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...TER-LEVEL GAMING
...NALYSIS WORKSHOP
...FORCE PLANNING

...tober 27-28, 1977, held at Xerox
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Management Development, Leesburg,
Virginia

... — Summary, Discussion of
... and Requirements for Research

By
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THEATER-LEVEL GAMING AND ANALYSIS WORKSHOP FOR FORCE PLANNING.

September 27-29, 1977, held at Xerox International Center for Training and Management Development, Leesburg, Virginia

Volume II — Summary, Discussion of Issues and Requirements for Research

By
Lawrence J. Low

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An investigation of the many issues and problems associated with combat modeling at the theater-level for force planning was conducted and is presented in two volumes. Volume I is a transcript of the proceedings of a workshop whose agenda was structured to address gaming utility from the model user's viewpoint, the status of theater-level simulation models and problems of model structure, theater-level combat modeling methodology, game theory in theater-level modeling, data base requirements for theater-level models and problems associated with the generation of data bases. Volume II constitutes a synthesis and summary of the

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20 ABSTRACT (Continued)

issues and concerns that surfaced at the workshop relative to theater-level gaming and the diverse activities, both technical and organizational, that support such gaming. In addition, Volume II outlines requirements for further research and describes a number of approaches to such research that appear to be viable. The most crucial problem affecting the analytical or simulation modeling of combat at virtually any level of intensity is identified as the lack of a body of knowledge, or a theory, that defines the relationship between combat modeling and the conduct of war in the real world. The importance of this issue was clearly established in workshop discussion and is addressed in considerable detail in Volume II.

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Foreword

The "*Theater-Level Gaming and Analysis Workshop for Military Force Planning*" meeting, sponsored by the Office of Naval Research (Code 431), was held at the Xerox International Center for Training and Management Development, Leesburg, Virginia, on 27-29 September 1977. Volume I documents the proceedings of this meeting. Volume II contains a summary and a discussion of the meeting and a concept for further research. This research concept would address problem issues systematically across a broad front of theater-level gaming methodology, *problems of a fundamental nature that, in a relative sense,* have received only scant attention but that have plagued combat modeling endeavors since their inception.

The proceedings presented in Volume I constitute a form of "data base" from which observations have been made and conclusions have been drawn for Volume II. The author is quick to note, however, that other material on war gaming of a similar introspective, "soul searching" nature has been used in preparing the contents of this volume. Furthermore it should be emphasized that much of the commentary and many of the opinions expressed are subjective, which is unavoidable in an effort of this kind. It is hoped, however, that the imperfections of subjectivity, if such they be, are tempered by the author's attempt to be rational and objective in the overall treatment of an extraordinarily complex, multidimensional topic.

During the final phases of preparing this document, a highly significant report to the Congress, most relevant to this effort, was released by the Comptroller General of the United States.* This report also addresses the problem of computerized models and games and the role they play in defense decision making. There is considerable overlap in the material covered by the subject volume and the GAO report. Hence, there are rightfully many references to the GAO work that should appear in certain parts of this study. It is in the interest of expediting the publication of this document, however, that general rather than specific reference is made to the GAO report. Of greater significance, perhaps, than the coincidence of information in the two reports is the complementarity of the material presented and, as a consequence, the reader would greatly benefit from a review of the GAO study.

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*"Models, Data, and War: A Critique of the Foundation for Defense Analysis", Report No. PAD-80-21, U.S. General Accounting Office, Washington, DC (12 March 1980)

1. Introduction

To give the reader a contextual backdrop against which both the proceedings of Volume I and the discussion of specific issues to follow in this volume can be set, this introduction contains some general observations and impressions of the meeting itself, its scope, attendee cross-section, how it was conducted, and a comment or two on attendee reactions (including those of the author). Furthermore, and of greater importance, is the fact that some of these observations do indeed reflect the methodological maturity, credibility, and general state of health of theater-level gaming as an aid to force planners.

1.1 Meeting Scope

The distinguishing feature, perhaps, of this meeting was the breadth of its scope. A conscious attempt was made in the planning stages to cover, in one meeting, all of the major factors that pertain to the development of theater-level models and that affect or constrain their applications. The reason for doing this was straightforward enough; it simply had not been done before and there were compelling reasons stemming from the importance of the decisions supported by the models, why it should have been. As demonstrated in Volume I, major factors involved in the development of a theater model are (1) the model structure, (2) the combat modeling technique, (3) the mathematical or heuristic optimization techniques, and (4) the data base(s). There is strong interdependency among these four factors, yet each* represents a significant area of endeavor in research, development, and implementation and each is large and complex enough to have generated its unique set of problems. Knowledge of these problems and the progress being made towards their solution has tended to remain compartmentalized within the communities working in each area. When it comes to theater gaming, however, and how it impacts on decision making (actually, the fifth factor or area of "user attitudes and concerns" identified in Volume I), one cannot properly treat just a piece of the problem, neglecting consideration of the whole. For this reason the scope of the meeting took on perhaps a degree of unusual breadth.

As with most situations involving trade-offs between breadth and depth, certain compromises had to be made. Depth was clearly sacrificed for breadth. For the "specialist," e.g., for the model developer or the game theoretician, the meeting may have been disappointing for its overview rather than its in-depth treatment of the individual's particular area of interest. However, for the most part, there appeared to be a general feeling of satisfaction with the material covered. For example, the model builder could appreciate or be reminded that command and control, the representation of which was judged to be inadequate in all current models, had a game theory dimension to it, and the investigator in game theory could see that the combat modeling structures on which his optimization algorithms might operate had many unique, difficult problems of their own. Furthermore, all attendees could, if they chose, benefit from exposure to the magnitude of the data base development problem, the status of the data base programs, and the staggering dimensions of the validation problem for both models and data. An attitude shared by most, I believe, could be summarized by a comment that was made to me by an experienced analyst at the meeting's end: "This is the first meeting in theater gaming that I have attended where I didn't know everybody in the room." This, of course, reflects on the meeting's scope and past tendencies, mentioned earlier, to look at pieces of the problem in relative isolation with little information exchange between the various communities involved.

One further observation should be noted in connection with the meeting's breadth of coverage at the sacrifice of depth. This was the fact that the macro view adopted for the meeting not too surprisingly brings to the surface a multitude of problems that beg for

*Actually, theater model development is concerned with the inseparable involvement of (1) and (2) (model structures and combat modeling techniques. Yet, there is considerable research activity in the area of (2) above, quite independent of larger model development, as evidenced by the work of Weiss, Taylor, Helmbold and others.[8]

attention before we ever become immersed in the finer points of methodology and technique. It seems logical that these larger problems should first be addressed, and if feasible paths to solutions can be found, we might then proceed to do battle with the microstructure. It is almost certain that whatever is to be done at the more detailed levels will be a fallout of just how the issues and problems at the higher levels are addressed. Therefore, coming back to material coverage at the meeting, I would question the wisdom of time spent in the detailed shredding of various attrition, force ratio, or FEBA movement algorithms and equations when the very concepts that use these parameters to represent land combat in diverse and fundamental ways could be open to question.

1.2 Attendance Profile

As one might expect, attendee backgrounds were as diversified as the meeting scope was broad. The list of attendees (Volume I, pp. XXV, XXVI) includes representation from three distinct communities engaged in one or more of the five topical designations used for the meeting sessions. The communities represented were:

- Government (defense and defense-related activities: U.S. and foreign [Allied])
- Contractor (U.S. and foreign)
- Academic (government and private, U.S. and foreign)

It is in relation to user activities (nested, for the most part, in government) that some comments are in order. First, there are, in reality, two categories of user. One is the decision/policy maker on whose shoulders rests the responsibility for receiving and filtering all information pertinent to a particular problem area and ultimately making the decision to take some action. The other is his staff of analysts and advisors who make use of certain techniques to generate information, which is provided to the decision maker, and on which his decision will be based. This is shown in Slide A (Volume I). The staff analyst category of user was well represented at the meeting, while the decision/policy maker was not. This was noted by several of the speakers and attendees during the meeting.

This very matter was discussed in committee during one of several meetings of the Steering Committee* that preceded the conference. One cannot take lightly the benefits of having presented first hand to those in attendance the intricate steps, the complex constraints, and the diversity of information that all enter into the decision process. Nevertheless, the feeling prevailed that those representing the user community at the meeting should have simultaneous knowledge of the approximate requirements for analysis in the decision process, a feeling for the contribution analysis makes along with its limitations, *and* a familiarity with the models and techniques that provide the analytical input to the process. More often than not, the staff analyst comes closer to meeting these requirements than does the individual who ultimately makes the decisions. On reflection, it is difficult to escape the feeling that if top decision and policy makers had been induced to attend the meeting, they would have been severely disturbed by what appeared to be the shaky and uncertain state of affairs in the subject area; this, despite the fact that much effort has been expended and considerable ingenuity has been brought to bear. Taking a cue from Frank Kapper's remarks at the meeting, these people must be brought into the deliberations at some point but only, perhaps, after we tidy up our affairs a bit.

Noteworthy, I feel, were the contributions made by the foreign attendees, particularly those from the United Kingdom (UK) and the Federal Republic of Germany (FRG). Their efforts in theater gaming seem to be tighter, more cohesive, perhaps better organized, and, in all probability, smaller and less extravagant than those in the United States. Of most significance here is the fact that the threatening forces of the Warsaw Pact are at their

*See Volume I, Foreword

doorstep, so to speak, and in the case of the FRG, in particular, most of the gaming discussed at the meeting takes place on German soil. Consequently, there appears to be a greater sense of urgency and pragmatism in what is being done by the Europeans. I strongly believe that they have much to offer any effort aimed at improving the gaming state-of-the-art not only by virtue of their analytical expertise and ingenuity but also as information sources and advocates for those factors of tactics and operations that are reflective of their national interests and objectives.

In selecting invitees for the meeting, an effort was made to select individuals who were recognized to have conflicting points of view about the "issues and answers" in theater-level gaming. Furthermore, in asking Jim Dunnigan of Simulation Publications to attend (his noteworthy contribution being a very entertaining banquet speech), we hoped to inject a fresh point of view into the discussions from someone who designs, markets, and produces war games in the private sector. I think we succeeded in meeting these objectives.

One last observation on meeting attendance has to do with the preponderance of "Western World" representation. This was not by design in that Far Eastern representation (Pacific Command) was planned in our original list of invitees but last minute, unexpected commitments and the great traveling distances to the Washington area mitigated against such attendance, save for a lone CINCPAC representative.

1.3 Conduct of the Meeting

The meeting was conducted in an informal manner and the presentations, comments, and exchanges were all quite candid. The atmosphere was "workshop" insofar as speakers and panelists were completely open to questions from the floor, constrained only by the time allotted to a session. There were, however, no working groups assigned, as the custom goes, to special topics. The three-day period prescribed for the meeting was too short to permit a working group arrangement without having the meetings of such groups run in parallel to the main session presentations. Rather than encourage further compartmentalization of specialty groups in the theater gaming community, the meeting structure favored by the Steering Committee was one that permitted all attendees to be present at all of the sessions. In this manner they could be exposed to the *total* gaming problem as its definition evolved during the meeting and, as a consequence, develop a better appreciation for all of the related pieces of the problems and their interfaces.

Only a small number of formal papers were prepared for the meeting. Since the meeting transactions were transcribed in their entirety, it was decided that for the sake of consistency in style and improved readability these transcripts would be used for preparation of the proceedings. In two instances, where the material presented was more mathematically oriented, the formal papers that were prepared were included in the Appendix to Volume I. The use of the transcripts resulted in an editing task of staggering proportions that required an inordinate amount of time. This difficulty should be recognized and circumvented in future meetings of this type, where much material is compressed in time and is of "high density," by calling for the submission of formal papers and abstracts when presentations are made.

There appeared to be the distinct tendency by many of the speakers in Sessions II and III to broaden the subject matter of their presentations beyond (and sometimes at the expense of) the material specified in the "call for papers." This was often done by a speaker's own admission and was somewhat disappointing in view of the fact that the meeting had been carefully structured. Nevertheless, in most instances, these deviations contributed provocative and significant information to the store of knowledge.

Having an unclassified meeting did not seem to inhibit the exploration of major topical issues and problems. Only in the discussion of the MCSSG Tri-National Comparison and the status of gaming in the Soviet Union (which came up during the meeting quite unexpectedly) were we somewhat constrained by our inability to present classified information. All things considered, the freer exchange afforded among U.S. and foreign attendees by an unclassified meeting more than offset, I feel, several opportunities that were missed because of their involvement with classified information. The possibility of follow-on splinter group meetings that can be classified and that will explore certain issues in greater depth is attractive and is discussed in Section 4.

1.4 General Observations

It was evident that the meeting attendees had either worked together in small groups or were familiar with each other's professional activities but that there existed little more than nodding acquaintance among groups, if that. This general lack of cohesiveness in the attendance and among participants manifested itself, I think, by a good deal of repetition of the same thoughts and ideas expressed in many different ways, and because of the prevailing informality this was often done imprecisely. This repetition is mentioned because it was generally distributed in random fashion throughout the meeting, adding to the difficulties of summarizing the issues that were discussed.

The need for a "theory of combat" or for a better understanding of the "phenomenology of combat" came up many times. This trend in the discussion was eventually capped by Jack Stockfisch who, in his inimitable way, expressed both concern and wonderment as to how the gaming community had existed for so long and had become so deeply involved in modeling without any such theory or basic understanding.

Many participants also expressed the need for more research in the field of a fundamental nature, and for the first time there was an awareness of the amount of research that various organizations had been compelled to undertake on their own. Again, much of this might have been lost to the community as a whole, were it not for the occasion presented by the meeting to pass on the information.

Although the meeting was primarily concerned with methodology issues, the degree to which such issues are driven by scenario factors leaves one with some feeling of concern over the meeting's total and exclusive involvement with the Atlantic and European theaters. There is little doubt that the enormous problem of the Central Front in Europe cast its shadow over virtually all of the presentations made that were tied in any way to a piece of geography. This heavy imbalance in terms of neglecting problems faced by the United States in other parts of the world should be rectified in future meetings so that possible changes needed in methodological emphasis or structure can be explored and indentified.

2. Summary Information

2.1 Workshop Structure and Presentation Summaries

Summarized here are the issues and problems that emerged from a workshop in computerized gaming at the theater level for force planning (Reference 1)* and the indications of the direction to be taken in further gaming research. The workshop was sponsored by the Mathematical and Information Sciences Division of the Office of Naval Research in response to the need for a better understanding of the technical issues involved in gaming models of combat and the better communication of these issues among model users and decision makers, model designers and developers, and the basic research community. More explicitly, the goals of the workshop (Vol. I), and the subsequent analysis that was performed (Vol. II), were to:

- Promote among all attendees the broadest dissemination of the technical discussions that took place and the expressed concerns of user activities.
- Resolve to the extent possible the problem issues that were identified and to bring to light other related problems.
- Produce for each session a panel summary of the status and the research state-of-the-art in the associated technical areas.
- Develop from the discussion and findings of the meeting as a whole a strategy for responding to the needs for research that were identified.

The agenda for the workshop was structured to cover a definable subset of a much broader area of endeavor encompassing all of military (combat) gaming. A morphological matrix was postulated for all gaming activities constructed around three basic dimensions of gaming and analysis technique, scope, and application. These dimensions are expanded as shown below:

- Gaming and analysis technique
  - Military exercises (field, fleet, air, joint)
  - Manual war games
  - Computer assisted manual war games
  - Analytic computer games (analytic models, simulation, optimization)
  - Interactive (or player-assisted) computer games.
- Gaming and analysis scope
  - Global and theater-level conflict
  - Major engagement or battle (in-theater)
  - Local engagement, "many-on-many units"
  - Local engagement, "one-on-one" duel.
- Gaming and analysis application
  - Force planning
  - R&D planning, management, and evaluation
  - Operational planning and evaluation
  - Training and education.

