change from year to year, but the lower levels of the tree represent local operational procedures and the systems which support those, and these are likely to change. We assume therefore that 40 nodes, 10 questionnaires, might change and that the changes could be covered in two visits.

1.	Preliminary visit	
	- two people at 1/2 day per questionnaire	10 days
	- from the major commands, three people at 1/2 day per questionnaire	15 days
2.	Final visit	
	- ESD effort (same as above)	10 days
	- major command effort (same as above)	15 days
3.	Data Entry	3 days
4.	Data Reduction	3 days
5.	Modify VAST	5 days

Other charges:

1.	4 round trips to the West	$2,000
2.	travel at $100 per day	$2,000
3.	VAX time - ten hours	$3,000

6. RECOMMENDATIONS

A. ABOUT VANGUARD DATA COLLECTION

1. Program data should be collected in a more structured way.

   We recommend developing checklists for collecting program data and incorporating these into the Vanguard data call. These should also be incorporated into the automated data base now being developed for Vanguard. Eventually much of the program data collection could be automated. As we have recommended in previous tasks, data collection for Vanguard should not be an isolated effort: the evolving body of program data should become a resource for other planning activities; thus it should be consistent with data collection requirements for other planning tasks.

B. ABOUT QUANTITATIVE TOOLS FOR VANGUARD

1. As we discussed in our task 3 report, we do not recommend that ESD acquire large computer models for Vanguard. Large computer models are expensive, the few available models of command and control in Vanguard mission areas are either difficult to use or do not cover the mission area adequately.

2. This task tested the Subjective Transfer Function method for constructing and quantifying a model of one Vanguard sub-mission area. Our summary conclusion is that this method will work, it is still less expensive than a large computer model, but it is not inexpensive. We estimate that, for the complete Strategic C^2 Vanguard sub-mission area, this method would require 183 person-days of effort, totaling approximately one person-year. If we estimate one person year at $100K, this is probably one quarter — or less — of what a computer model would cost.

C. ABOUT STRUCTURAL MODELING

1. Do more structural modeling of sub-mission areas using causal hierarchies.

   We found that the construction of causal hierarchies (trees) was an excellent vehicle for discussion of mission area requirements. As with any good modelling method, it provides a way to decompose the problem into subproblems (nodes of the tree). This allows the analyst to discuss different parts of the problem with different groups of operational and development personnel. Even if transfer functions are not derived, the resulting representation of the mission provides a basis for discussion that is meaningful to analyst, operational personnel and system developers. For these reasons, ESD/XR should also consider extending structural modeling using causal hierarchies to other areas of development planning.

2. Develop structural models of other development planning activities.

Our experience with modeling the Vanguard process using IDEF and with modeling the strategic defense mission using causal hierarchies, has convinced us of the value of structural modeling of diverse activities. Structural models give people a graphic basis for discussion and provide insights not available from descriptive narrative. Other development planning activities, besides Vanguard, and other modeling methods (Petri nets, data flow diagrams, etc.) should be considered.

D. ABOUT STF

1. Consider modifying the data collection methodology of STF to adapt to evolving missions.

As discussed previously, operational personnel currently working with information systems are not, initially, particularly attuned to possible future technologies or evolving mission requirements. Consideration should be given either to locating more appropriate "experts," or quickly making current operational personnel familiar with the required new concepts, or using teams comprised of both operational and technological experts.

2. Consider simplifications of measures and ways to quantify them other than by deriving subjective transfer functions.

More thought needs to be given to the appropriate "principles of information:" timeliness, accuracy, completeness, relevance, etc. -- What are the appropriate principles and how should they be measured? In particular, qualitative measures using range instead of point estimates should be considered where appropriate.

E. ABOUT DECISION AIDS

1. Insist that decision aids be "user-friendly."

Decision aids should not only incorporate good ideas, they should also embed good ideas in software that is above all self-explanatory; it should also be portable, keep data entry to a minimum and be reasonably interesting to use. These are the principles we have attempted to incorporate into our prototype, especially by providing mouse-driven input and interaction and graphics. ESD/XR should insist on decision aids that meet and even exceed these standards.

F. OTHER RECOMMENDATIONS

1. Establish a framework for future analytic modeling efforts.

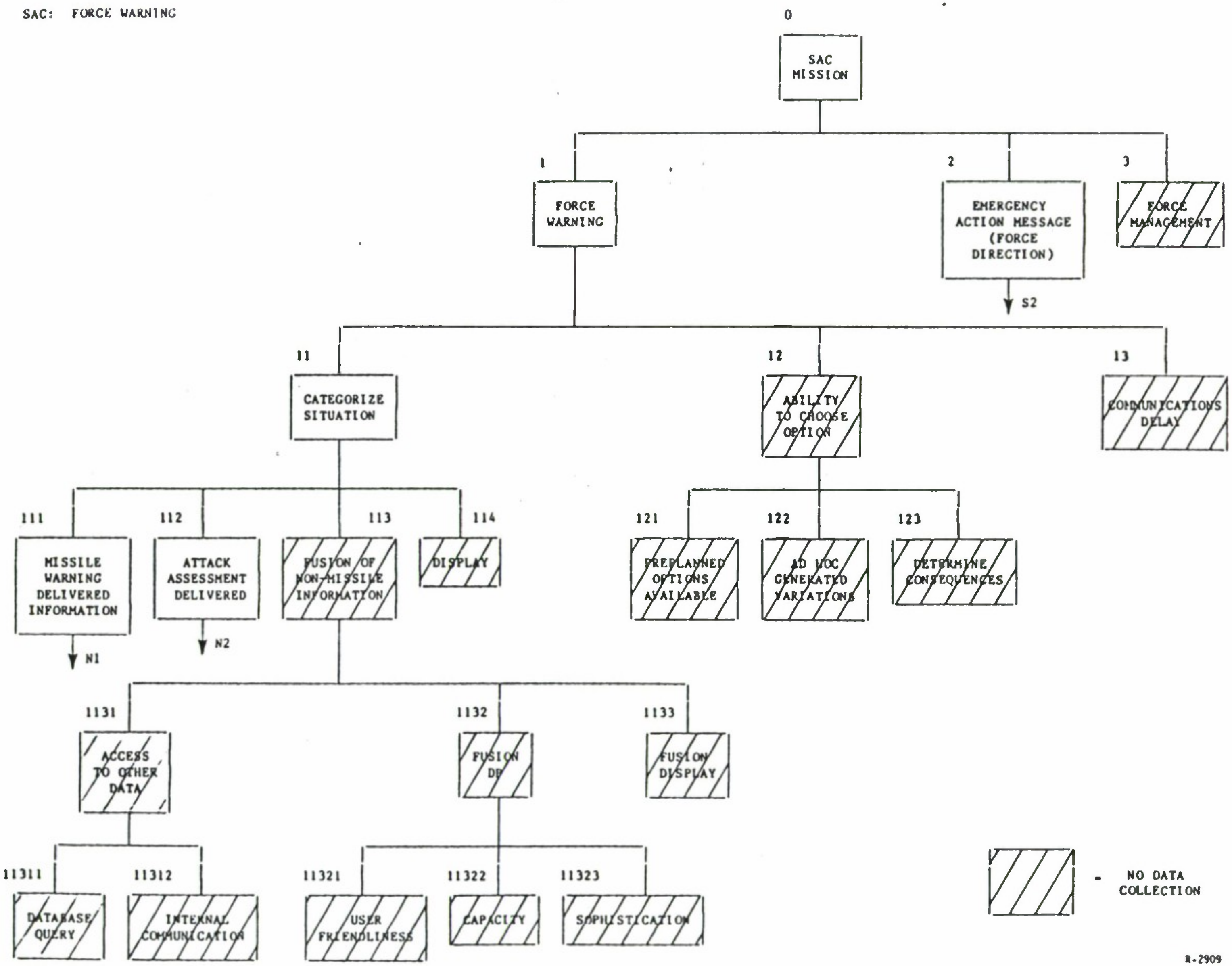
In task three of this project we determined that computer models which were both applicable to ESD needs and practical for ESD Vanguard analysts' use, did not exist. ESD/XR should establish minimum standards for applicability and practicality of future modeling efforts. The latter should include a user-friendly interface, a case generator, a data checker and an explainer.