The region of the three dimensional matrix selected as the subject area to be addressed by the workshop was that defined by analytic/computer games and interactive computer games under the heading of technique, theater-level conflict under the heading of scope, and force planning under the heading of application. This region is shown by the shaded sections of Figure S-1. In Figure S-2, which is believed to be self-explanatory, are summarized the characteristic trends of the gaming spectrum listed above under gaming and analysis tech-

*Held at Xerox International Center for Training and Management Development, Leesburg, Virginia, 27-29 September 1977

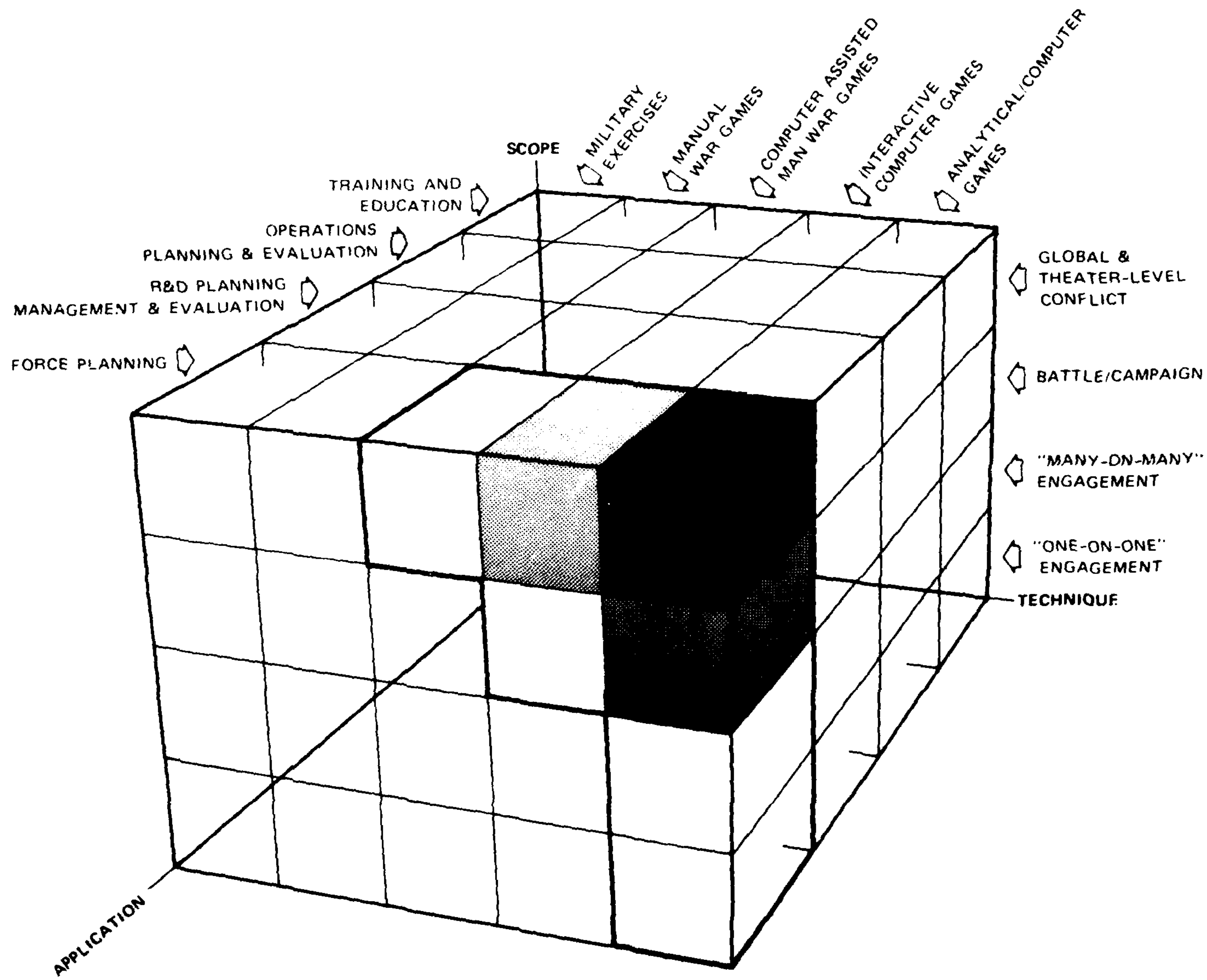

FIGURE S-1 GAMING CLASSIFICATION MATRIX AND AREAS OF WORKSHOP EMPHASIS

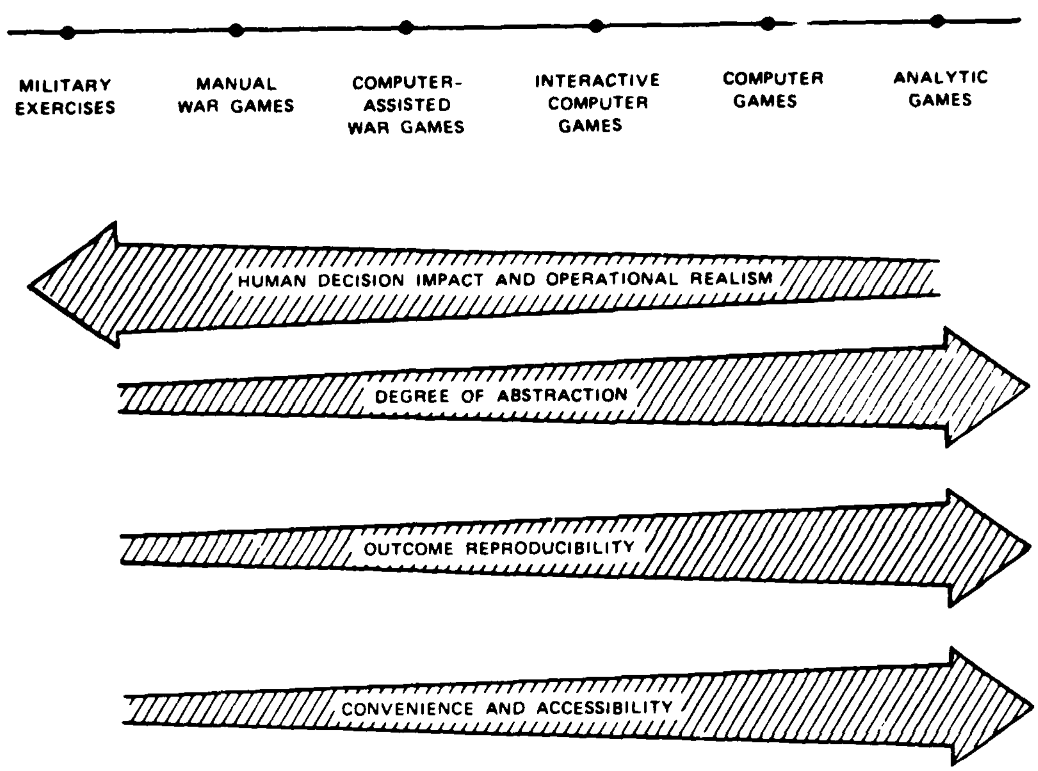

FIGURE S-2 GAMING SPECTRUM AND GAME CHARACTERISTIC TRENDS

nique. A relative cost-ranking in descending order for implementation of the games within the spectrum would generally be as follows:

- Military exercises
- Interactive computer games
- Computer games
- Computer-assisted manual war games
- Manual war games
- Analytic games.

The agenda for the workshop was based on consideration of the critical elements that are involved in applying computer gaming techniques to a problem of any sort. These are:

- The user/decision maker and the problem to be solved.
- The gaming model, its flexibility of structure and its adaptability to the user's problem.
- The combat modeling techniques employed in the gaming model, their adequacy, and validity.
- The data base available for input preparation and its validity.

Accordingly, the following topical designations suggested themselves for the workshop agenda:

- User attitudes and concerns
- Combat model structures

- Combat modeling techniques
- Game theory (mathematical and heuristic optimization)
- Data base and validation problems.

It should be noted that game theory is introduced in the above listing to account for the accommodation of human behavioral characteristics in automated or semiautomated gaming.

A series of invited papers were presented in each of the five subject areas listed above and are summarized below.

- KEYNOTE ADDRESS: "Some Random Thoughts on Models and Force Planning" MGEN Jasper Welch, USAF

The evolution of Air Force involvement in theater-level gaming and analysis is traced. Experience has now been gained with both large-scale "global" theater models and the serial use of hierarchical models in theater-level analyses. Problems in working with hierarchical models identified as those of consistency, enforcement and the accommodation of initial condition/boundary condition constraints are discussed. Also the use of preprocessors is proposed in order to isolate the meaningful areas in an analysis around which sensitivity investigations concerned with the variations of key parameters can be performed. In this manner the inordinate amount of time required for the systematic investigation of parameter sensitivity can be considerably shortened.

- SESSION I: GAMING UTILITY FROM THE USER's POINT OF VIEW

"Theater-Level Gaming in the Formulation of Plans and Policies"

1. Army — Philip Louer

The types of studies and analyses performed by Department of the Army to meet its objective as a part of national and military objectives are described. Included are combat force requirements (number, types of units, mix of combat arms), the numbers and types of support units, evaluation of current force readiness and sustainability, and studies of tactical nuclear issues. To this end, the Army uses the CEM, ATLAS and IDAGAM II Theater Models in deriving the major analysis inputs to its decision process.

2. Navy — John Shewmaker

PRM-10 is presented as an example of how serious discrepancies can arise between the services and OSD in estimating force level requirements. In this instance, the Department of the Navy was in disagreement with OSD in the analysis of requirements in the Atlantic Theater (more specifically, the North Flank [Norwegian Sea] and Middle Atlantic). Reasons for the differences in Navy and OSD PRM-10 estimates are discussed in some detail. Problems identified that confront the Navy include the failure to identify clearly and pass on to the high-level decision maker all of the assumptions that are crucial to an analysis, the absence of naval warfare representation in existing theater models particularly where naval functions interface with and complement other service activities, and a tendency when performing analyses to reflect U.S. rather than published Soviet strategy for the employment of naval forces.

3. OSD PA&E — Robert Schneider

The use by PA&E of the spectrum of techniques ranging from simple force number comparisons to theater models in making force balance assessments is described with the observation that no single technique or tool is always adequate. At this level of decision-making, "proponency" or "advocacy" issues that arise in the competition for budget dollars within the bureaucracy are the most troublesome. Model development is considered to be significantly ahead of data availability for the models. Examples are presented of PA&E involvement with theater models in the past year (PRM-10, Ammunition Rates Study, Tank War Reserve Study and Military Committee Special Study Group (MCSSG) FRG/U.K./U.S. model comparisons).

4. Net Assessment — Andrew Marshall

The presentation emphasizes the fact that as a diagnostic, rather than a force planning, activity net assessment brings to the attention of the Secretary of Defense those emerging problems and adverse trends affecting force balance as well as unusual opportunities, for the United States and its allies that should be pursued within the DoD or elsewhere. For such applications, theater models have been assessed to have virtually no utility, particularly since they lack the ability to treat the major asymmetries that exist on both sides in tactical doctrine and the structures of command and control. In addition, the failure of present theater models to account for certain factors (surprise, deception, leadership, etc.) that historically have permitted a force that is inferior in numbers and equipment to defeat a superior one does not inspire confidence in the use of such models.

5. CIA — James Starkey

The Agency's involvement with theater models has just begun. Primary interest in such models is to study the present and future force postures of potential adversaries so that better estimates of the threat to U.S. and allied forces can be made. Few models are presently in use or under development at CIA and the assessment of such techniques is proceeding slowly and cautiously.

6. ACDA — COL Miles March

The relatively minor participation of ACDA in the Mutual and Balanced Force Reduction (MBFR) efforts, which were undertaken primarily by DoD and the service in 1971, is described as are the uses made in this exercise of the ATLAS, FORPEM and Static Force Ratio models. It is noted that in ACDA, more emphasis and effort are directed toward strategy issues; matters relating to strategic arms limitations and nuclear test ban verification. Possible future uses of theater-level models by ACDA in the areas of MBFR option comparisons, arms control impact statements, arms transfers, and arms limitation agreements are discussed.

7. JCS — Frank Kapper

The canonical decision process and the role that models and analyses play in the process at the JCS level are described. The JCS makes considerable use of theater models in developing the Joint Strategic Objectives Plan (JSOP), in developing information for the Joint Force Memorandum (JFM), and for special analyses such as the MBFR, the CAP studies in logistics and mobility and the MCSSG comparison of German, British, and U.S. theater models. Difficulties in understanding, using, and maintaining various theater-level models within SAGA are described as is the apparent lack of concern among model developers relative to the availability of suitable data to serve as inputs for their models. The urgent need is expressed for a better understanding of the phenomenology of combat, particularly as it is affected by the interactions of combined arms and the employment of nuclear and chemical munitions.

- SESSION II: STATUS OF THEATER-LEVEL SIMULATION MODELS; PRESENT AND FUTURE, AND PROBLEMS OF MODEL STRUCTURE

8. "Theater-Level Models" — Seth Bonder

The evolution of the Vector series of theater-level models (VECTOR 0, 1, 2) is traced, along with descriptions of the various spinoff models that steamed from the mainstream series such as DIVOPS, VECTOR 1-NUC, and COROPS. The need for theater-level models that did not rely on firepower scores for the determination of attrition or FEBA movement gave rise to the Vector efforts in 1972 and also initiated similar developments by IDA and Lulejian. The thrust in Vector model development towards the explicit, rather than implicit, representation of such factors as intelligence and target acquisition, command, control and communications, combat activity, and FEBA movement as a function of such activity, terrain, weather, etc. is described. It is suggested that a future trend may be embodied in a shift away from high-resolution simulations as exemplified by VECTOR 2 toward a concept of hybrid analytic simulation, with the development of pure analytic models as an ultimate goal. Moves in this direction would derive from the knowledge and experience gained from the development and exercise of high-resolution simulations. The speaker addresses the troublesome contradiction involved in user demands for more model detail and realism on the one hand and user complaints about the resultant complexity of models and attendant operating difficulties, on the other. He further emphasizes the need for research in the area of model validation.

9. "A Critique of Four Theater Models" — Alan Karr

This discussion is a comparison and critique of four deterministic theater-level models — CEM, Lulejian 1, IDAGAM 1 and VECTOR 1 — from the standpoint of the assumptions in each that underlie the treatment of attrition and FEBA movement. It is noted that these assumptions, which are, after all, limitations, are not explicitly described or defined in most of the model documentation.

10. "Four Model Comparison Study" — Lanny Walker

This presentation describes another comparative study of CEM, Lulejian 1, IDAGAM 1 and VECTOR 1, sponsored by WSEG. It is based on the technique of applying subjective rankings to the ways in which these models represent a number of functional areas derived from a military perception of what is important to theater-level combat. The functional areas considered are organization and mission, geography, combat force interactions, logistics, unit/personnel replacements, and intelligence. No dominance of a particular model is noted in the ranking process, and the intrafunctional rankings are observed to be more meaningful than the interfunctional ones.

11. "Theater-Level Modeling of Conventional Nuclear and Chemical Warfare" — Edward Kerlin

The evolution of TACWAR, a low-resolution theater model capable of handling conventional, nuclear, and chemical warfare, is described. The model structure is patterned after that of IDAGAM with the SATAN models (detailed nuclear, Monte Carlo models treating platoon-size units) and models from the Ballistics Research Laboratory, Aberdeen, being used to generate analytical functions that, respectively, accommodate the employment of nuclear and chemical munitions. Resolution is down to company/battery size for purposes of unit identification when nuclear strikes are considered and both supply networks and target acquisition systems are simulated in considerable detail, all of which represent departures from IDAGAM. These steps are made necessary by the fact that unconventional munitions are scarce and must be targeted in somewhat realistic fashion and by the fact that they possess massive destructive power. The speaker comments on the many tactical and doctrinal uncertainties associated with nuclear and chemical warfare and describes user decision options available in TACWAR for escalation from conventional to nuclear and chemical warfare.

12. "Experience with Interfacing Ground/Air and Sea War Combat Models" — Carl Hess

The CAPSTONE/CAPLOCK series of studies (1972-1975), which were an examination of the NATO reinforcement flow from CONUS to final destination in-theater, is described. A study of heroic scope and proportions, it is presented as a rare example of the use of multiple models, both serially and in parallel, even though the effort is not concerned with theater-level combat in the traditional sense. In-theater supply demands and both intertheater and intratheater attrition to the supply lines are determined in the process of estimating logistic throughput. A dozen different models of widely varying complexity used to accomplish this are described. The many difficulties inherent in this type of endeavor are discussed, particularly those of manually interfacing between models that are run serially and reconciling conflicting results from models run in parallel.

13. "Problems of Aggregation and Resolution in Theater-Level Models" — John Bode
The speaker points to the general lack of sufficient theoretical work in combat modeling over the past several years inferring the subject area to be a particularly troublesome one that is in need of attention. It is noted that a fundamental problem with increasing aggregation is the general loss of information content with the process and the fact that the process is irreversible. Once one deals with aggregate properties, one cannot turn about and properly disaggregate or decompose the information into its detailed elements. Furthermore, he observes, there is a discernible shift in emphasis of interest at decision-making levels from force level issues to structures issues like command and control, new tactics and doctrine, and the impact of new weapons of mass destruction. These are not macroproblems any more (in a relative sense) and macroaggregation, as used in the past, is no longer adequate. Examples are cited from actual gaming experience that illustrate how the "leverage" in controlling combat outcome resides in the fine structure of the combat process in the areas of maneuver, attrition, and C^3I. To address such problems, the speaker suggests the investigation of alternative aggregation schemes such as aggregation by force element ("player-centered modeling") and the possible use of nonuniform resolution concepts in model structures.

14. "Outcome, Effectiveness, and Decision Criteria for Combat Gaming" — George Pugh
A concept is presented, using the unifying perspective of decision theory, that relates the problem areas of outcome measures (which outcome is "best"), decision criteria (which course of action is "best"), and measures of effectiveness (which system is "best") in theater-level gaming. From this perspective, the selection of outcome measures and measures of effectiveness simply become different aspects of a more general problem concerning the role of values in the decision process; a process with which all three problem areas are involved. Despite scientific training and its dictates of objectivity, the speaker suggests that more recourse be made to intuitive problem solving and that judgmental values be allowed to play a major role in military analysis and simulation. The advantages of doing so are described, and a method is outlined that stresses intermediate goals, decisions, and outcomes with shorter time horizons that are more reflective of real world combat. The final outcome, then, is the cumulative result of these intermediate outcomes. Value criteria, inherently judgmental in nature, form the basis for defining outcome measures, serve as decision criteria within the simulation for selection of the best courses of action, and provide a foundation for estimating measures of effectiveness (since weighted values for various types of combat forces and and their weaponry should be directly related to their combat value, or effectiveness).

- SESSION III: THEATER-LEVEL COMBAT MODELING METHODOLOGY

15. "Attrition of Ground System Modeling Overview" — Robert Farrell
The speaker addresses the subject from a broader perspective than just that of the attrition function. After an examination of the modeling of ground combat in six major

operating U.S. theater models*, he concludes that there is almost nothing in common among them, except for their treatment of the broadest modeling aspects such as the representation of combat forces (surviving people, combat vehicles, weapon systems, *etc.*), the organizational hierarchy of ground forces, and the abbreviated set of ground combat mission types that they consider. Despite the absence of commonality among the models in functional areas like target acquisition, which is generally handled implicitly in the data base (where the assumptions are not clear and remain hidden), and in their attrition equations, the speaker identifies a characteristic ratio which he calls the Conditional Exchange Direction† that remains generally invariant, to within about ±10%, among the models compared. The hope is expressed that further investigation might reveal a degree of constancy in this characteristic ratio over some reasonable class of conditions.

The issue of explicit modeling versus the implicit treatment of combat effects through manipulation of the data base is discussed as are the related concepts of model logic visibility, transparency, and "clutter." Explicit treatment enhances the visibility of model logic, but produces "clutter" by virtue of the volume and complexity of the logic that must be presented. Implicit treatment, on the other hand, enhances the transparency of model logic since most of the effects are embedded in the data base. The difficulty here is that factors that should perhaps vary with conditions as the game proceeds cannot do so because they are fixed in the data base. Furthermore, the assumptions made about these effects in generating the data base are usually *not* documented and consequently are lost to others who have a need to understand the model.

16. "Attrition of Air Systems Modeling Overview" — Bruce Anderson

The speaker notes that because of a simpler, less cluttered operating environment and because of the multipurpose nature of aircraft in general, air systems modeling provides a natural transition to the use of game theory. The necessity for the exercise of judgment in the analysis process and the different types of judgment that are required, whether results are to be obtained from theater models or from the integration of lower level analyses, are discussed. Some uses of theater-level models are identified, particularly by the concept of testing for consistency between staff work and model results, or between the work of one staff versus that of another.

IDATAM, a tactical air model, is described as an enriched version of the air combat model of IDAGAM. It includes treatment of the missions of airbase neutralization, interdiction, belt SAM-suppression, and close air support for both sides, although the employment of aircraft by opposing sides need not be symmetric. The payoff or measure of effectiveness (MOE) for IDATAM is the number of penetrating attack aircraft for both sides. IDATAM is not tied to modeling of land combat, although a simplified version of the model has been incorporated in TACWAR, described earlier by Dr. Kerlin.

The utility of theater-level models is addressed for those instances where effectiveness comparisons are to be made between single- and multi-purpose systems.

17. "Attrition of Marine Systems Modeling Overview" — John Underwood

In force planning, the Navy does not make use of theater models that are directly comparable to the air/ground combat models that have been the main topic of discussion at the meeting. Instead, a more analytical and less formal approach is used involving the integration of results from a hierarchical set of analyses and models that address a range of

*CEM, IDAGAM, Lulejian, VECTOR 1, VECTOR 2, Atlas

† Conditional Exchange Direction $= \dfrac{\text{losses of system } i \text{ in Condition C,}}{\text{losses of system } j \text{ in Condition C}}$ where all systems, i, are considered for a fixed system, j.

activity from the tactical or unit level up to the campaign level. Variations in key parameters are explored at each level so that productive tactics and strategies can be identified for both sides. The process is referred to as analytical war gaming.

Major Navy force level studies of the last fifteen years are discussed briefly and, in greater detail, the speaker describes a current study, SEA WAR 85. In this study the analysis work is performed on three levels; campaign level, task force or convoy engagement level, and the tactical or unit level. First, a sequence of steps involves the definition of national objectives, the development of scenarios, national strategies, tasks for naval forces, naval strategies, and force concepts and plans, all leading to a rationale for the deployment of forces. After selection of strategies and force deployments, analyses are conducted at the campaign level in time steps using three basic campaign models* that can operate in parallel. Decision processes are treated heuristically, "by inspection," within a time step, to ensure that both sides make logical decisions. The models themselves are "bookkeeping" devices, Markov in nature. Inputs to the campaign models are derived from detailed analyses of both single unit engagements (one-on-one) and task group or force engagements against specific types of threats (many-on-many). On-going programs for continual improvement of data bases for these inputs (SEATAC and Navy Force Mix Studies) are described.

18. "Techniques for Modeling Tactical Nuclear Warfare" — Stanley Spaulding

A tactical nuclear warfare model development by VRI, generally paralleling IDA TAC-WAR, is presented. The model is designed to accommodate a variety of nuclear delivery systems and weapons including "dial-a-yield" options and is mainly concerned with the impact of nuclear weapons employment on conventional warfare. Nuclear doctrine, except for the broad enunciation of NCA control policies and the "package," "time-frame," and "pulse" concepts, is poorly defined and is presently under study by DNA and the Army. Consequently, the model must be flexible enough and of high enough resolution to treat not only the weapons effect parameters, but most importantly, the interfacing between target acquisition, target movement, and the response time for weapon delivery as well as the entire issue of how weapons should be allocated to targets on the battlefield and in the rear area.

The speaker describes the VECTOR 1/NUCLEAR model, a combination of the UNICORN target allocation and damage assessment model and the VECTOR 1 conventional warfare model, that satisfies many but not all of the problem requirements as outlined. UNICORN is compatible with VECTOR 1 in level of detail. It is an expected value damage model and uses linear programming to optimize the allocation of weapons to targets based on a maximization of target value destroyed within an imposed set of constraints.

A critical but little explored area in model development is the behavioral response of combat units that are attacked with nuclear weapons and the response of adjacent civilian populations. An approach to solving this problem was to run the VECTOR 1/NUCLEAR model some 300 times in a VRI study for DNA to investigate a wide range of response. Also the VECTOR 1/NUCLEAR model used a "man-in-the-loop" scheme to develop a reasonable set of tactical decision rules that were incorporated into a "rules package" and were subsequently run automatically as part of the model. The speaker further touches on improvements that are contemplated in the development of a VECTOR 2/NUCLEAR model.

19. "Logistic Support and Combat Unit Effectiveness" — Ellwood Hurford

The work discussed in this presentation is being performed by the TRADOC Logistics Center in support of the Theater Nuclear Force Survivability Study (TNFS), being conducted by Dr. Wilbur Payne of TRASANA for TRADOC. The speaker points out, and correctly so, that while many of the presentations describing the various theater models at the meeting

*Submarine/air anti-shipping, carrier task group/enemy force encounter, naval force (non-carrier)/enemy force encounter have recognized the importance of logistics and the vulnerability of supply lines, stockage points, and transportation networks to the outcome of combat activities in the forward area, few, if any of the models have yet managed to address these effects explicitly. The current effort to do so at the Logistics Center has as its mainstay the Logistics Attack Model, or LOGATAK, developed initially by the BDM Corporation for DNA. The point of departure for LOGATAK has been the MAWLOGS (Model of the Army World-Wide Logistics System) series of models that model maintenance, supply, and transportation through the various echelons in great detail. The models have been adapted to the European theater and applied to the European roads, railroads, and supply points with the logistic system users being the combat divisions.

The LOGATAK model introduces the capability of selectively attacking the logistics system to permit an evaluation of supply and transportation vulnerabilities. There is no capability at present to assess the vulnerability of the maintenance system and an effort to do this is presently under way by adding the vulnerability dimension to the MASC (Maintenance Support Concepts) model. The speaker briefly describes each of the models discussed; MAWLOGS, LOGATAK, and MASC. He notes the inordinately heavy demands for data that logistics models impose in general and the MASC model in particular.

20. "Comparison of Results from IDAGAM with an Aggregated Combat Model" — Norig Asbed

This presentation describes a highly aggregated analytical model, oriented to the environment of the European Central Front for estimating fixed-wing close air support requirements. It was developed by CAA, patterned after a suggested formulation by Dr. Wilbur Payne (TRASANA), and was subsequently checked against IDAGAM 1 with respect to the results that it produced.

It is a relatively simple force ratio model, described as quasidynamic, that assumes a massing of enemy forces for a breakthrough in a critical subsector. The model is solely concerned with armored combat vehicles, antitank weapons, attack helicopters, and close air support. The defender's reinforcements to the critical subsector are drawn exclusively from the remainder of the sector and the close air support requirements are expressed in terms of additional kills that must be provided by tac air to sustain a threshold force ratio in the critical subsector. The key variables in the analysis are identified as the fraction of the sector FEBA over which the attacker chooses to mount his breakthrough, the threshold force ratio in the critical subsector that the defending commander feels will contain the enemy thrust, and the percentage of losses relative to the ground forces committed to defense of the critical subsector that the defense commander feels he can accept. A step-by-step development of the quasidynamic model is presented as is a comparison of results obtained with the model and IDAGAM. The comparison shows surprisingly good correlation between the two.

21. "Modeling of Tactical Decision Processes in Theater-Level Gaming" — Robert Robinson

The extremely difficult problem of adequately representing the command and control function in theater-level combat models is addressed in this presentation. The speaker first discusses the evolution of attempts in this direction from an historical viewpoint, starting with the simplistic "force ratio-at-the-FEBA" approach to command control, which governs the advance or retreat of opposing forces in many of the modeling efforts. This was improved upon considerably in the early 1970s when some serious attempts were made with game theoretic techniques to derive "rational" decisions for both sides in theater games, at least with respect to resource allocation decisions of a high-level nature. Relatively little, however, was done with the representation of decision processes at lower levels in the command structure.

The speaker next discusses the key reasons for simulating decision processes in theater-level models which are (a) to establish credibility in the model, (b) to provide a means for the assessment of strategies and tactics in relation to weapon systems and force structures, and (c) to provide a means for assessing the value of information and of command and control per se, something that should be done in the context of a particular theater campaign.

The essential elements of C^3I are presented as the decision making functions at the various command levels, the hierarchical nature of the command and control system (with different time and space horizons at different levels of the hierarchy), and the uncertainties in the system with respect to events, information, communications, and decisions. Each of these is discussed in some detail.

The speaker then ties together these essential elements of command and control into a two-sided model concept that includes representation of ground/air combat interactions, support forces, and information systems, and that is structurally adapted to the hierarchical nature of C^3I.

While the speaker is not optimistic about the success of further game-theoretic approaches to the C^3I problem, he does suggest a game concept in which the commanders of each side play to different payoffs that reflect the differences in their objectives and planning horizons. He also suggests that the weighting factors in the payoff equations be varied during the game in accordance with possible changes in objectives on both sides.

Mention is made of advanced research in command and control involving robot developments and other artificial intelligence techniques. The speaker concludes with suggestions for further research on developing better input data from the study of existing C^3I systems, command post exercises, and historical data; manned interactive simulations; and, finally, on developing a theory of command and control.

- SESSION IV: GAME THEORY IN THEATER-LEVEL MODELING: OPTIMAL SOLUTIONS AND HEURISTIC SOLUTIONS

22. "The Role of Game Theory in Force Planning and Game Associated Problems" — Martin Shubik

The speaker, an avowed believer in the utility of game theory, gives an overview of the theory with emphasis on applications to military problems. A 3x2 matrix of distinctive classes of game theory is identified (2-person zero sum, 2-person nonzero sum, N-person theories and static and dynamic games), and the ties that exist between game theory and both simulations and other forms of analytical modeling are stressed. The speaker identifies three very important values of game theory; they are an antidote for "spurious reality," they can be used as a logic check in modeling, and, most importantly, they serve as a sorting device for truly relevant variables. He underscores the importance of two rules; the game theory modeling rule of logic, consistency, and completeness and the gaming area of playability. He reviews the significant literature in game theory, allowing that very little 2-person nonzero sum theory and essentially no N-person theory has been applied in a military sense. Yet, he observes, in nonmilitary applications the storehouse of knowledge in game theory has been increasing dramatically.

The speaker deplores the trend over the past several years to separate gaming from the all-computerized model (simulation), much to the detriment of the former, placing it, like game theory, in the "curiosity box". He also observes with concern the ever-increasing average age of those engaged in the gaming profession noting that this type of age contour reflects unfavorably on the profession's health.

Looking to the future, the speaker seeks a reversal of the trend toward simulation at the expense of gaming and game theory; he feels there is a need for better communication between the military, the theorists, and the model builders and he looks for more experimental gaming combined with game theory, particularly in the threat area.

After discussing some highly interesting possibilities of applying Colonel Blotto games to various military problems, he concludes by identifying several key areas of military interest that could profitably be approached from a game theoretic point of view. These include the use of game theoretic solutions in duels with breaking point parameters added, the sensitivity of game theoretic solutions to varying information conditions, the use of nonsymmetric gaming in modeling U.S./Soviet conflict, and the use of "foul-up" or fuzzy gaming in which there are probabilities of information lag or of failure to obey commands. As a last comment, the speaker hopes for a return to political exercise gaming that might involve a few historians and political scientists in order to identify the parameters that really count in these broader scenarios.