APPENDIX A

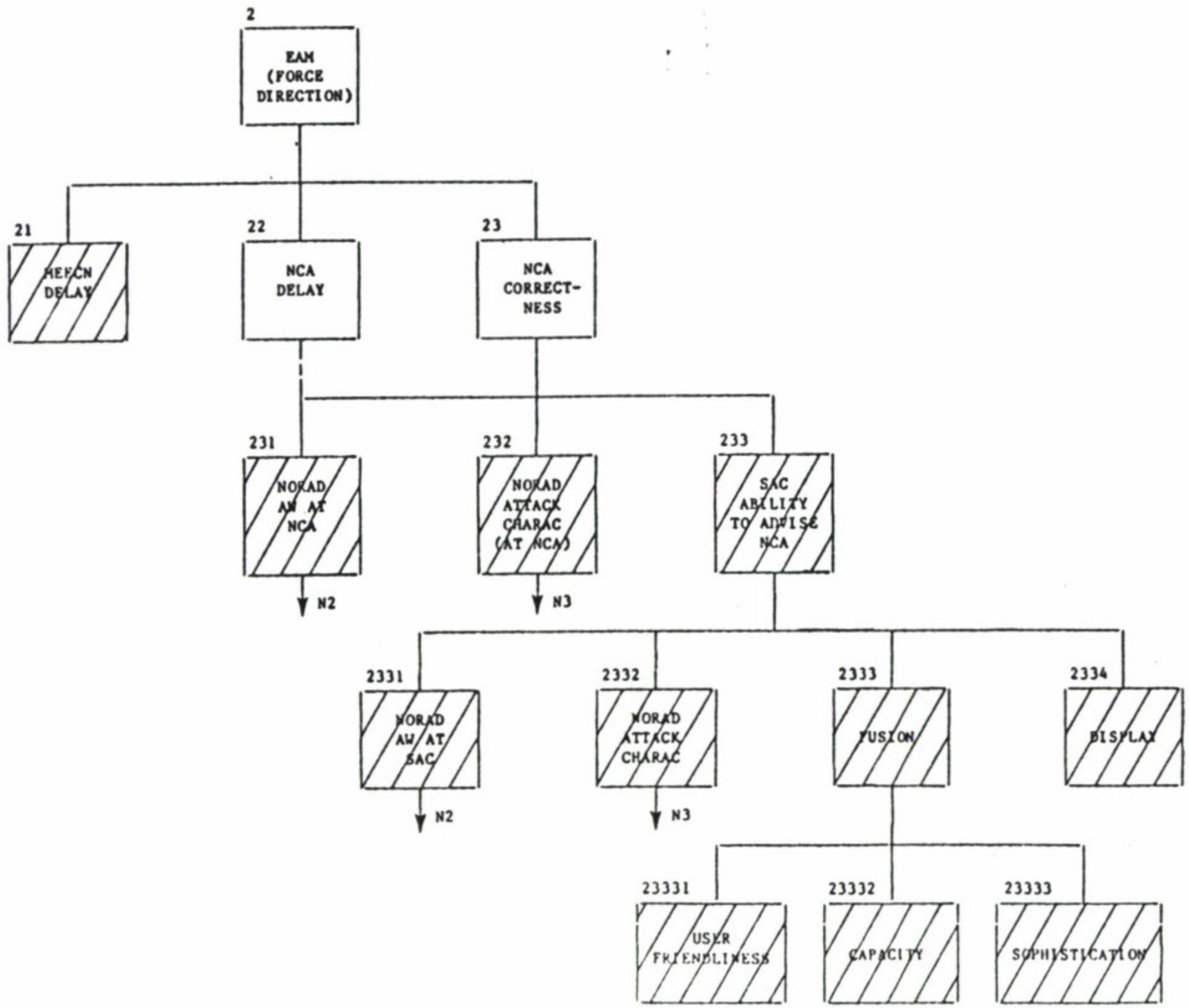
TREE STRUCTURE

These five charts show the tree as originally developed. The portions of the tree for which we were not able to collect data are indicated.