23. "Solution Procedures for Multistage Games at the Theater-Level: DYGAM — An Algorithm for Solving Multistage Games" — Zachary Lansdowne

This paper is a description of a computer programming system called DYGAM (Dynamic Games Solver), which is designed to aid in the solution of a broad class of multistage decision problems including (and of particular interest to the present audience) multistage games. In the latter instance, the games can be either sequential or simultaneous, played over a fixed number of periods or stages. The system is written in FORTRAN, is based upon the basic Bellman dynamic programming recursion, using polynomials to approximate the payoff surfaces, and then uses a forward "look ahead" algorithm to improve the accuracy of these surfaces. The speaker presents an example of a multistage game solved by both rigorous analytical methods and DYGAM. He further discusses the difficulties encountered in attempts to solve "realistic" games in a reasonable amount of time with the DYGAM technique.

24. "Solution Procedures for Multistage Games at the Theater-Level: Description of the Solution Procedure Used in ATACM" — Frederick Miercort

The procedure described by the speaker is incorporated in the ACDA Tactical Air Campaign Model (ATACM) developed for ACDA to analyze various MBFR proposals. The model treats an air campaign as a zero-sum multistage game and, like DYGAM, employs dynamic programming to solve this game for approximate, optimal aircraft allocation strategies for both sides at each stage in the campaign. The air campaign model can accommodate up to four user-defined aircraft per side with as many as eight different missions per aircraft type. While the attrition/drawdown algorithms used for aircraft on both sides and the payoff functions selected can be varied, what is really fundamental to the approach is the concept of "conservative play" by both sides, which leads to the calculation of firm upper and lower bounds on the payoff, or objective function value associated with the strategies employed. Using this technique, the air campaign model produces three kinds of answers: the max/min outcome, the min/max outcome, and the outcome that would occur if both sides employ conservative strategies.

The speaker presents numerical examples to illustrate the approach and describes the economies associated with this optimization methodology.

25. "Man/Machine Interactive Gaming and Heuristic Solutions: Game Theory in Theater-Level Modeling: Optimal Solutions and Heuristic Solutions" — Alexander Dobieski

The speaker departs significantly from the subject matter suggested by the title and provides, instead, a description of an existing man-machine interactive training system for battalion commanders known as the Combined Arms Tactical Training Simulator (CATTS). It was developed by TRW for the U.S. Army and is installed at Fort Leavenworth, Kansas. Despite its development as a training device, CATTS has an operating man-machine interface that, in principle, could be applied to "man-in-the-loop" simulations used to support decision-making. The speaker describes CATTS as a specific operating, man-machine system, a description which includes the operators of the system and their functions, the real-time simulation models of battalion operations, and its data base that resides in the computer, the alphanumeric and map displays with their controls and associated software that drive the displays and the mock-ups of vehicles and communication links used to provide the trainees with a realistic operational environment. He is optimistic about the application and extension of the techniques developed for CATTS to the broader theater-level games used for force planning purposes. The concept is particularly well-suited to treatment of the C^3I problem in simulations with the map displays and alphanumerics contributing in a significant way to game playability.

26. "Man/Machine Interactive Gaming and Heuristic Solutions: Some Common Problems with Man/Machine Interactive Modeling" — Paul Tuan

A general discussion is given of some of the difficulties that are encountered in the development of man-computer interactive models used to solve a variety of problems (both military and nonmilitary). The speaker distinguishes between two levels of human control in such games or processes and presents examples of each. These are macro-level control in which function or parameter values in the model can be changed that have a "global" influence on the outcome, and micro-level or heuristic control where the human makes subjective decisions at certain selected decision points, based on on-line evaluations of existing conditions at these points. He also identifies problems associated with human judgment versus algorithmic judgment, particularly where interactive procedures are involved in optimization models. The possibility of human judgment conflicting with or violating the principles or objectives of optimization, expressed in algorithmic form, is always present. The use of decomposition schemes (partitioning of the interactive process by time, geography, decision-making hierarchy, or aggregation level) is presented as a way to minimize such conflicts. The speaker discusses the advantages of the distributed simulation process (where mainframe computers are time-shared) over centralized data processing and describes for the future an intelligent, interactive terminal that incorporates CRT displays for graphics and makes use of low-cost microprocessors.

27. "Problems in the Applications of Game Theory at the Theater-Level" — James Mayberry

This is a philosophical presentation that discusses the applicability of two-person zero-sum and nonzero sum games to the modeling of competitive situations (including those of warfare) in society. The speaker, through some everyday examples, demonstrates that there are few if any real-world situations that can be modeled strictly and rigorously as "zero sum." The zero-sum game, however, affords us a mechanism to come to grips with a more sophisticated notion, that of the cooperative (nonzero sum) game. The Nash and Kalai-Smoroginski solutions to such games, as well as definitions of "no-agreement" points according to Raiffa and Shapley, are briefly described and discussed. While this class of games is formally limited in applicability to situations where bargaining and negotiation can take place, it is suggested that implicit or explicit negotiation, used in conjunction with models that could reveal to antagonists the outcome of armed confrontation, might aid in the conduct or resolution of a conflict.

The speaker also addresses games of incomplete information which, in recent years, constitute an active area in game theory research. He believes such games have tremendous potential in their future applicability to military problems, particularly those of C^3I.The computational difficulties, however, as foreseen, are considered to be enormous.

• SESSION V: DATA BASE REQUIREMENTS FOR THEATER-LEVEL MODELS AND DATA-RELATED DATA INPUT GENERATION PROBLEMS

28. "Overview of Data Base Problems in Theater-Level Modeling" — MAJ Raymond Bednarsky

Data base requirements, and data gathering and management problems, are generally conceded to be most formidable of all the problems associated with theater-level gaming. The models, despite the difficulties inherent in their development and use, have progressed much farther as an area of endeavor than has the generation of reliable data for the input information required by the models.

The speaker addresses in some detail the enormous data needs of a model such as VECTOR 1 for "low" level data (raw data) and "high" level data (raw data subjected to aggregation and manipulation for direct input to a particular model). VECTOR 1 requires some 200,000 pieces of low-level data and 20,000 pieces of high-level data for a case study, while VECTOR 2, a next-generation model, is estimated to need about 380,000 low-level data items for the simulation of a large-scale conflict. The structure and contents of the DoD Force Planning Data Base (DFPDB), developed under the auspices of OSD (PA&E) for U.S., Mid-East, NATO, and Warsaw Pact Forces, are described.

Examples of information to be found within the DFPDB are presented along with its uses in supporting decisions and providing information at various levels in DoD. Problems cited with the DFPDB include the large size of the data base, the lack of quality control over inputs, the existence of information gaps, the absence of standardized reporting procedures, and the institutional bias in certain data sources.

The lack of low-level weapons data is particularly noted as a serious data base deficiency. To overcome this deficiency, a plan to develop a Weapons Characteristics and Performance Data Base (WCPDB) has been proposed, approved, and is currently being executed. The speaker describes the WCPDB Program, which has been under way since October 1976 and is currently in the design phase. The description covers the kinds of characteristic and performance information being sought for each weapon system that plays a role in theater-level conflict as well as the logic links that relate these characteristics to targets and to weather and terrain, as appropriate. In addition, there is the difficult linking of the WCPDB to the DFPDB that is being contemplated. He further outlines a schedule for the WCPDB, discusses the technical problems associated with the construction of the data base, (including those of data base structure, location, and validation of data, and data base security), and presents the significant management problems associated with execution of the program, by no means the least of which is program funding, estimated to cost millions of dollars.

While the logic of what is being attempted is quite clear, the difficulties contemplated in the next step, the implementation phase, are considerable and the speaker turns to the community represented by those at the conference for suggestions and support.

2.2 Summary of Issues and Requirements for Research

Approximately 40% of the total time allocated to the workshop was devoted to panel discussions in each of the five subject areas covered by the meeting. Much of this discussion material is interspersed with the summary of issues, presented below.

To place the bulk of technical material covered by the workshop in proper perspective, it was deemed advisable to trace the evolution of models of large-scale ground/air combat from their earliest beginnings. Such a procedure, apart from tying together many individual and diverse contributions made to the state-of-the-art in combat modeling, offers an explanation for the direction that this modeling has taken and accounts for the state in which it is presently found. Accordingly, one is perhaps afforded a better understanding of the nature of the problems that have arisen in this chain of development.

In conducting such an effort, one observes an unfortunate preoccupation with the importance of the attrition process (discussed at greater length below) in spearheading the development of ground/air combat models and, in fact, pervading their continuing evolution. This notwithstanding, there appears to have been historically three basic approaches used to ascertain attrition in models of ground combat:

- Differential equation approach (based on Lanchester theory)
- Process modeling and simulation approach
- Firepower scores and indices approach.

Chronologically, the differential equation approach was the first to appear (1914) and, after an incubation period of some 30 years,* took a position in the forefront of combat modeling, orienting such modeling entirely around attrition. This occurred as the result of considerable expansion and enrichment of Lanchester's original attrition equations to the point where the differential equations themselves could pass for complete models of combat in the eyes of some analysts.

Explicit process modeling and the appearance of the high-speed computer in the 1950s, leading to the development and refinement of simulation techniques, defined the main route followed in creating all of the subsequent major combat models. These can be characterized as efforts that strived for greater "realism" in representing combat processes beyond attrition while attempting to address problems of increasing conflict scope. This was naturally accomplished at the cost of greater complexity. The simulation approach started with models of one-on-one duels and expanded from these to the modeling of engagements at platoon, company, battalion, division, corps, and theater levels. So that the models would remain tractable as force sizes and the scope of battle increased, recourse to the aggregation of certain combat phenomena had to be made.

The third fundamental approach to appear chronologically was that of firepower scores and indices. This approach constitutes a highly implicit representation of attrition, in that it supports a methodology that assumes the dependency of casualty rates and rates of advance in the engagement of adversaries on the ratio of the "firepower potentials" of the forces involved. The firepower scores for each weapon system type were derived using some admixture of proof test and field data and expert military judgment. The firepower indices were constructed from the products of the firepower scores for particular weapons and the number of such weapons in a force summed over all the weapon types in the force. The ratio of firepower indices of friendly and enemy forces in effect constituted the ratio of firepower potentials, known quite simply as the force ratio. The relationship between force ratio and casualty rate percentages was derived from the analysis of historical combat records.

The concept of firepower indices as they relate to attrition is rather straightforward and logical. In practice, however, the methodology is, for numerous reasons, contrived and found wanting for use beyond that of a static indicator in effecting crude force comparisons. As an extension of the firepower score/index-casualty rate line of reasoning, at least one complete, empirical model of combat has been developed to track with historical outcomes. This model, the Quantified Judgment Model, is enriched with the consideration of over seventy combat variables.

With virtually all modeling of large-scale combat employing simulation techniques, and the need for aggregation manifesting itself as the scope of combat being simulated increased, it was only natural for there to be considerable bleed-off of differential equation attrition methodology, or firepower index methodology (or both), into the mainstream of simulation development in order to aggregate attrition processes in the larger combat models. The resulting methodology mixtures remain, at best, controversial regarding their validity.

*Coinciding with the recognition of operations research as an area of scientific inquiry

The evolution of several dozen combat models is traced in this volume (see Section 3.2). In so doing, an idealized structure for the modeling of combat has been derived (Figure S-3) that is implicit in all of the models but is never satisfied in its entirety by any one model. Such a construct is needed for any attempt to evaluate the relative merits and the completeness of different combat models in simulating the actual conduct of ground warfare. In brief, Figure S-3 consists of a dynamic combat loop concerned with friendly force/enemy counterforce activity coupled to a command control loop (friendly) through intelligence, reconnaissance, and surveillance means by which friendly perceptions of combat activities and outcomes are generated. To a degree, these are subject to enemy disruption. The command control loop also includes the important but often neglected function (in modeling) of logistics support, recognizing that elements of this support system are also vulnerable to enemy attack and disruption. Major communication links are identified in the figure. It should be recognized further that an identical figure can be constructed for the enemy forces around the "counterforce activity" block, so that the conflict is properly represented by two dynamic, symmetrical flow paths of activity and information for friend and foe that interact with one another in the combat environment.

In addition to the flow path decomposition of combat modeling, another decomposition concept considers the algorithms effecting input/output transformations at activity nodes in Figure S-3. In this concept, the inputs are described as the circumstantial elements of combat, the outputs as combat outcomes, and the algorithms that relate combat elements to outcomes are generally complex functions described as combat processes. Elements (essentially the "givens" in a problem) are defined as follows:

- Combat circumstances, initial objectives, and missions for both sides.
- Natural and man-made environments in the area of operations.
- Human resources, numbers, characteristics.
- Material resources (equipment and devices for waging and support of war), numbers, characteristics.
- Organization and structure of opposing forces.
- Tactics, doctrine, and operational concepts.

Combat processes are identified as:

- Attrition
- Suppression
- Movement
- Command, control, communications, and intelligence (C^3I)
- Combat support
- Combat service support.

The mathematical expression of the relationships among combat outcomes, elements, and processes is shown in Appendix C. Suffice to say that the early emphasis placed on the attrition process in the modeling of ground combat (to the relative neglect of other processes) has perhaps been ill-advised. However, one must hasten to observe that we have little understanding of the relative importance assumed by each of the above factors in shaping overall conflict outcomes, or of the conditions under which they might do so.

The review in Section 3.2 of the many combat models (U.S. and foreign, at varying conflict levels) conducted against a comparative backdrop of the decomposition concepts outlined above has revealed that:

- Models have retained a strong "engineering" orientation. They are notably weak in their

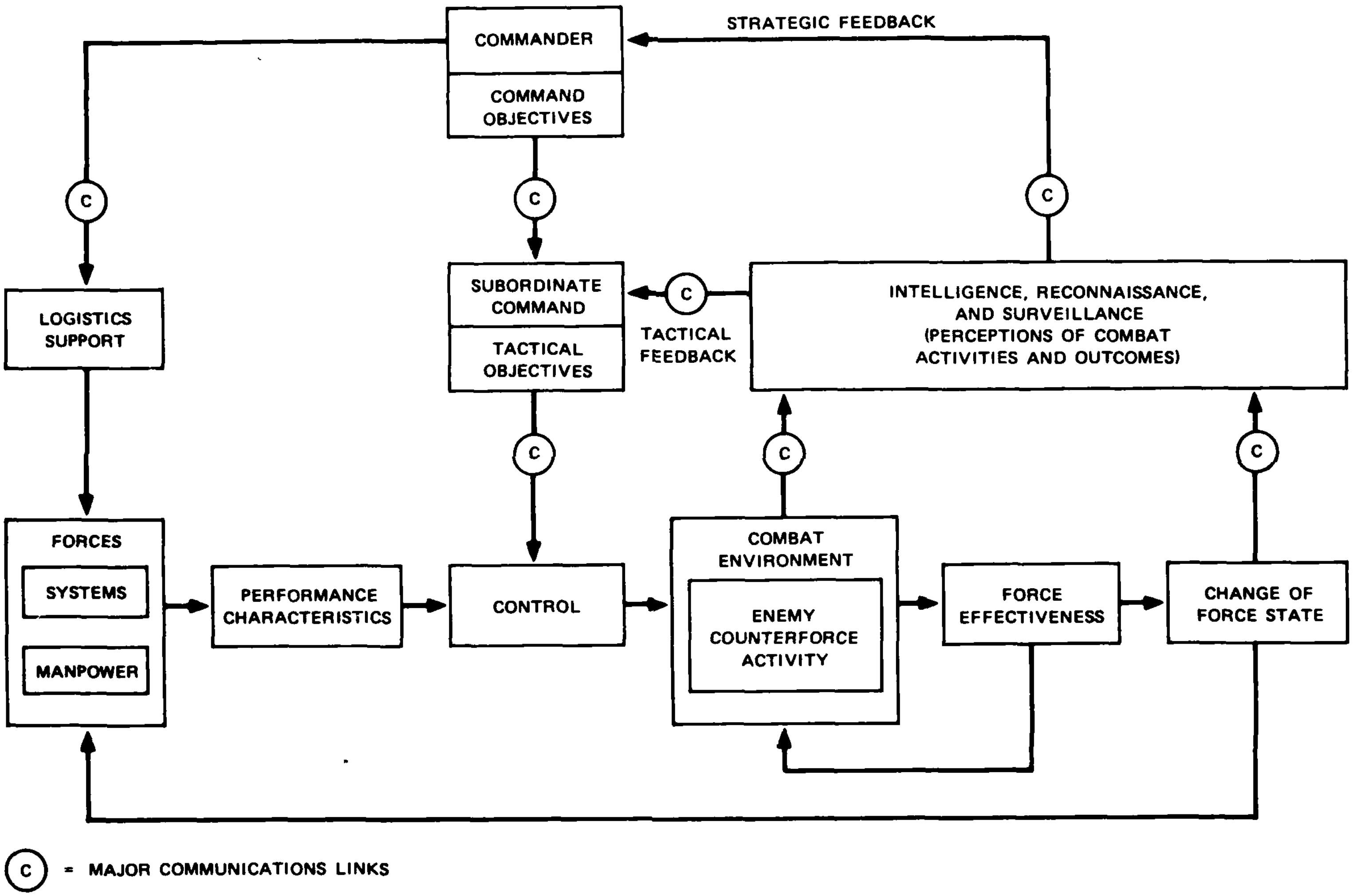

FIGURE S-3 STRUCTURAL CONCEPT OF COMBAT

treatment of human behavioral characteristics and the impact of such characteristics on combat processes.

• Models are lacking in capability to reflect flexibility of movement of ground forces that encompass non-integral FEBA situations such as breakthroughs and flanking maneuvers. There are serious difficulties in the modeling of other combat processes such as C^3I, combat support (electronic warfare), and combat service support (the dependency of combat resources on logistics and enemy interdiction thereof).

To carry on with the assessment of combat modeling in its present form and condition, it is necessary to consider the origins of technique and hence the origins of operations research (OR) as a scientific pursuit during World War II. Then one should trace the evolution of OR through an explosive expansion of postwar activity. The cradle of OR was indeed to be found in the analysis of wartime operations and its wellsprings were those of mathematics and physics. The ongoing conflict provided a "laboratory," rich in feedback for these analytic activities, which tended to focus on the technical aspects of the operations problems being addressed. Nonetheless, the true *sociotechnical* nature of the subject matter was recognized and, from the outset, it was clear that the practice of OR was to be a somewhat unusual, interdisciplinary undertaking.

Postwar, the theory and application of OR expanded into commercial and industrial problems, while its continued application in military affairs increased at an impressive rate. The utility of OR was generally measurable in instances where mathematical models could be constructed and tried in parallel with some ongoing operation in the real world. The purpose of OR was to "optimize" or improve the operation. Whether or not the OR solution to the problem met this objective could be ascertained with reasonable accuracy and little delay by direct experimentation within the operation. These are instances of OR application in a "closed-loop" mode.

In military OR, quite naturally, postwar attention shifted from the conduct of ongoing operations to analyses concerned with weapons and operations likely to be used in future conflicts. No longer was there opportunity to experimentally interact with an ongoing process and we were, and are, in effect, confronted by an "open-loop" condition.

The advent and rapid evolution of the high-speed computer and the emergence of a branch of OR known as systems analysis gave impetus to the development of larger, more complex models of military systems and various forms of warfare, employing a problem-solving technique known as simulation. This development has been noted previously in discussing the evolution of land combat computer games. Despite the added complexity and sophistication afforded by simulation techniques, which are called on to achieve greater "realism" in building models of combat, the inescapable fact remains that the entire field of endeavor is one of an "open-loop" nature. Most of the difficulties attending the use of combat models as an aid to decision making can be laid at this doorstep.

Acceptance of a body of information as scientific knowledge requires that there be clear expositions that lead to an understanding of how the information was obtained or derived (consensibility) and, once understood, a consensus among scientific peers that the procedures and methodology used are sound and proper (consensuality).* Neither condition is satisfied in the computer gaming of combat. More often than not, difficulties with style and format associated with computer model documentation obscure the assumptions made in developing the computer code. Even more serious, however, is the fact that consensus in the adequacy of the model, even were it perfectly understood, is hardly possible in view of the lack of closure with the real-world phenomenon of armed conflict. Perceived as compensating for the failure to attain scientific rigor is the heavy reliance placed on heuristic modeling

*Reference 56

largely based on "expert judgment." Scientific specialization in training and background among individuals of the community exposed to combat modeling serves to aggravate the difficulties in achieving consensus. This is further abetted by considerable variation in the standards of excellence, as a personal matter, among individuals that governs his or her acceptance of an analysis as being reasonable, sound, and professional.

Thus, we find that computer gaming continually faces a crisis of credibility among those who are engaged as developers and users of such models. Given the fact that these models carry an aura of scientism because they involve mathematical techniques and high-speed computers, it is no small wonder that lay people are even more confused about their validity. It should be noted that many of those responsible for high-level decision making and the setting of policy in government are indeed lay people relative to the intricacies of combat modeling.

The prevailing competitive environment to be found in the Department of Defense relative to the budgetary control of military forces and systems can frequently lead to the misuse of models and analysis in a "proponency" or "advocacy" mode. With no laws to govern the formulation of combat models, there can hardly be judge or jury to assess their correctness or applicability. The general awareness that such practices are prevalent only serves to further undermine the credibility of these modeling endeavors. Finally, there is a competitive spirit at play among the model developers themselves that leads to perhaps an exaggerated touting of certain modeling procedures they have chosen to employ. This is done at the expense of pointing out deficiencies in rival efforts and only serves to heighten the confusion surrounding the subject area.

That gaming models do have constrained but nonetheless significant utility cannot be denied. This utility is premised on the ability of a well-executed model to properly order the effectiveness of competing alternative force or systems concepts on a strictly relative basis. Certain interactions with mutually supportive combat components may also be instructive (counter-intuitive at times), but before they are added to the fund of existing knowledge they warrant close scrutiny to ascertain whether they result from peculiarities of the model or whether they indeed derive from the operating characteristics of the system(s). The limitations on model attributes are rather subtle and familiarity with them, while it is the subject of some debate within the analysis community, are little understood outside this community.

For the foregoing reasons, much of what is said in this volume is focused on the problem of developing a better coupling between the real world and the abstract world of modeling. This is addressed as an attempt to forge the "missing link." The missing link we seek is, by definition, embodied in a theory of combat or war and the requirement to uncover such a theory through further research is clearly the most important requirement to emerge from the workshop at Leesburg. Although it is to some degree an exercise in semantics, an argument is presented for the hypothesis that model verification, the theory of combat, and our missing link are essentially all one and the same.

Surprising is the fact that there have been only a few efforts to date to couple model abstractions of combat to the real world. Of these, the attempts to verify Lanchester's equations, discussed earlier, represent the most significant undertaking of this kind. More recently, the empirical "design-to-correlate-with-history" concept of the QJM also represents an attempt at theory development. However, the imbalance of effort expended in creating larger, more complex "open-loop" models compared with that expended in seeking model closure with the real world has been enormous and some attempt to rectify this imbalance seems highly appropriate.

Also explored in this volume is the form and substance of the missing link because these must be shaped by the constraints that reality imposes on us. It is suggested that the best approach to the development of a combat theory is via the process of model verification. Thus, while a combat theory need not have a mathematical form, it seems that it most certainly will if it is tied to model verification, for the models themselves are all mathematically structured. Model verification, in turn, involves some form of calibrating the models against actual outcomes of combat, and calibration is concerned with the concept of a difference error between the model results and the historical evidence. Since combat constitutes a stochastic process, the "error" is generally composed of two parts; a random error and a systematic error. The random error relates to the distribution of combat outcomes, and it is here that we run into serious difficulty. History gives us only a single sample of evidence for any instance of armed conflict so that we have no knowledge of the form (or the mean or the variance) of the distribution of combat outcomes. Therefore, we have no way of isolating the random component of error and, hence, no way of separating random from systematic errors.

Another serious constraint is that imposed by the inadequacy of available data to permit straightforward closure in the model verification process. Possible sources for data (pertaining to the past, present, future) germane to the analysis of combat are:

- National archives
- Official military histories
- Field/fleet/air exercises
- Combat experiments
- War games, models, and simulations
- Operational test and evaluation (OT&E)
- Proof tests
- Engineering laboratory tests and design studies.

The various strengths and weaknesses of the above sources are discussed in this volume as they *pertain to the problem at hand.* The first two sources, of an historical nature, reflect *real* combat data whereas the following four sources are those of *simulated* combat data. Data for the *technical* characteristics and performance of military equipment are represented by the last two sources in the list. Despite the variety of data sources, it develops that they are collectively inadequate ever to fully satisfy model verification needs. These difficulties lead one to a concept of model "quasi-verification," discussed in the main portion of this volume, which is based on a relaxation of verification criteria.

In the search for the missing link, a point of departure is suggested, using an idealized structure for modeling combat that derives from an agglomeration of existing model constructs (i.e., Figure S-3). This idealized structure is further tied to the concept of combat elements, processes, and outcomes described previously. The approach, in effect, decomposes the larger problem of modeling armed conflict into a set of smaller but highly interrelated problems and, in so doing, places in perspective the importance of processes other than that of attrition (such as C^3, intelligence, logistics, movement, etc.). It also should afford an opportunity to derive analytic expressions for the conflict that would permit the identification of key variables in determining outcomes, and, perhaps, piecemeal validation of the modeling process by comparison with empirical constructs employing historical data, such as the QJM.

Issues of an organizational nature or those that pertain to the management of model development and employment in the DoD surfaced frequently in the Leesburg workshop. Most significant of these were the following:

- The persistence of "advocacy" as a motivating factor (whether deliberate or suspected) in defense analysis activities that undermines the remaining vestige of credibility in open-loop modeling. The motivation is attributable to a strong competitive spirit within the bureaucracy for exaggerated shares of the defense budget.

- The inadequacy of model documentation in presenting clearly the underlying assumptions made in model design and the development of algorithms, a particularly important shortcoming when a model is considered for application to problems beyond that for which it was initially developed. For large models, there has been a general failure to achieve "transferability" from model developer to other activities, despite the existence of a formal set of documentation specifications and procedures.
- The need for a nesting place within the OSD to assure stewardship responsibilities for the development of gaming models of large-scale conflict and their data bases; their application to high-level problems of a policy nature that transcend domains of the individual services and the proper and appropriate dissemination of technical information on the inner workings of models in use. Guidance in research activities pertaining to combat models and in uniform scenarios development more properly reflecting U.S. global commitments should also be a function of this OSD activity.

Issues that more directly relate to the model user community were identified as the perplexing trade-offs in model credibility and understanding among such concepts as "transparency," "playability," and "realism," terms that repeatedly crept into the workshop discussions at Leesburg. Also noted were the large investments in time and money involved in the development, operation, and maintenance of combat models and data bases. It is in the areas of model operation and maintenance that shortcomings in model documentation, noted above, impact directly on the user community. Additionally, it is suggested that analysis staffs of U.S. and allied commands, comprising the bulk of the model user community, could profit significantly from periodic exchanges of planning study methodologies and modeling techniques, with these monitored and coordinated by the "focal point" OSD activity proposed above.

To examine modeling and methodological issues, two additional decomposition schemes were devised in this volume to assist in discussing the myriad of technical problems identified by the workshop. One scheme (Figure 7) defines the relationship between armed conflict in the real world and the analysis of such conflict. It concentrates on gaming model abstractions of conflict as a subset of conflict analysis. It then proceeds to break the gaming models down into the numerous techniques of analysis that pertain to model structural design. The second scheme (Figure 8) charts the relationships among all major military operations and their outcomes in warfare at the theater-level and is related logically to the decomposition scheme of Figure S-3. While these methods of decomposing gaming afford a structured way of presenting the various problem areas associated with the activity, no effort is made in this volume to indicate preferences in analysis technique or to offer solutions to combat modeling problems. Rather, one looks upon the universe of conflict model abstraction as one that is totally isolated from the real world in the absence of that coupling we have termed the missing link. This being the case, we have no yardstick for evaluating methodological alternatives.

With respect to model structures, the pros and cons of the following are addressed in this volume:

- Analytic models vs simulations vs hybrid analytic/simulation models
- Hierarchical vs global structures
- Deterministic vs stochastic modeling
- Fixed strategy/tactics vs variable strategies/tactics.

In considering variable strategies and tactics, the following techniques are discussed:

- Contingency rules (table look-up)
- Game theory (analytic and computational)

- Man-machine interactive or player-assisted gaming.

With respect to combat modeling at theater level, the major problem areas addressed are:

- Conventional theater warfare and the transition to unconventional warfare (tactical nuclear and chemical).
- Treatment of strategic and tactical doctrine in unconventional warfare.
- Ground, air, sea, and amphibious operations, with the emphasis given to the former two in modeling at the expense of any meaningful treatment of the latter two.
- Treatment of C^3I in the conduct of the ground/air war.
- Treatment of reconnaissance, surveillance, and electronic warfare as components of the intelligence and target acquisition functions.
- Treatment of movement and maneuver on the battlefield.
- Handling of force break points and engagement termination.
- Treatment of force reconstitution and reinforcement.
- Representation of mobilization bases and resources.
- Representation of inter- and intra-theater lines of communication and the interdiction of these LOCs by the adversary(ies).
- Effects of enemy logistical interdiction on the effectiveness of combat forces.

Issues concerning data bases in support of combat models were generally conceded at the workshop to be the most critical in the world of model abstractions as we know it today. Despite countless shortcomings, model development is considered to be far ahead of supporting data development. In no small measure is the disparity attributable to the frequent absence of real concern on the part of the model builder about what data are available (or can ever be obtained) as he proceeds with the task of model design.

It is noted that data, like the models themselves, is hierarchical in nature. Furthermore, depending in degree on the hierarchical level under consideration, data and models become interfused.*

The concepts of "low-level" and "high-level" data are introduced and the contrasts between them are discussed. Low-level data are, in the limit, factual and fundamental, whereas high-level data, reflecting broader characteristics or broader measures of performance or behavior, usually build on the former through the use of models or computational routines. Furthermore, low-level data tend to be immutable, whereas high-level data must be tailored to fit a particular model. Thus, we find that the same basic information, constituting a sample of high-level data, must be expressed in several different ways to conform to the different models in which the data might be used. In general, this tailoring of high-level data is best performed by the model developer. Unfortunately, this is seldom done because of a peculiar partitioning of activity in the modeling community and the fact that model builders and data gatherers tend to be a breed apart.

More specifically, two DoD data base efforts are addressed in this volume: the DoD Force Planning Data Base (DFPDB) and the Weapons Characteristics and Performance Data Base (WCPDB). The former contains force characteristics data (personnel strength, equipment, ammunition, etc.) and the latter, as the name implies, is concerned with weapons data. Both are developed under the cognizance of the Command and Control Technical Center (CCTC). In developing these data bases, two major problems are evident. One concerns the designing and structuring of the data base and the other is associated with the actual

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*In the sense that at higher levels, the modeler can interchangeably model directly with data (if it is available) or can employ explicit process modeling techniques to develop the same information gathering of data. Of the two data bases, development of the WCPDB is far and away the most difficult in that the derivation of high-level from low-level data must be linked to an array of environmental factors and target types as well as to the forces with which they are associated in the DFPDB. Furthermore, there is a reluctance on the part of the individual services to release "hard" weapon systems data for fear that to do so might be incriminating in the unending struggle over budgets. One finds, instead, a proliferation of data bases among service activities which do not appear to be coordinated with the DoD data base in the CCTC.