SAC: FORCE WARNING



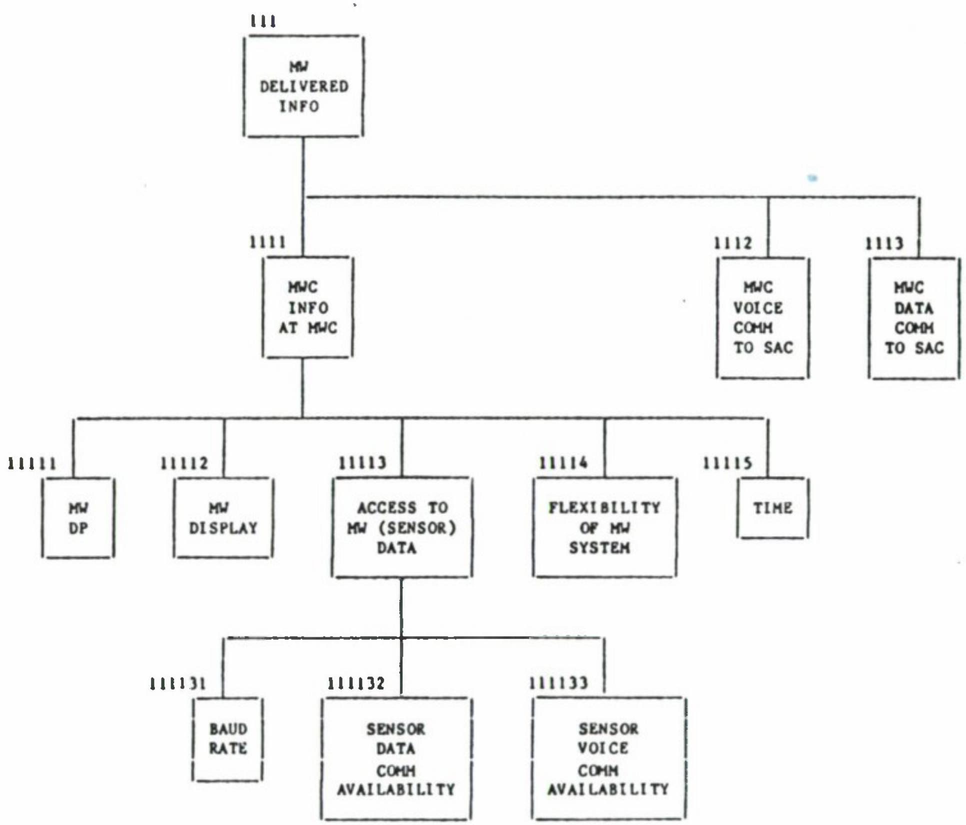
SAC: EAM



R-2910

NI:

NORAD: MISSILE WARNING

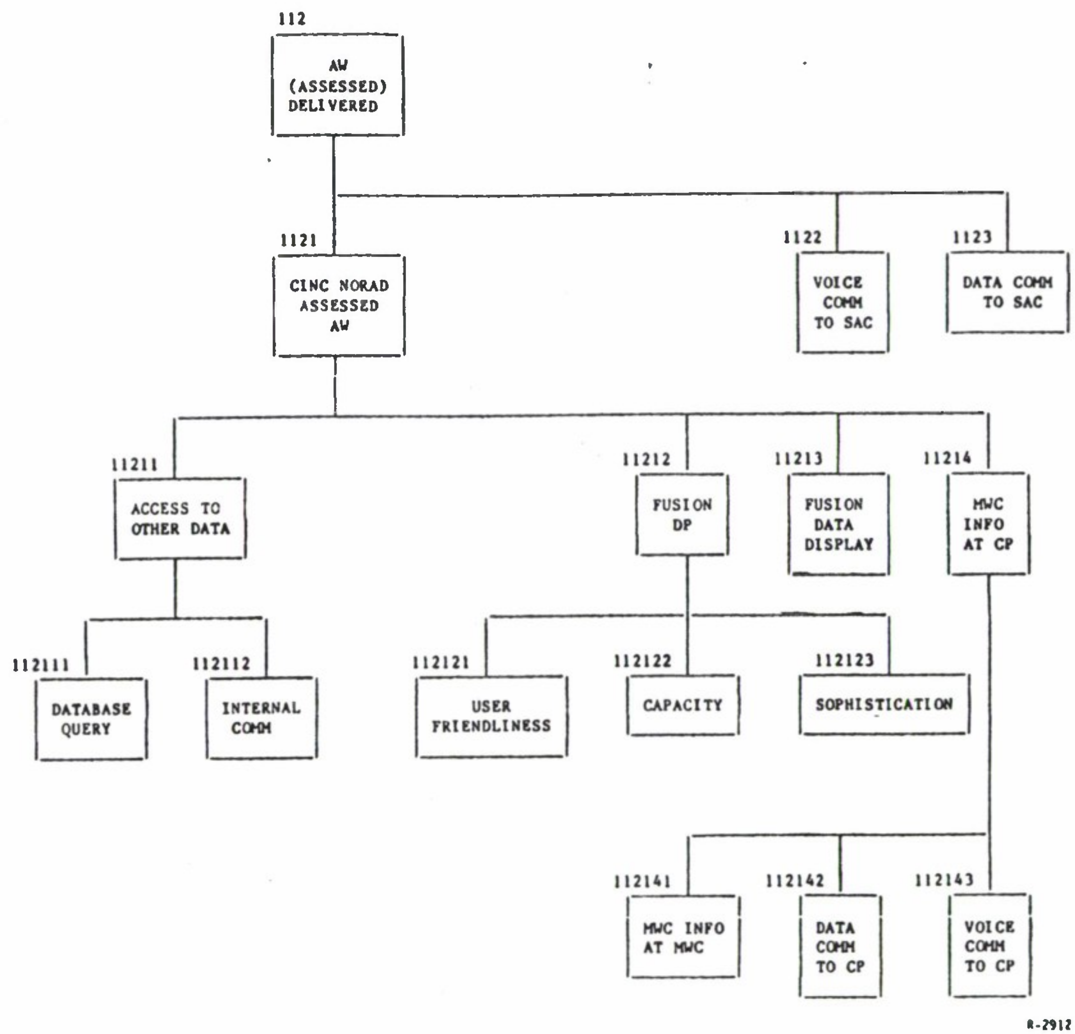


DECOMPOSITION
OF NODE 111

R-2911

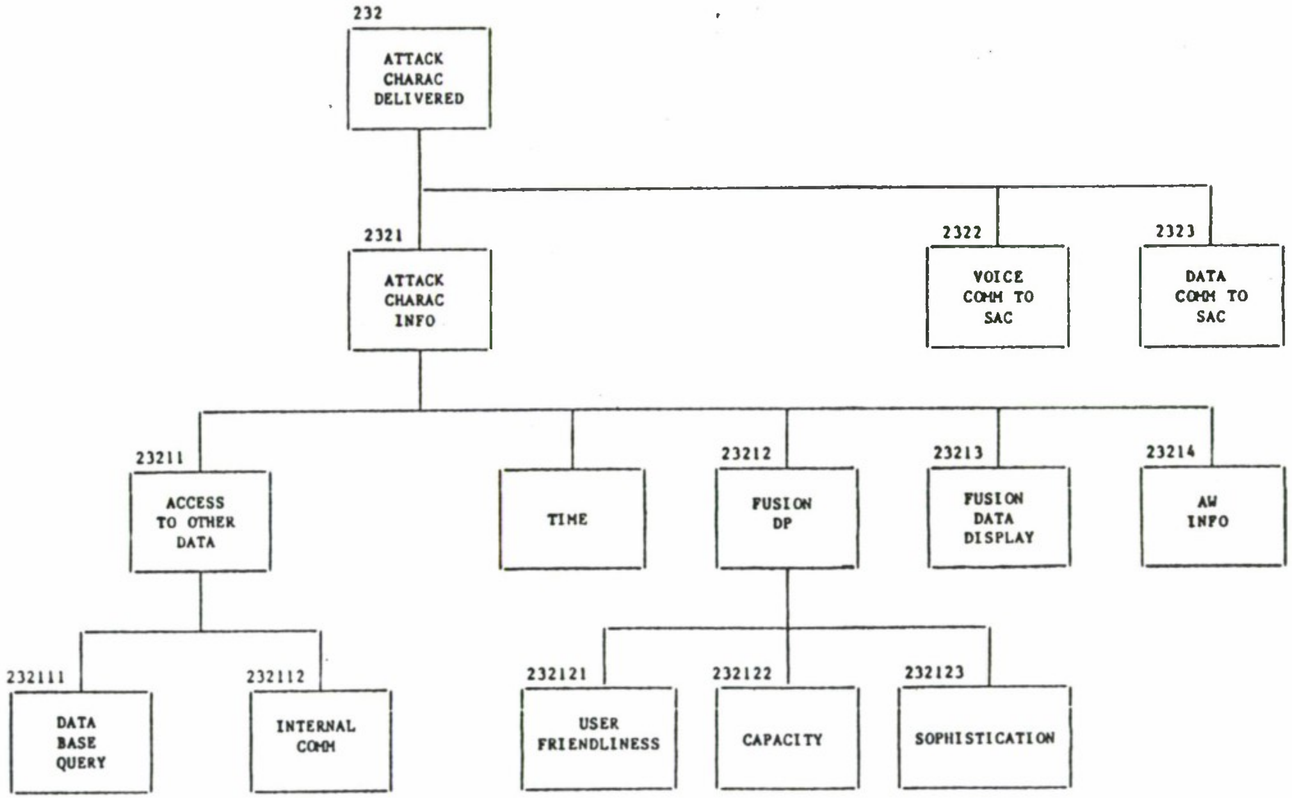
N2:

NORAD: ATTACK WARNING



N3:

NORAD: ATTACK CHARACTERIZATION



DECOMPOSITION OF NODE 232

R-2913

APPENDIX B

DEFINITIONS

AVAILABLE WARNING INFORMATION (node 1111) is the missile warning data stream generated by the Missile Warning Center (MWC). Availability is described by the completeness of the information -- i.e., of the information items that could be ready for use at a given time, how much has actually been processed and is in fact ready for the user. Specific information items include: sensor data (discrete event messages, status messages, summary messages); confidence factors; summary data generated by the MWC: other information items if appropriate.

DELIVERED WARNING INFORMATION to SAC (node 111) is the missile warning data stream generated by the MWC and degraded by communication delay and quality on its way to SAC.

DELIVERED WARNING INFORMATION to NCP (node 214) is the MWC data delivered to the NORAD Command Post. Despite the close proximity of the MWC and the CP, explicit allowance must be made for the intermediate systems that make MWC information products available to CINCNORAD and his staff.

DELIVERED CINCNORAD ASSESSMENT (node 112) is the assessment produced in the NORAD Command Post and delivered, principally by voice, to the SAC Command Post; as degraded by delay in setting up the voice circuit. This assessment, together with subsequent detailed Attack Characterization information, is also provided to the NCA to support response decisions.

ABILITY TO FUSE [integrate information and assess] (node 113) is the capability of the SAC Command Post system to provide "complete" non-missile warning information to the Senior Controller. The system is described by the degree of completeness of that other information at particular times after the initial event detection (alarm).

The corresponding fusion capability for NORAD is captured by the <u>Available Attack Warning</u> node.

MWC DATA PROCESSING CAPABILITY (node 11111) defines the capacity of the ADP support to the MWC. The measure is how quickly messages from the sensors can be processed by the system. There is clearly a relationship between how quickly messages can arrive (<u>Access to Sensor Data</u>) and how quickly they can be handled.

CURRENCY OF MWC SYSTEM (system Flexibility) (node 11114) indicates how well the system can respond to changing requirements for the warning mission. Typical changes include new processing algorithms, new and revised display requirements, addition of new sensors, revised message sets, and changes in data bases. If the system cannot keep up with these evolving mission requirements its performance (completeness of information available) may go down.

CLARITY OF DISPLAY (nodes 11112, 11213, 114) describes the sophistication of the display system that presents missile warning and other information to the decision maker and his staff. The NORAD MWC, the NORAD Command Post, and SAC Hq each have their own display system.

- <u>paper only</u> means no automated display. Manuals, reports and written notes are available. Manually generated viewgraphs are a half step up from "paper only."

- <u>automated tabular display</u> means that all information can be presented on group or workstation display devices as text or simple tables.

- <u>basic graphics display</u> means a variety of charts, histograms, diagrams, and maps with overlays are available forms for portraying essentially all of the information in the Command Post. Note that the level of capability in many existing (1985) command center systems lies roughly between "automated tabular" and "basic graphics."

- <u>enhanced, real time, interactive graphics</u> is the top quality display. Maps and charts are continuously updated as new data arrives. Users may interact directly with the display (via menus, pointers, etc.) to request different/detailed information. Ad hoc charts may be generated quickly.

ACCESS TO SENSOR DATA (node 11113) is the effective rate at which information arrives from the sensors to the MWC. This is essentially a measure of the communications systems. MWC information can be less complete if potentially useful sensor data is delayed (or lost) by communications problems.

DATA COMMUNICATIONS AVAILABILITY (node 111132) is the percent of active (surviving) sensors for which the data links to the MWC are working. This will of course depend on which communications systems are deployed and how each of them performs against potential threats and other scenario-defined stress.

DATA COMMUNICATIONS BANDWIDTH (node 111131) is the overall description of the capacity of the communications systems. Of the sensors that are connected and sending status and event messages to the MWC, this factor tells how fast those messages can be sent on the automated data links.

VOICE AVAILABILITY (node 111133) is a measure of the availabilty of voice communications with a typical sensor. Voice is critical both as an alternative medium for sending messages if automated communications are degraded and as the primary means of validating the operational status of the sensors and the accuracy of the data being sent to the MWC.

ACCESS TO OTHER DATA (node 11211) describes how well the Attack Warning (Fusion) function is supported by systems to retrieve information from other sources that are available to the decision maker in his command post. ["Other" means other than the missile warning data from the MWC and can include information from other mission areas (e.g. Air Defense), resource status, Intel, trend data, historical data, order of battle and system characteristic descriptions, check lists and procedural information, etc.] The factor is measured by how much of that information (completeness) can be moved from its source and into the command post in a reasonably short time.

FUSION DATA PROCESSING (node 11212) tells how well the ADP system supports the Fusion function.