The validation or verification of high-level data is very much the same problem as it is for models. Additionally, there are problems with updating data as weapons and force compositions change with time as well as with the maintenance of data base security, a most important factor when one considers the information content present in the kinds of data bases being discussed.

A case supporting the requirement for further research in the modeling of large-scale conflict has been painstakingly developed throughout the presentation of material in this volume. What emerges most clearly as one tracks through scores of different problems associated with such modeling or gaming is the fact that virtually all of them are related in one way or another to the absence of a verifiable connection between reality and the model abstractions. It is this glaring and most serious deficiency that renders quite meaningless the addressing of any lesser issue. As a consequence, the discussion of a requirement for research is focused on model verification and combat theory development, recalling the hypothesis that both are essentially one and the same.

It is suggested that the research in combat theory should proceed along the following lines:

- That it be concerned with the identification of the controlling factors in combat and the conditions under which such factors prevail. This would appear to involve some systematic form of *measurement*, compelling the use of quantitative techniques; hence, an expression of the theory in mathematical terms.
- That it be broadly interdisciplinary with emphasis on military history and theory, the behavioral sciences, and the physics and engineering of military systems.
- That it be concerned (initially) with ground combat as the oldest and most traditional of all forms of warfare and one that depends most strongly on characteristics of human behavior. Any theory resulting from this approach should be applicable to other forms of warfare.

It is clear that the undertaking is one of high risk because of the conceptual difficulties that the problem presents. However, while conceding the enormity of the problem, it does not appear that its tractability to solution has ever been afforded a careful evaluation. This should be done in view of the importance of the issue to the combat analysis community-at-large.

The feasible approaches to research in combat theory involve the following classes of endeavor:

- Historical and military theory research, historical data development and analysis
- Analytical experimentation
- Behavioral experimentation
- Combat (phenomenological) experimentation.

It is worth noting that analytical experimentation is chiefly concerned with small, simple models that are used to explore relationships among variables and to ascertain those variables that are significant drivers of combat outcomes. Behavioral experimentation is focused on human decision-making behavior under combat conditions and, as such, is involved with the techniques of manual, computer-assisted manual, and player-assisted gaming. The purpose of the experimentation is to capture, through the observation of human players in a gaming environment, the fundamental characteristics of player behavior either by algorithm or by contingency rules. Combat experimentation pertains to full-fledged experimentation at any combat level on instrumented ranges and, as such, embraces both the systems and human behavioral aspects of the combat phenomenon. However, these activities are very complex and costly and recourse to them, for other than the data and information they may already provide, is unlikely.

An overall structure for the research activities leading to the development of a combat theory is presented in this volume (Figure 9). Qualitative combat hypotheses are developed from a synthesis of combat experiments, military history, and theory, and then these are subjected to treatment by quantitative methods to produce any number of quantitative hypotheses. For purposes of verification, these hypotheses, in turn, are carefully evaluated against any or all information that can be extracted from the original experimental and historical sources and from military theory. Once reasonable closure is achieved in what will be an iterative process, the hypotheses attain the more exalted status of combat laws. A body of such laws, properly related one to another in the structure of a combat model, constitutes, in effect, an expression of a combat theory.

To shed more light on the nature of the quantitative methods that might be employed in the structure of research activities outlined above, the paper briefly examines four examples of differing methodologies, each of which constitutes a different approach to the problem.

The first example is concerned with extensive analysis of select historical data in a search for persisting relationships between combat variables and mission outcomes. These can be expressed empirically or in the form of simple models. The second example is the decomposition of combat models in accordance with Figure S-3 and the scheme described in the earlier discussion of the "missing link." The third example derives from the second in relation to the basic structure of the methodology. However, it builds on the concept of individual discrete combat units as microcosms of combat (Figure 10) with simple but reasonable rules defining objectives and unit behavior toward each other and the enemy. One would start with engagements of small numbers of such units, testing sensitivity to varying parameter values, and work up to larger engagements, changing the command and control structure accordingly. Simulation techniques would be employed. The fourth example is chiefly concerned with command and control. Artificial intelligence (AI) techniques are employed in which man-machine interactive games are conducted and observations are made of player behavior. Since computer algorithms are used to generate the outcomes of human decision making in the game, "good" decisions can be captured in sets of contingency rules that may have broader applications to other models and to theory development.

3. The Workshop Focus on Gaming Models; Their Genesis and Evolution

3.1 Concern with Computer Gaming

Theater-Level analytical/computer gaming as a preferred methodological aid in force planning and therefore as the topic to be explored in the workshop is discussed in Volume I, Proceedings.[1] As we anticipated and as it was borne out in the workshop, there are no clean lines to demark the general, relative utility of analytical/simulation gaming at the theater-level and gaming at lower hierarchical levels of conflict or, for that matter, among pure computer games, interactive man-machine games, and manual games. However, the emphasis for force planning application is, and has been, clearly on computer gaming at the theater level with other categories of technique and scope[2] entering into the process in support of the realism, credibility, transparency and/or the playability of such gaming. This emphasis is graphically depicted in Figure 1.

More than anything else, the evolution of emphasis on computer gaming is perhaps more attributable to the convenience and accessibility of this form of gaming over other forms as well as to the control over and the basic understanding of the conflict process and its outcome afforded by a model (complex though it may be). Without the development of modern high-speed computer technology, however, this emphasis on simulation could not have materialized. Furthermore, I believe a strong case can be made for tying the origins of combat modeling and computer gaming back to the somewhat incongruous contribution of F. W. Lanchester, who in 1914 published his now-famous equations of warfare in a paper[3] that is conceded to be one of the first formally recorded pieces of military operations research.

3.2 Evolution of the Theater Model

It is appropriate at this point to review the evolution of campaign and theater models to provide some perspective for the discussions of models and modeling techniques that appear in the Proceedings.[1] In short, before we attempt to ascertain where we are going, we might do well to establish where we have been.

As one surveys the entire field of ground/air combat modeling and traces its development, it becomes readily apparent that attrition (casualties inflicted by either side on the other) is regarded as the functional ne plus ultra for the engaged forces.* For in the world of modeling, it is through the attrition process, expressed either implicitly or explicitly, that force ratios are caused to change and it is the prevailing force ratios that in many models drive the movement of the FEBA, thus controlling the gain or loss of territory.

With the importance of attrition thus established (for better or worse) it is interesting to note that there are three fundamental routes along which the modeling of combat has progressed (Figure 2) noting further that all three eventually coalesce to a degree in division and theater-level modeling.

The first route stems from the early work of Lanchester, who simply and unpretentiously, in "engineering" fashion, expressed the casualty rates of combatant forces in "modern warfare"† as a constant casualty rate on either side per enemy soldier multiplied by the total number of enemy soldiers engaged. These relationships for sides X and Y are as follows:

*The emphasis from the start should probably have more properly been on attrition and movement, for these factors do, in some sense, trade off. The focus of interest on attrition apparently stems from a preoccupation with "wars of attrition" such as occurred during virtually all of World War I and most of World War II. In conflicts of this type, the forces of opposing sides are in contact and engaged and there is generally resistance to the movement of forces in either direction. Therefore, a forward edge of battle (FEBA) can be drawn or "bomb lines" defined delineating the line or area of contact between opposing forces. In a war of movement or in fluid operations, such as in the 1940 blitzkrieg tactics employed by the Germans in World War II, decidedly different conditions prevail. Territory is rapidly invaded, generally with little or no enemy resistance and, as a consequence, casualties are invariably lighter. To quote Ardant DuPicq[4] "The less mobile the troops, the deadlier are battles."

†Involving "aimed fire" in which each combatant on one side aims and fires on a live combatant on the other, and all combatants on either side are within firing range of each other. The precise assumptions inherent in Lanchester's derivation of his equations are listed in Reference 5.

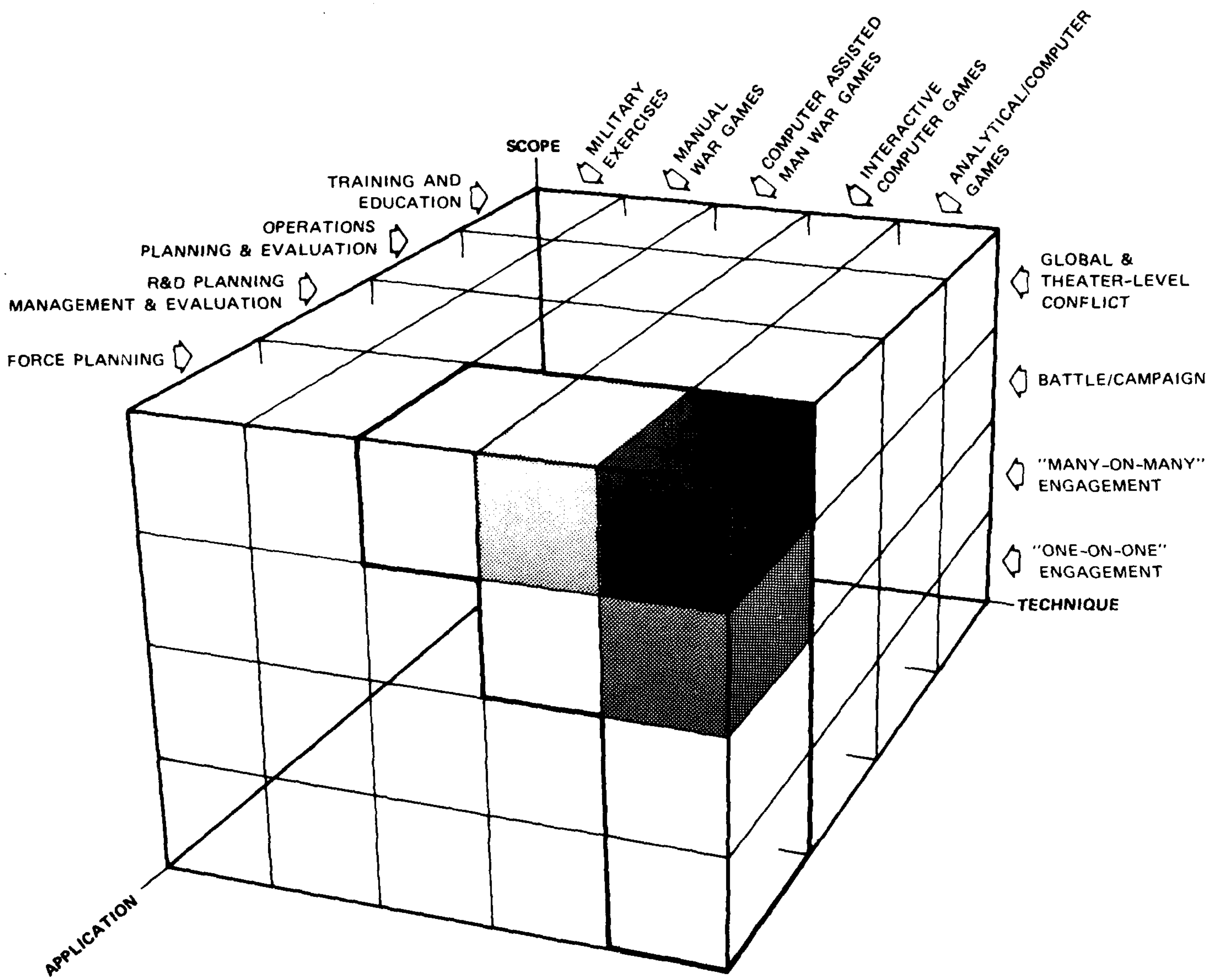

FIGURE 1 GAMING CLASSIFICATION MATRIX AND AREAS OF WORKSHOP EMPHASIS

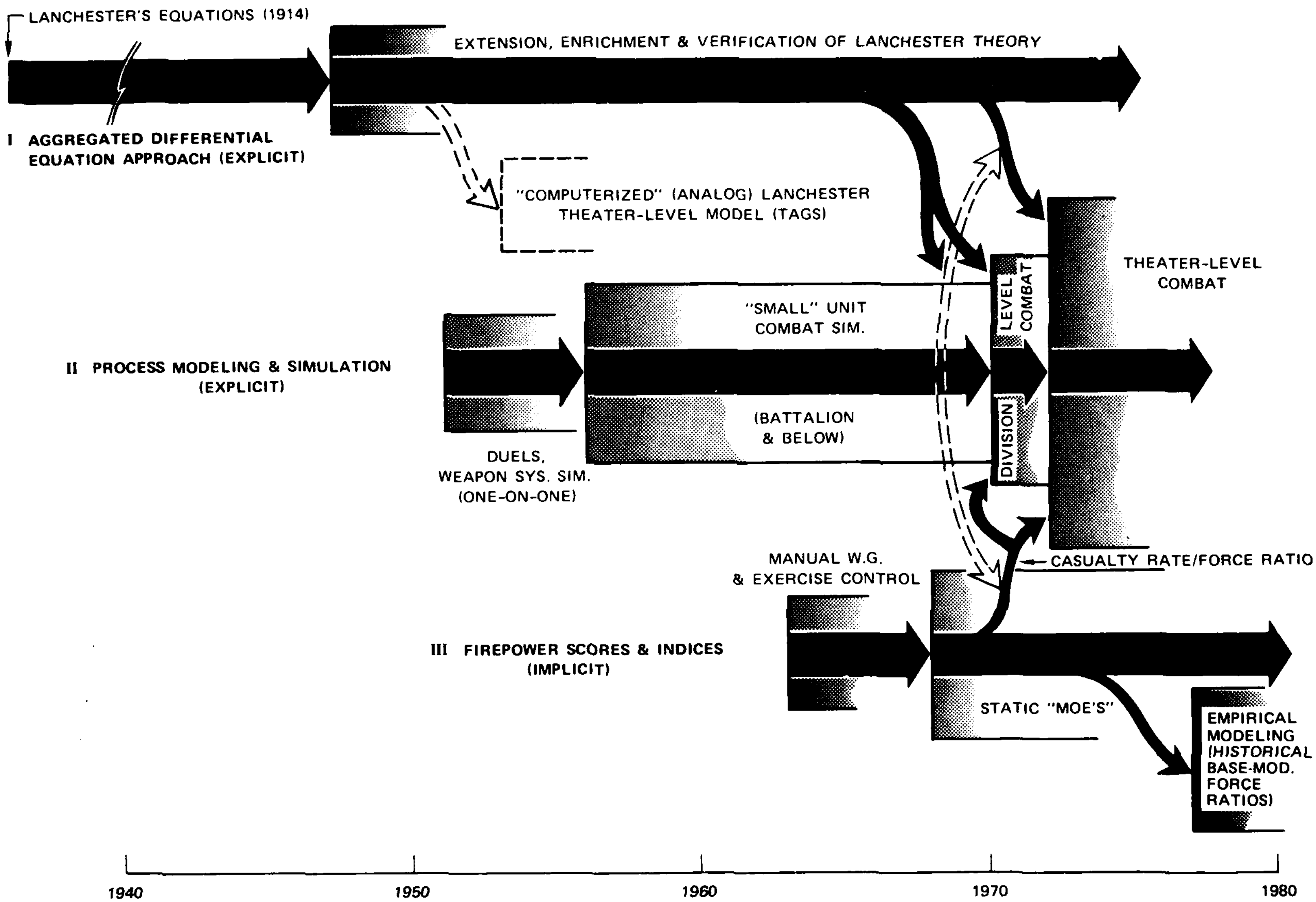

FIGURE 2 BASIC APPROACHES TO ATTRITION MODELING

$$\dot{x} = -ay$$
$$\dot{y} = -bx \qquad [3.1]$$

where

$\dot{x}, \dot{y}$ = casualty rates on sides X and Y

x, y = number of combatants on sides X and Y

a, b = constants = $\frac{-\dot{x}}{y}$, $\frac{-\dot{y}}{x}$ = Lanchester attrition-rate coefficients for sides Y and X (for aimed fire)

Since attrition to the X and Y forces is occurring simultaneously, we are dealing with two differential equations that must be solved simultaneously to obtain x and y as a function of time. The solution involves a bit of nontrivial mathematics. However, Lanchester further suggested that for two forces to be of equal fighting strength the fractional casualties per unit time must be equal for both sides. Thus:

$$\frac{\dot{x}}{x} = \frac{\dot{y}}{y} \qquad [3.2]$$

or, by substitution of [3.1],

$$ay^2 = bx^2 \qquad [3.3]$$

It is from [3.2] that the term "Lanchester Square Law" is derived to describe the relationships expressed in [3.1]. It is an equality based on the square of the forces on both sides at any point in time. In a similar manner, Lanchester postulates that for area fire:*

$$\dot{x} = a'xy$$
$$\dot{y} = b'xy \qquad [3.4]$$

where $\dot{x}$, $\dot{y}$, x, and y are the same as for [3.1] and where a', b' = constants = $\frac{-\dot{x}}{xy}$, $\frac{-\dot{y}}{xy}$ = Lanchester attrition-rate coefficients for Y and X (for area fire).