-no automated fusion means that there is no ADP support for the fusion function. Fusion is still possible with manual (and mental) systems and with semi-automated systems such as CCTV and phone conferences. [corresponds to value = 0]

-limited peacetime data fusion means the ADP system supports continuous warning with several indicators of overall situation status. Various kinds of information from multiple sources are combined. Information associated with a single missile event can be handled. [corresponds to value = 3]

-small scenario data fusion with limited complexity means that information from a scenario with a relatively small number of events can be handled. Multiple sensor inputs, correlations among events, and correlation with data from multiple missions/sources are fused into a "big picture" of the situation. But not all relevant information from all sources can be considered at once; and not all fusion is automatically performed, considerable human intervention may be necessary to guide the evaluation of data. [value = 6]

-large complex scenario data fusion means that essentially all relevant information from all sources is automatically considered for a high-load scenario. The fusion results are reported to decision makers as soon as or even before they ask for them. [There is of course an assumption here that the ADP system will have been pre-programmed with the set of questions/evaluations that decision makers are interested in knowing about.] [corresponds to value = 9]

USER FRIENDLINESS (node 112121) means how easy it is for a user to operate the system and get it to do what s/he wants.

-Hostile to user means that the user has to adjust to the deficiencies of the automated system. The burden is on the user to understand exactly what to do and how to do it. Mistakes are not tolerated kindly.

-Polite to user means the system tolerates some common user errors, offers simple menus or other interactive input aids, includes a "help" function and other built in training aids.

-Gracious and accommodating to user needs means that in addition to "polite" the user friendly interface takes on all the burden of figuring out how the system accomplishes a task. Via a range of optional techniques (interactive screens, multiple windows, natural language, etc.) the user only indicates what s/he wants. Ad hoc questions may be asked, new output displays can be created dynamically, etc.

FUSION SOPHISTICATION (node 112123) means the complexity of the algorithms and decision aids (software complexity) of the ADP system. The lowest reasonable level of fusion sophistication would simply be the ability to put information from multiple, diverse sources into a common format for subsequent manual fusion. A CCTV system, for example, would provide this level of sophistication. Though this is a useful and non-trivial level of fusion capability, we expect that an ADP system would also provide some minimal apability to combine the information from multiple sources. Hence, "simple algorithms" is the lowest defined level for ADP fusion sophistication.

-simple algorithms for few data items implies a variety of warning and situation status indicators.

-complex algorithms are comparable to the sophisticated calculations used in processing missile warning data in the MWC. Many data items from several sources are combined to provide one new information item for the decision maker.

-decision aids would guide the decision maker toward new questions he might ask in a given assessed situation. Aids could include automated checklists and a variety of "what if" calculations. Comparisions between current event information and historic trends could be another form of decision aid. Graphic display might be an important adjunct to this capability.

-<u>expert systems</u> would automatically decide which new questions and evaluations were necessary to further assess some aspect of the situation and would gather supporting data directly, without additional user guidance. Expert systems could include pattern recognition algorithms, options for explaining to the user how particular evaluations/recommendations were arrived at, etc. Expert programs could run continuously on any of the command center's ADP systems, and continually monitor information and warning indicators from multiple sources. However, development of a sophisticated expert system, expert in strategic command and control, is not a trivial undertaking and they are not likely to be readily available in quantity in the very near future.

CAPACITY (node 112122) Whereas sophistication is a measure of quality; capacity is a measure of quantity and describes how much fusion the ADP system can support.

-<u>None</u> means no ADP fusion capability. If the level of capacity = "None" then the level of Fusion Data Processing = "No Automated Fusion". Hence, it is not necessary to include this level in the questionnaires.

-<u>Minimal</u> capacity means that the system can support a fixed number of algorithms which continuously provide indications and warning during peacetime operations. There is no support for extremely complex algorithms, for expert systems, or for the increased information load associated with an attack scenario.

-<u>Limited</u> capacity means that not all the information can be combined in all the ways that seem reasonable for decision makers to look at. Limited may mean that only one expert system is available and that it can deal with only a few aspects of the situation. With a limited system users must be selective about which questions they ask or which indicators they want to monitor. "Limited" may be the result of either hardware limitations or software limitations. Hardware may limit the number or complexity of computations that the system can perform in a given time. Software, which is likely to be the actual constraint on the operational systems of interest, may be limited by the difficulty of defining complex sophisticated algorithms and decision aids, or the time and cost of developing expert systems for command centers.

A more rigid definition for "Limited" -- Ability to support on a continuous day-to-day basis: 20 simple indicators (algorithms) that each combine information from 3 different sources; and 10 complex algorithms (if the ADP system is sophisticated enough to have them) that combine multiple information items from 3 different sources; and 4 decision aids (if the system is sophisticated enough) that help the user identify the most important things that should be looked at if missile events occur; and only one small expert system that takes 3 minutes to provide an evaluation of the overall situation.

-Not Limited capacity means that the above limitations are not present and that any reasonable combination of information items from many sources about many events could be processed in a very sophisticated manner in near real time.

DATA BASE QUERY CAPABILITY (node 112111) describes how easy it is to identify and extract information, from sources other than the MWC, that the command center needs to fuse with MWC information. There are two steps to this: first, for the command center to determine what information it wants, where it is, and how to ask for it (query formulation); and second, for the source/holder of the information to locate the information and extract a copy from the source's data base. It seems natural to measure this capability by the combined time it takes to carry out these two steps.

Clearly, the less time it takes to get any single item of information, the more complete the information will be for the user in the command center.

INTERNAL COMMUNICATIONS (node 112112) is a possible source of delay in accessing data from other sources. If the source can only be asked questions by phone, if answers must be reported by voice or hand delivered, or if slides must be manually prepared, then there will be additional delays in completing information.

APPENDIX C

THE CONCEPT OF COMPLETENESS

COMPLETENESS AS A MEASURE FOR C^2 SYSTEMS

Implementation of the STF approach requires specifying an appropriate quantitative measures at each node/questionnaire. For several nodes we found that "Completeness of Information" was a useful concept for saying what a C^2 system did. The initial definition of Completeness that we used during data collection is attached.

During the course of the experiment we found that our naive definition could capture only part of the effect that we were trying to measure. We determined that "Completeness" has a content dependence; some information was more useful than other information. The more useful information had higher priority for decisionmakers and counted more toward completeness. For example, summary information about a situation is usually more valuable than individual event messages.

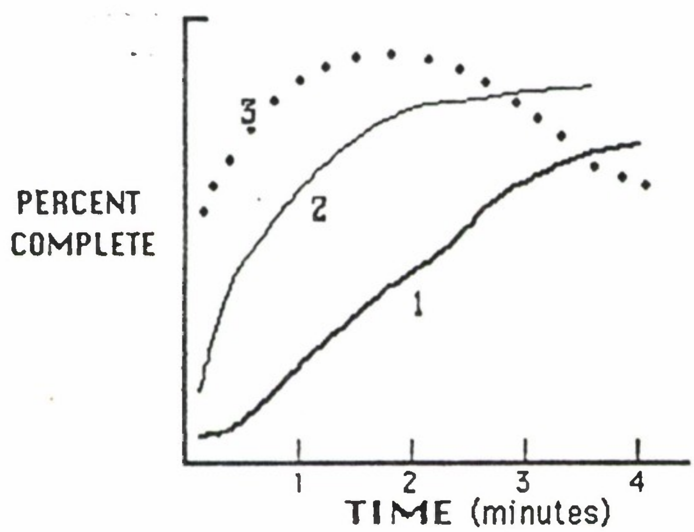
We also found in our discussions of information requirements for future C^2 systems that an explicit list of the items of information that a system generated was important for participants, both respondents and observers, to understand clearly the concept of completeness and what the questionnaires were about. Producing explicit lists is an additional cost of implementing STF.

Initial definition

COMPLETENESS OF INFORMATION vs TIME

Completeness is concerned with how much information about the current situation is available to a decision maker or other user. Information is complete if all potentially available data, within the capacity of the existing sensor, Intel or other collection systems, has been acquired, processed and put into a form that the decision maker can use.

TIME DEPENDENCE: At any given time some amount of raw data has accumulated or could have been accumulated. If all of that data has been processed into usable information with negligible time delay, we say that the information is 100% complete. In practice there will always be some minimum comm and processing delays, usable information will always lag the accumulated raw data, and information will not be fully 100% complete.



The figure above shows the performance of three possible information processing systems as a scenario (series of events) begins to develop. System 1 is a slow, reactive system that gradually collects available information. After a while the system begins to "get its act together" and catch up with the data. After 4 minutes it is presenting roughly 70% of the information in real time, i.e. as fast as new data arrives. [New data is data with new information, in contrast to repeated or redundant information.]

System 2 is a better system in two respects. First it reacts more rapidly to the new situation. Second it reaches, and maintains, a higher level of completeness than System 1.

System 3 is a proactive information processing system with limited capacity. The proactive system has already got its act together when the new situation begins to develop, is continuously processing multiple data sources and takes only a minute to get to a state where it can present 80% of the available information in real time.

The limited capacity of the system is evident in the gradual decrease of completeness after two minutes. In the scenario portrayed, as more data with more information content accumulates, this information processing system gets overloaded and begins to fall behind.

AS THE USER SEES IT

The mission requirements analyst, on behalf of the user, is concerned with specifying the overall system performance. Does the mission demand an information processing capability that gets its act together in just 2 minutes (System 2) or is it sufficient to have a system that takes 4 minutes to get running (System 1) and even then provides no more than 70% complete information in real time? Does the mission require a proactive system? Does the capacity of the system have to be big enough to keep up with arbitrarily large amounts of raw data?

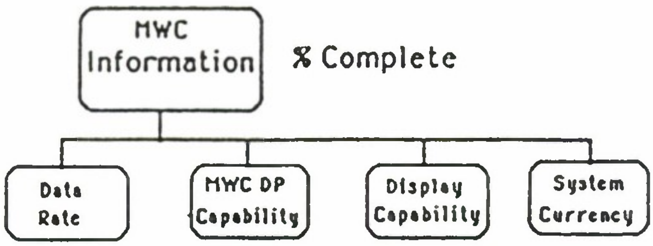
AS THE SYSTEM DEVELOPER SEES IT

The system designer/developer is concerned with what system capabilities make an information processing system better. How do data processing capacity, data base management systems, various display alternatives, etc. contribute to differences in system performance? How can we change System 1 in the above example into System 2?

APPENDIX D

A TYPICAL QUESTIONNAIRE

Questionnaire 1111: MWC Information



Data Rate	MWC DP Capability	Display Capability	System Currency
Messages per second	Messages per second		Time for Modification
- 1/10	- 1/10	- Hardcopy	- 3 months
- 1	- 1	- Tabular on CRT	- 1 week
- 10	- 10	- Basic Graphics	- 1 day
- 100	- 100	- Enhanced Graphics	

DESCRIPTION

This Questionnaire addresses the relationship between the completeness of information that is produced by the MWC and capabilities of systems within the MWC.

Output Measure

Completeness is concerned with how much information about the current situation is available to a decision maker or other user. Information is complete if all potentially available data has been acquired, processed and put into a form that a decision maker can use.

Input Measures

Data rate is the number of messages from the sensors that arrive at the MWC each second.

Data Processing Capability is measured by the number of messages from missile warning sensors (events) that can be processed by the MWC each second.

Display Capability is the means available by which missile warning information is displayed to the MWC decision maker and staff.

--- Hardcopy means paper only: manually prepared hard copy (notes, reports, etc.).

--- Tabular on CRT means information can be displayed on a CRT screen as text or simple tables.

--- Basic Graphics means information can be displayed as charts, diagrams and maps (as well as text).

--- Enhanced Graphics means real-time, interactive graphics, with continuous update of information, ability to respond to ad hoc requests, etc.

System Currency means the currency of the MWC system: the frequency with which changes in warning mission requirements can be incorporated into the system. Changes can include changes in processing algorithms, display requirements, etc.

In the following questions you are given a single piece of information. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, bothe at ten minutes after alarm and at twenty minutes after alarm.

Consider levels of this factor:

> Missile Warning Data Rate: the number of valid messages from the warning sensors that arrive at the MWC each second.

LEVEL	(Short Form)	OUTPUT
one tenth of a message per second	.1 / sec	@ 10 m ________ @ 20 m ________
one message per second	1 / sec	@ 10 m ________ @ 20 m ________
ten messages per second	10 / sec	@ 10 m ________ @ 20 m ________
one hundred messages per second	100 / sec	@ 10 m ________ @ 20 m ________

****

Consider levels of this factor:

MWC Data Processing Capability: the number of messages from the warning sensors (events) that can be processed by the MWC each second.

LEVEL	(Short Form)	OUTPUT
one tenth per second	.1 / sec	@ 10 m ________________ @ 20 m ________________
one per second	1 / sec	@ 10 m ________________ @ 20 m ________________
ten per second	10 / sec	@ 10 m ________________ @ 20 m ________________
one hundred per second	100 / sec	@ 10 m ________________ @ 20 m ________________

****

Consider levels of this factor:

Missile Warning Data Rate: the number of valid messages from the warning sensors that arrive at the MWC each second.

LEVEL	(Short Form)	OUTPUT
Paper Only: Manually prepared hard copy (notes, reports, etc.)	Paper Only	@ 10 m ______________ @ 20 m ______________
Automated Tabular Display: Information can be displayed as text or simple tables.	automated Tabular	@ 10 m ______________ @ 20 m ______________
Basic Graphics: Information can be displayed as charts, diagrams and maps (as well as text).	Basic Graphics	@ 10 m ______________ @ 20 m ______________
Enhanced, Real-time, Interactive Graphics: continuous update of information, ad hoc interactive requests	Enhanced Graphics	@ 10 m ______________ @ 20 m ______________

****

Consider levels of this factor:

Currency of MWC System: the frequency with which changes in warning mission requirements can be incorporated (processing algorithms, display requirements, etc.).