Again, for equal strength [3.2] applies and:

$$a'y = b'x \qquad [3.5]$$

It is from [3.5] that the term "Lanchester Linear Law" is derived to describe the relationships expressed in [3.4]. In [3.5] the equality is linear with respect to the forces on both sides.

From these humble beginnings, there emerged after a lapse of some 30 years, a discernable kindling of interest in Lanchester's original work among certain researchers in the then newly established operations research community. This interest took the shape of generally accepting the form of Lanchester's equations as proper models for the attrition of engaged forces (as constrained, of course, by certain relaxations of the original assumptions governing their derivation). Attention was turned and focused on the Lanchester attrition coefficients. These were partitioned into operation and weapon system performance elements, thereby enriching the expressions for attrition coefficients and permitting their extension in

Fire delivered over a fixed area with time, rather than fire aimed against individual targets a more explicit manner to a wider range of combat forces and their attendant weaponry. In addition, the original form of Lanchester's equations was modified to incorporate the use of supporting fires (supporting the principal combatants) that are not subject to attrition; to introduce considerations and treatment of engagement termination (such as combat unit "breakpoints"), and to permit generalization of the Lanchester formulation by introducing an exponent parameter that, depending on the parameter value assigned, would yield the square law, the linear law, the logarithmic law, or for that matter, any number of "laws" falling between these three. Furthermore, the concept of time-dependent, variable, attrition rate coefficients was introduced where the coefficient depends on the rate of closure between the firing combatants and their targets, thus bringing battle dynamics into the attrition process. Finally, modifications to the Lanchester formulation were derived to permit the accommodation of heterogeneous force mixes that reflect the "combined arms" nature of warfare.

Most of this work was done between 1959 and 1971 (by investigators such as R. L. Helmbold, H. K. Weiss, H. Brackney, R. H. Peterson, S. Bonder, R. L. Farrell, S. I. Deitchman, and others). It is also to be noted in Figure 2 that at a relatively early date (circa 1953) one of the first examples of an air/ground theater-level model was developed (TAGS[7]), directly based on Lanchester's equations for the calculation of ground and air attrition. These equations were programmed on the Reeves Electronic Analog Computer (REAC), which reflects the model's vintage. An excellent overview of these developments in Lanchester attrition is presented by J. G. Taylor in Reference 8 (with appropriate references) relating them to broader aspects of combat modeling and gaming.

Proceeding somewhat in parallel with these efforts to enrich and expand Lanchester theory were a number of attempts to verify his equations against historical combat data (see, for example, References 9-15). In the main, these validation efforts have been judged to be inconclusive; this, despite the generally encouraging results obtained by Engel[9] in his analysis of the Battle of Iwo Jima in World War II. Of significance is the fact that some effort was made (from the mid-1950s to the mid-1960s) to fit Lanchester theory in its several modified forms to battles ranging over some 200-300 years of recorded history, albeit with decidedly mixed results.

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*The logarithmic law attributed to R. H. Peterson[6] is given by

$$\dot{x} = -a''x$$

$$\dot{y} = -b''y$$

using the same notation as for (3.1) and (3.3). For equal fighting strength (see (3.2)), we find a'' = b''. The "logarithmic law" descriptor derives from the state equation that is obtained by eliminating the time variable in (3.6) in the following manner:

$$\frac{\dot{x}}{\dot{y}} = \frac{dx}{dy} = \frac{a''y}{b''x}$$

$$b''x\,dx = a''y\,dy$$

from which is obtained:

$$b''\ln\left(\frac{x_o}{x}\right) = a''\ln\left(\frac{y_o}{y}\right), \text{ where } \left.\begin{matrix} x = x_o \\ y = y_o \end{matrix}\right\} \text{at } t = o$$

The corresponding state equations for the square law (3.1) and the linear law (3.4) respectively are:

$$b(x_o^2 - x^2) = a(y_o^2 - y^2)$$

and

$$b'(x_o - x) = a'(y_o - y)$$

with x_o and y_o as defined above.

The attempts to enlarge upon Lanchester's original work, described above, added to the burden of solving the resulting simultaneous differential equations for purposes of their application. Particularly in those instances involving the modeling of heterogeneous forces, the solution of the equations by analytical methods becomes virtually impossible and recourse must be made to numerical integration and the computer. Once on the computer, the transition into combat simulation would appear as a rather easy and natural step to take, offering in the bargain the flexibility to exploit other computer "freedoms" such as battle dynamics, Monte Carlo, high resolution modeling, etc. Whatever the reasons, this is essentially what happened as shown by the curved arrows in Figure 2 leading from the mainstream Lanchester/differential equation efforts to the area of simulation.

The second approach (chronologically) to attrition modeling (Figure 2) is that of having it embedded in modeling of the broader combat process of "shoot, move and communicate." This type of modeling had its beginnings in "one-on-one" and "one-on-several" weapon system duels, employing either analytical or simulation techniques. More or less paralleling and keeping pace with the development of the high-speed computer was the expansion of the Monte Carlo duels into models of more complex ground combat operations involving an ever-increasing number of units up to organizational levels of about battalion size. Generally, the models, less detailed at first, moved in the direction of ever greater "realism" and higher resolution. CARMONETTE represents a good example of this type of model development, evolving over a period of some 23 years and now in its sixth revision. Other major examples of models of this type are DYNTACS, IUA (Individual Unit Action), and Bonder/IUA.*

The treatment of attrition is broadly similar in CARMONETTE, DYNTACS, and IUA, (differing, of course, in weapons considered, degree of detail, and manner of execution). That is, firer-target pairings are treated more or less discretely and the engagements are modeled stochastically round by round with *explicit* consideration of the functional steps that start with target acquisition and end with the delivery of munitions and the assessment of weapons effects. Along with this enrichment of attrition modeling afforded by Monte Carlo simulation came the opportunity to model many other important combat functions and variables such as weapons and sensor mixes, movement, terrain, communications, doctrine, intelligence, etc. All of the above models treat these factors to varying degrees.

Bonder/IUA is a deterministic derivative of IUA, replacing the stochastic modeling of attrition in IUA with generalized differential equations that are extensions of Lanchester's equations[16]. Measurable weapon system parameters, rather than historical data, are used in computing the attrition coefficients for the modified Lanchester equations and the methodology essentially derives from earlier work performed by Bonder and Farrell in enriching the Lanchester formulation, as previously mentioned. It is with the Bonder/IUA model that we come across one of the first significant cross-overs from Lanchester methodology research into the mainstream of combat simulation development.

All of the models concerned with the combat activities of battalion-sized units or below are generally considered to be the "high-resolution" models in a hierarchy of models. This hierarchy, in working from bottom to top, can be characterized as a series of models that are capable of treating in ever-diminishing degree of detail and resolution, military forces of ever-increasing size.† One can broadly ascribe this fundamental trade-off between the size of forces that are modeled (and hence the scale of conflict) and the degree of detail to which they are modeled to an overall constraint imposed by core size in the modern, high-speed computer

*Descriptions of CARMONETTE, DYNTACS, IUA, Bonder/IUA, and BLDM (Battalion Level Differential Model, a Bonder/IUA derivative) may be found in References 17, 18.

†The generality of this observation is contradicted to a degree by a series of models developed by Vector Research, Inc. (VRI)

and, to a lesser extent, perhaps, by central processing unit (CPU) availability. While computer characteristics and capabilities continue to improve with advancing technology, they can in no way keep pace with the demands that would be placed on the computer were one to model theater conflict to the same degree of detail as are modeled platoon, company, or battalion engagements. Methods of aggregating the effects of combat activities must be sought as one proceeds up the hierarchical ladder. The Lanchester-type of attrition methodology is, of course, such a form of aggregation.

At this juncture, other observations are pertinent to developments in the analysis of land combat and, for this purpose, reference is made to Figure 3. This figure illustrates the breakdown of land combat forces into a series of man/machine systems, each with its inherent performance characteristics and capabilities that are measurable in an engineering, laboratory, or proving ground sense. The forces are supported by a logistics and supply system that provides them with manpower, food, fuel, ammunition, replacement equipment, repair facilities and spares. Furthermore, they are influenced by a set of variables of human behavior as shown in the figure. The force configuration is dictated by battle objectives and, based on these objectives, the capabilities of the various systems associated with a force are "controlled" and melded to yield an appropriate vector or total combat power to be directed against the enemy.

This command/control function should recognize and attempt to capitalize on the synergistic effects of several or all of the ground warfare systems operating in a mutually supportive role against an enemy. In effect, this will define the employment tactics for the systems within the force.

The concept of an effectiveness measure for each of the systems in the friendly force emerges from the interaction of these systems with the enemy forces, the battlefield environment, and with one another. These systems effectiveness measures functionally combine in some manner to produce an overall measure of effectiveness for the friendly force(s). This measure encompasses the effects of weapon system combat performance relative to that of specific enemy units in a specific geographical and climatological environment, the behavioral characteristics of the human beings involved in the conflict, the differences in command objectives and in the nature and degree of control for both sides, and the ability of the logistics support system (which may well be subject to enemy attrition) to meet force demands. In effect, force effectiveness is an operator on the states of both the enemy and friendly forces, influencing whatever changes in state that may occur. From these changes in state one can determine whether the friendly force advances, retreats, or is in a stand-off condition with respect to the enemy force.

To complete this cursory description of a very complex process, Figure 3 contains an "Intelligence" block which is where some "noise" is introduced into the system. This noise relates to the degree of difference between the perception and the realities of combat activities, outcomes, and related factors. This difference exists because of certain imperfections and delays in the gathering and passing of information under battle conditions and, to a certain extent, these imperfections can be modeled. The perceptions of what is occurring are fed back in the command structure to perhaps change objectives and hence the level, composition, or employment (control) of forces (strategic feedback). On the other hand, at a more local level on the battlefield, and with characteristically shorter time delays, these perceptions can influence changes in tactics (control) with the intent to alter the course of battle in a way favorable to the friendly forces (tactical feedback). In association with the feedback loops and control block of Figure 3, there is implied an appropriate netting of communications which is also subject fo failure, delays, and errors.

From the foregoing, it is apparent that there exists an analytical flow diagram for the enemy forces that is identical to the one shown in Figure 3 for the friendly forces. This would

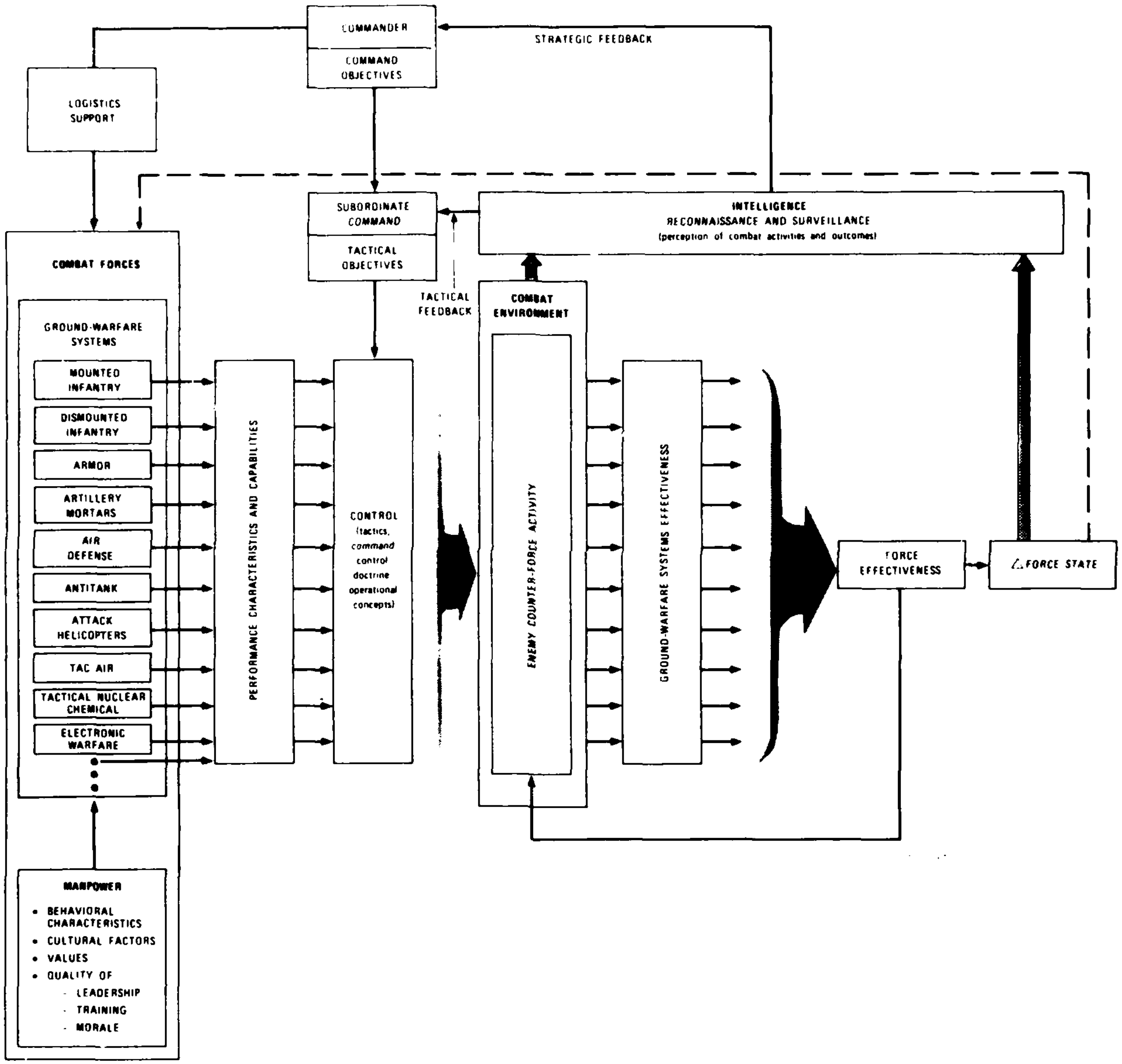

FIGURE 3 ANALYTICAL ELEMENTS OF GROUND COMBAT

branch out from the block labeled "Enemy Counter-Force Activity" in much the same way that Figure 3 is oriented about the friendly "forces" block but has been omitted for reasons of clarity. The entire process is dynamic, and the existence of two such dynamic, symmetrical flow paths of information and activity for friend and foe graphically portrays the complex, two-sided nature of armed conflict.