LEVEL	(Short Form)	OUTPUT
three months	three months	@ 10 m ______________ @ 20 m ______________
one week	one week	@ 10 m ______________ @ 20 m ______________
one day	one day	@ 10 m ______________ @ 20 m ______________

****

On these pages you are given two pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten minutes after alarm and at twenty minutes after alarm.

DP CAPABILITY		MISSILE WARNING DATA RATE: .1 / sec	1 / sec	10 / sec	100 / sec
.1 / sec	@ 10 m	______	______	______	______
	@ 20 m	______	______	______	______
1 / sec	@ 10 m	______	______	______	______
	@ 20 m	______	______	______	______
10 / sec	@ 10 m	______	______	______	______
	@ 20 m	______	______	______	______
100 / sec	@ 10 m	______	______	______	______
	@ 20 m	______	______	______	______

****

On these pages you are given two pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten minutes after alarm and at twenty minutes after alarm.

DISPLAY CAPABILITY		MISSILE WARNING DATA RATE .1 / sec	1 / sec	10 / sec	100 / sec
Paper Only	@ 10 m	________	________	________	________
	@ 20 m	________	________	________	________
Automated Tabular	@ 10 m	________	________	________	________
	@ 20 m	________	________	________	________
Basic Graphics	@ 10 m	________	________	________	________
	@ 20 m	________	________	________	________
Enhanced Graphics	@ 10 m	________	________	________	________
	@ 20 m	________	________	________	________

****

On these pages you are given two pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten minutes after alarm and at twenty minutes after alarm.

DISPLAY CAPABILITY		MWC DATA PROCESSING CAPABILITY			
		.1 / sec	1 / sec	10 / sec	100 / sec
Paper Only	@ 10 m				
	@ 20 m				
Automated Tabular	@ 10 m				
	@ 20 m				
Basic Graphics	@ 10 m				
	@ 20 m				
Enhanced Graphics	@ 10 m				
	@ 20 m				

****

On these pages you are given two pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten minutes after alarm and at twenty minutes after alarm.

DP CAPABILITY		CURRENCY OF MWC SYSTEM: three months	one week	one day
.1 / sec	@ 10 m	________	________	________
	@ 20 m	________	________	________
1 / sec	@ 10 m	________	________	________
	@ 20 m	________	________	________
10 / sec	@ 10 m	________	________	________
	@ 20 m	________	________	________
100 / sec	@ 10 m	________	________	________
	@ 20 m	________	________	________

****

On these pages you are given two pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten minutes after alarm and at twenty minutes after alarm.

		CURRENCY OF MWC SYSTEM		
DISPLAY CAPABILITY		three months	one week	one day
Paper Only	@ 10 m	______	______	______
	@ 20 m	______	______	______
Automated Tabular	@ 10 m	______	______	______
	@ 20 m	______	______	______
Basic Graphics	@ 10 m	______	______	______
	@ 20 m	______	______	______
Enhanced Graphics	@ 10 m	______	______	______
	@ 20 m	______	______	______

****

On these pages you are given four pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten nimutes after alarm and at twenty minutes after alarm.

Message Rate	DP CAPABILITY	DISPLAY CAPABILITY	SYSTEM CURRENCY	MWC INFO
.1 / sec	10 / sec	Basic Graphics	one day	@ 10 m ________ @ 20 m ________
100 / sec	10 / sec	Basic Graphics	one day	@ 10 m ________ @ 20 m ________
10 / sec	.1 / sec	Basic Graphics	one day	@ 10 m ________ @ 20 m ________
10 / sec	100 / sec	Basic Graphics	one day	@ 10 m ________ @ 20 m ________
10 / sec	10 / sec	Paper Only	one day	@ 10 m ________ @ 20 m ________
10 / sec	10 / sec	Enhanced Graphics	one day	@ 10 m ________ @ 20 m ________
1 / sec	1 / sec	Automated Tabular	three months	@ 10 m ________ @ 20 m ________
1 / sec	1 / sec	Automated Tabular	one day	@ 10 m ________ @ 20 m ________
10 / sec	10 / sec	Basic Graphics	one week	@ 10 m ________ @ 20 m ________

On these pages you are given four pieces of information together. For each question please give your best estimate of Completeness, 0-100%, of MWC Information, both at ten minutes after alarm and at twenty minutes after alarm.

Message Rate is FIXED at 1 / sec

DP CAPABILITY	SYSTEM CURRENCY		MWC Display Capability: Automated Tabular	MWC Display Capability: Basic Graphics
1 / sec	three months	@ 10 m	____________	____________
		@ 20 m	____________	____________
1 / sec	one day	@ 10 m	____________	____________
		@ 20 m	____________	____________

****

Message Rate is FIXED at 1 / sec

DP CAPABILITY	SYSTEM CURRENCY		MWC Display Capability: Automated Tabular	MWC Display Capability: Basic Graphics
10 / sec	three months	@ 10 m	____________	____________
		@ 20 m	____________	____________
10 / sec	one day	@ 10 m	____________	____________
		@ 20 m	____________	____________

****

Message Rate is FIXED at 10 / sec

DP CAPABILITY	SYSTEM CURRENCY		MWC Display Capability: Automated Tabular	Basic Graphics
1 / sec	three months	@ 10 m	______	______
		@ 20 m	______	______
1 / sec	one day	@ 10 m	______	______
		@ 20 m	______	______

****

Message Rate is FIXED at 10 / sec

DP CAPABILITY	SYSTEM CURRENCY		MWC Display Capability: Automated Tabular	Basic Graphics
10 / sec	three months	@ 10 m	______	______
		@ 20 m	______	______
10 / sec	one day	@ 10 m	______	______
		@ 20 m	______	______

****

APPENDIX E

ESTIMATING PROGRAM CONTRIBUTION

This appendix summarizes our exploration of methods to provide program capability inputs to the bottom of the STF tree.

Checklists are multiple choice responses that sharply restrict the range of responses and ensure uniformity of data. Data so collected is suitable for quantitative (and ultimately automated) processing. A simplified checklist approach to Vanguard data collection will be useful even if an STF scheme is not attempted. We recommend using checklists in the Vanguard data call.

ESD has funded research to establish detailed checklists which enumerate many of the system attributes that add up to what we have called operationally oriented measures of capability (ESD-TR-83-133, Mar 83). The checklists were originally developed to aid in requirements definition. However, we did not discover any instances where this approach is actually used.

Abridged versions of those checklists can be useful for collecting relevant program information in the Vanguard data calls. Checklists can also be developed for other information of interest.

The following charts show the checklists that were developed for Clarity of Display, User Friendliness, Database Query Capability and Sophistication. The last chart is the program contribution sheet which is used to summarize data about a program, including information from the checklists, for input to VAST.

Measuring Program Contribution to CLARITY OF DISPLAY

(check all that apply unless otherwise noted)

Physical Devices			
• display area (dedicated to display function)	___1 manual	___2 electric	___3 electronic/digital
• large display (suitable for group viewing: greaseboard, vugraph, video projector)	___1 manual	___2 electric	___3 electronic/digital
• CCTV		___3 electric	
with two-way voice		___2 electric	
• Printed output	___1 text		___1 + graphics
User Aids			
• pre-recorded material (books, briefings, data files)	___1 manual		___3 electronic/digital
• pre-formatted display (blank forms, background maps)	___1 manual	___2 vugraph, typewriter	___3 electronic/digital
• training aids	___1 manual		___3 electronic/digital
• data conversion aids	___1 manual		___3 automated
Display Mode			
• alphanumeric free, formatted, man-readable	___1 formatted		___1 man-readable
• tabular (arrayed display) (check one)	___1 fixed		___2 variable
• basic graphics (simple maps, pie/bar charts)	___1 manual	___2 vugraph	___3 electronic/digital
• enhanced graphics (overlays, split screens)		___2 vugraph	___3 electronic/digital
• video options/color (bold, blink, inverse)	___1 color		___1 video options

Interactiveness

• typical time to get "standard" display (check one)	___1 5 min.	___2 1 minute	___3 1 - 15 seconds
• interaction mode	___1 keyboard	___2 menus	___3 mouse/touch
• screen updating (check one)	___1 manual	___2 1 minute	___3 continuous
• alarm mechanisms	___1 visual	___1 audible	___1 synthetic voice,etc
Briefing Support (check one)		___2 limited automated	___3 enhanced automated
Ad hoc capabilities	___1 some commands	___2 DBMS and forms mode	___1 real-time 'programming'
Evolutionary Flexibility (check one)	___1 semi-annual modification		___3 weekly upgrade

TOTAL PROGRAM VALUE FOR CLARITY OF DISPLAY ______

Measuring Program Contribution to User Friendliness

Item			
User Aids			
• Help Function	1 some on-line	1 robust on-line	2 built-in training
• "Standardized" keyboard/panel	1 Yes		
• Special Function Keys	1 Yes	1 user defined	
• "Standardized" screen layouts	1 Yes		
Response to Input Errors			
• Reports invalid entries	1 visual alarm	1 audible alarm	
• Allows edit/retry	1 edit inputs	2 reenter/retry	
• Provides defaults	1 basic entry	1 prompt strings	
Interaction			
• Display Capabilities	1 Basic Graphics	2 Enhanced Graphics	2 Interactive Graphics
• with choice of interactive mode	1 Yes		
• Natural Language modes	1 Basic mode	1 Conversational Mode	
• Graphics input	1 Yes		
• While computing	2 minimizes delay	1 keeps screen current	
Local Capabilities			
• Customized interface	1 Yes	1 user definable	
• "Desktop" functions (clock, calendar, notes, calculator, etc.)	1 basic functions	1 + local memory	

TOTAL PROGRAM VALUE FOR USER FRIENDLINESS ________

Measuring Program Contribution to Data Base Query Capability
assuming intersystem information exchange requirements

Query Formulation

• Preparation	______1 fixed manual request options	______2 ad hoc queries	______2 programmable queries
with Natural Language?		______1 Yes	
• User Aids	______2 Interactive Help	______1 Data Dictionary	
	______1 Special Function Keys	______2 Interactive Menu	
• Preparation Time (check only one) for typical query	______1 1 minute or less	______2 2-10 seconds	______3 < 2 seconds

Information Retrieval

• "Standard" Intersystem Query Protocol	______4 Yes		
• Compatible DBMS among connecting systems	______1 Yes		
• Retrieval Time (check only one) for typical record	______1 1 minute or less	______2 2-10 seconds	______3 < 2 seconds
• Interoperability with Internal Communications	______4 Protocol Designed for Communications Capacity	______1 Protocol adapts to system loading	

Output Formatting

• Report Generator	______1 Yes		
• Graphics Generator	______1 Yes		
• Intersystem Protocol Standards	______1 for ASCII	______2 data files	______1 graphics

TOTAL PROGRAM VALUE FOR DATA BASE QUERY CAPABILITY ______

Measuring Program Contribution to Sophistication
(software complexity of fusion processing)

Algorithm Complexity		
• simple arithmetic computations (= spread sheet level)		1
• • involved algebraic computations		1
• • iterative/recursive computations		1
• working memory requirements:		
– small		1
– large	{or}	3
• logical complexity:		
– sequential		0
– conditional(up to 5)	{or}	2
– multi-conditional(>5)	{or}	4
• error handling routines		2
Operator Interface		
• – requires operator		0
– runs autonomously	{or}	1
• runs continually (background)		1
• allows operator intervention		1
Data Availability		
• uses supplied data		0
• accesses local data base		1
• accesses intersystem data		1
• accesses large data bases (historical; plans)		2
• interactive with data base		2
Decision Aids		
• compares		1
• shows trends		2
• evaluates situation (numerical computation)		1
• indicates alternatives		1
• maintains checklists		1
• responds to ad hoc questions (What if? Compare these...)		2
• graphics display		2

Expert Systems

• evaluates situation	1
• recognizes elaborate patterns of sensor and intel data	2
• extrapolates situation (what next?)	2
• generates alternatives	1
• provides explanations	2

TOTAL PROGRAM VALUE FOR SOPHISTICATION ______

SUMMARY CHECKLIST FOR CAPABILITY INPUTS

CONTRIBUTION from Program ______________

NODE	NAME	RANGE	CONTRIBUTION
11111	MWC Data Processing	.1 -100 msg/sec	_
11112	MWC Clarity of Display	qualitative:1-4	_
111131	Sensor Message Rate	.1 -100 msg/sec	_
111133	Sensor Voice Availability	180 - 5 seconds	_
11114	MWC Flexibility(3mo,wk,day)	qualitative: 2-8	_
1113	NORAD/SAC Data	qualitative: 1 - 4	_
112111	Data Query, NORAD	180 - .5 seconds	_
112112	Internal Comm, NORAD	180 - 2 seconds	_
112121	User Friendliness, NORAD	qualitative: 1 - 3	_
112122	Capacity of NCP System	qualitative: 1 - 4	_
112123	Sophistication of NCP Sys.	qualitative: 1 - 4	_
11213	NCP Clarity of Data Display	qualitative: 1 - 4	_
112142	MWC to NCP Data Comm	qualitative: 1 - 3	_