It is appropriate to discuss the developments in combat modeling that have thus far been described in relation to the analytical elements that are flow-charted in Figure 3. The differential equation or Lanchester approach to attrition modeling discussed earlier and shown in Figure 2 is, as the words suggest, only concerned with the force-counterforce interaction process of Figure 3 when friendly and enemy forces are in contact. If analytical, closed form solutions are sought, it is capable of treating homogeneous forces and, to a very limited degree, mixed forces (barring the use of weighting factors for the aggregation of weapon systems mixes in the attrition coefficients). Furthermore, it can accommodate, in the computation of attrition coefficients, some of the first order operational and weapon system performance parameters. Effectiveness is measured in terms of casualties inflicted on both sides, and the attrition process, which in reality is a discrete, stochastic one, is treated in the Lanchester approach as one that is continuous and deterministic. As such, this approach represents an aggregation of the attrition process. Finally, the approach permits treatment of movement of the contact zone between opposing forces (FEBA) based on the time rate of change of force ratios for both sides and other battle-related factors.

Turning to the simulation approach (Figure 2), we find that the use of the computer generally affords some consideration of all of the elements shown in Figure 3. In simulations of combat at the level of battalion and below, discussed above, limited numbers of a particular weapon system or small mixes of weapons can be modeled on a detailed, "round-by-round" basis to determine their effectiveness in engaging enemy systems. It is, in fact, for the purposes of evaluating weapon systems in simulated "realistic" combat environments that *small unit combat models are most frequently* used. While systems characteristics and performance and the environment (terrain) are treated in relatively great detail in such models, consideration of other factors shown in Figure 3, such as objectives, command, control, intelligence, logistics, etc., are generally scaled down to a degree commensurate with the size and duration of company or battalion operations, or are not treated at all.

One might note that the simulation of dismounted infantry, a classical force element in land combat, presents a troublesome problem at the "high-resolution" level of modeling. While this in itself is not surprising, it supports a broader observation that is made with respect to systems analysis and combat modeling in general. If one recognizes the fact that combat involves a life and death struggle between arrays of various man/machine systems (Reference 1, Figure 1) it follows that the effectiveness of these systems in performing their function depends on the characteristics of machines or equipment, which are generally measurable and the characteristics of human behavior under stress, which generally are not. The more automated the equipment, or conversely, the less the human has to do with its operation or control in a fundamental way, the more amenable is the system and its environment to credible, acceptable modeling. At the lower, or high-resolution, levels of the modeling hierarchy, the impact of human behavior is more pronounced in the areas of weapons, tactics, and maneuver, while in modeling the higher levels of conflict, it is the human element in command-control decision making and resource allocation that is of greater importance. The dismounted combat infantryman, then, cannot be (and is not) explicitly represented in detailed fashion in existing high-resolution models since, in this instance, weapon performance is undoubtedly subordinate to human behavior in the effectiveness equation. CARMONETTE, for example, resolves infantry down to squad or section size and advances the notion of groups of "doctrinal" soldiers with identical behavior patterns in executing orders.

Other models of up to battalion level activity stress armor/antiarmor engagements resolved down to individual vehicles and weapons and are generally not concerned with dismounted infantry.

In the hierarchy of combat simulations depicted in Figure 2, we come next to division and corps-level models. These models treat forces and engagements that are large enough in size and scope to include in a significant (but not always adequate) way all of the elements shown in Figure 3. In short, they are concerned with the smallest force size that, with proper combat support and command and control, is capable of sustained operations. They are of great importance to the Department of the Army in planning and evaluation, particularly in force structures, weapons mixes, and tactics.

It is beyond the intent of this overview to discuss in detail the characteristics of the several division/corps models that have been developed, or that evolved and were subsequently superceded by other models of similar scope. Rather, it is the trend in modeling attrition and representations of the key elements portrayed in Figure 3 that are of concern here.

Simulations of combat at this level appear to have evolved from a process of "computerizing" the manual war game. The increased requirement to represent the command and tactical decision making structure when going from battalion to division level, coupled with added difficulties of aggregation and data availability at division level, made it necessary (through at least the earlier model developments) to retain human decision makers as essential parts of the game. Thus, division-level models in their evolution went from the manual war game to computer-assisted war games to player-assisted simulation (or interactive computer games) with ever-diminishing human involvement (see Reference 1, Slides 8-9) but with a presentation, nevertheless, of the two-sided nature of combat. With this downward trend in human participation in the game-playing came an associated trend toward the more detailed modeling of combat force interactions under engagement. Examples of the computer-assisted war game at the division/corps level[17] are ADVICE, CBM (Corps Battle Model), and DBM (Division Battle Model). One should note in passing that DBM is a higher resolution derivative of CBM that permits player interactions with the game at any time compared with fixed game time intervals for human interaction in the CBM. Attrition of maneuver units in this class of models is generally aggregated through the use of firepower scores (discussed below) except in DBM. In the latter, the COMANEX model (Combat Analysis Extended) is used as a satellite model to extrapolate high-resolution casualty results obtained with CARMONETTE for a specified force mix, into casualties for force mixes of the same or similar weapons types but of differing force sizes, for use in DBM.[19] COMANEX actually fits the attrition results of replications with CARMONETTE into a Lanchester formulation, which is then used as the basis for determining casualties in DBM. Here, we see evidence of the formal use of a model hierarchy where the main combat simulations are linked by special processor satellite models like COMANEX. This particular hierarchy, in fact, extends up to the theater level, linking with the ATLAS model.

Turning to player-assisted simulations, we find a trend to incorporate much of the detailed decision making (usually that which occurs at the lower echelons) into the simulations in the form of rules that are either fixed or selected by the model on a contigency basis. This, in turn, is accompanied by a trend to use casualty assessment techniques for maneuver units of higher resolution than firepower scores. In fact, the attrition methodology used can generally be described as one that ties back to the primary characteristics of weapons and sensors (target acquisition capability, rate of fire, lethality, etc.) but combines them for assessement purposes in a more aggregated fashion than is normally done in modeling combat at the battalion level. Examples of these simulations[17] are LEGION and DIVTAG, both of which, because of complexity and certain shortcomings, have given way to other models for application to studies and analyses.

The next step in the evolution of division/corps models moves toward ever more simulation of decision processes through programming contingency "operational orders" into the model, with a corresponding cutback in the degree of human participation in the game-play. These are categorized as Minimum Player Assisted Simulations in Slides 8-9[1] and DIVWAG (Division War Game model[18, 20]) and DIVLEV (Division Level Wargame model [18, 21]) are examples of such games. Both models treat weapon systems effects or attrition as a discrete deterministic process that uses aggregated weapons and equipment performance data (much the same as with LEGION and DIVTAG), thus affording discrimination between weapon types within a class. DIVLEV places heavier emphasis than DIVWAG on modeling the performance and effectiveness of military equipment in the context of a broad engagement, treating, for example, such factors as system reliability and maintainability in addition to other systems characteristics. Concentration on the modeling of equipment in DIVLEV appears to occur at the expense of any consideration within the models of fixed-wing air support and of some aggregation (relative to DIVWAG and other models) in the treatment of terrain and logistics factors.

Finally, we come to a class of models at the division/corps level that do not involve any human player participation. One such model is FOURCE[22], a derivative of both DIVWAG and DIVOPS, which stresses staff decision-making through the use of preprogrammed staff decision rules based on the modeling of intelligence information. Other examples are DIVOPS[23] and COROPS[24] models which arrive on the division/corps modeling scene through the back door, so to speak, of the theater-level model. DIVOPS is a derivative (with certain added improvements) of VECTOR 1, a theater model, and COROPS is actually an integral slice of VECTOR 2. Both models employ a differential equation approach to the modeling of attrition similar in principle to that described earlier for the Bonder IUA model in which operational variables and weapons characteristics are incorporated into the attrition coefficients of Lanchester-like formulations.

As mentioned above, the division/corps level models are concerned with the lowest level of combat organization that contains all of the elements for sustained combat (Figure 3). There are interesting variations in the consideration given to the treatment of terrain and weather effects, the expenditure of consumables and resupply (logistics), air support, intelligence and command and control among the different division/corps level models. This ranges from no treatment at all of certain activities or effects within a model (as with dismounted infantry in most of the models, or fixed-wing air support in DIVLEV) to heavy emphasis on a particular aspect (such as command and control in FOURCE). Such variations in emphasis are attributable to special problem area interests that initially sparked the development of a particular model, or else the state of the art that prevailed at the time of model development that inhibited or precluded the representation of some of the more complex elements of combat.

Again, it is beyond the scope of this brief review of model evolution to describe all of the division level models in detail. However, there are discernible trends in the chronological development of these models. One such trend is the rather persistent progression toward the totally "automated" game or nonplayer-assisted simulation such as COROPS (see Reference 1, Slides 8-9); this, paradoxically enough, despite an increasing awareness and appreciation of the impact that command decision making and tactics and doctrine have on combat outcome. It is precisely these command and control functions that are generally considered to be best accommodated by human player involvement in a game. One can only attribute this trend to a desire (expressed or otherwise) to achieve greater reproducibility of outcome of the models, while in their application, turning to good account the fact that they are self-contained and do not call for player support or interaction (see Reference 1, and Figure 3). Also to be noted is the recognition of air-delivered supporting fire (close air support in modeling at the division level) and what appears to be increasing chronological emphasis that is placed on the treatment of air and anti-air missions involved in ground warfare. In the division/corps level models, we encounter a prelude to those at the next step up the hierarchical ladder: the theater-level model. In short, the division/corps level model basically contains all of the analytical elements of combat to be found in the theater model with the fundamental difference between these models being one of scale.

Note from Figure 2 that the model development progression from the lower to the higher levels of conflict scope, as is being discussed, occurs, with very few exceptions, as a rather clean chronological progression as well. However, before turning to simulation models at the theater level, it is appropriate to examine briefly the third approach to attrition modeling shown in Figure 2 — that which makes use of firepower scores and indices.

Much has been written about firepower scores and indices[8,17,25] and there are many variations of the concept. For this overview, a brief description will suffice. It can generally be stated that there are three fundamental approaches to the problem of developing an understanding of relationships among the many variables in combat. These are the historic approach (based on the study of historical combat records), the judgmental approach (based on field experience in combat and/or military exercises), and the experimental/analytical approach (based on the use of physical and/or formal models — from controlled field experiments to highly abstract models and simulations). The use of firepower indices in determining combat attrition can be characterized as a method that, in some way, involves all three of these approaches.

As shown in Figure 2, the origins of firepower scores can be traced to their use as an evaluation and control mechanism in the conduct of manual war games and map exercises. The concept of the *score* evolved from a necessity to place some value on each of the many different weapon types that might appear in a game. At the very least, while still providing some measure of utility, this value could be based on the *relative* potential contribution afforded by each type or class of weapon in inflicting casualties on opposing forces. In effect, these weapon value ratings were somewhat gross estimates of relative weapons effectiveness and initially, at least, the values assigned were determined by officers experienced in combat arms. Within a few short years (circa 1968) a new scores* concept emerged that derived from a base that can be described as more "scientifically" oriented. Weapons were essentially divided into two groups, antiarmor and antipersonnel, and within these two groups they were further subdivided as to whether they were area fire (explosive, fragmenting projectiles) or point fire (ball ammunition, solid projectiles, shaped charge projectiles, etc.) weapons. This 2x2 classification matrix is shown in Figure 4.

By way of summary, weapons described by element b of the matrix in Figure 4 were scored by the product of the projectile lethal areas and the number of projectiles fired per day (generally expressed as the "estimated daily expenditure of ammunition," defined by the Army for an average weapon of a particular type). For elements a and c of the matrix, the method generally used involved conditional single shot kill probabilities, given a hit (P_k/h), multiplied by a range factor and the estimated expenditure of ammunition. Element d appears to have presented difficulties in weapon scoring, particularly with respect to finding a common basis for comparing weapons of type d with type b. As solutions to this problem, the notion of "equivalent lethal areas" for ball ammunition was advanced along with an alternate scheme that made use of historical ratios of casualties due to small arms (point fire) and those due to mortar and artillery fire (area fire). It is only fair to state that the Army, in a review of its methodologies and techniques,[16] was less than enchanted with not only these approaches to deriving firepower scores or potentials but with the whole concept of scores

*Known as Firepower Score/Index of Combat Effectiveness (FPS/ICE).

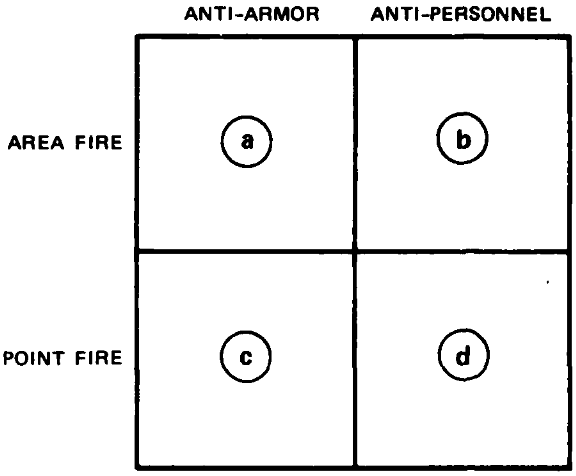

FIGURE 4 WEAPON CLASSIFICATION MATRIX FOR FIREPOWER SCORES/ POTENTIAL

and indices and the pervasive manner in which they wormed their way into division and theater-level models (as will be discussed below). Relevant to this overview, however, is the fact that the data used to obtain the necessary lethal area and kill probabilities for weapon scoring were derived for the most part from ballistics testing and research conducted by Army laboratories. In relatively rapid succession, there followed several minor modifications to the FPS/ICE concept that can be described as changes in form rather than substance. The WEI/WUV (Weapon Effectiveness Index/Weighted Unit Value), for example, is one of the more recent of these developments that adds subjective weighting factors, determined by a Delphi technique, to the weapons scoring concept discussed above.

We turn our attention next to firepower *indices*. These are always mentioned in conjunction with firepower scores and are generally used to reflect the firepower potential of a nonhomogenous combat force of roughly division size, or larger. Such a force is normally composed of infantry, armor, and artillery and is provided with air support. As such, the force has at its disposal a wide variety of weapon types, and to compute its firepower index one simply forms the products of firepower scores and the number of weapons in the force for each weapon type and then sums these products over all weapon types employed by the force. This simple mathematical operation does indeed produce some sort of indicator reflecting a force's capability or potential to inflict casualties on an enemy. However, even setting aside concerns one might have about the data used to generate the weapons scores (discussed in Reference 24), it is patently clear that the firepower index concept is totally devoid of operational authenticity in the context of actual engagement (i.e., weapons that can or cannot be brought to bear on the enemy as a function of time, targets presented by enemy forces, target acquisition capabilities of friendly forces, line-of-sight obstructions, ammunition supply constraints, and so forth). Then, one might ask, of what earthly use is this firepower index? Actually, it does impart more information about the combat capability of a force than, say, a strict number count of men in the force. It is an attempt to convey some idea of the force's weapon strength. As such, and when standing alone, the firepower index (in all of its several versions) is a *static* indicator that can be, and often is, used to compare the relative weapon strengths of friendly forces or friendly forces with enemy forces. The use of the word "effectiveness" with designation of at least one version of the firepower index (i.e., ICE, Index of Combat Effectiveness) is rather unfortunate. Interpreting ICE as a partial indicator of force effectiveness, in that it at least contains some of the important variables on which force effectiveness must depend, is reasonable if one appreciates the limited utility of this index. A full blown measure of force effectiveness (which must encompass considerations of the types of combat elements shown in Figure 3), it most assuredly is not.

As a simple concept that could be implemented with relative ease, the firepower index had a somewhat beguiling quality about it and was widely used in the late 1960s and early

1970s by a number of assessment and planning activities[1] as a stand-alone static indicator of relative force strengths (Figure 2). The compounding of mischief potentially attainable with the index concept and its varied interpretations came with a construct known as the "force ratio." The force ratio basically took the form of the manpower ratios times the firepower index ratios for the Blue and Red forces. Since it could be argued heuristically that certain local, elemental processes in a protracted conflict like casualty rates and rates of advance must, in some way, be related to prevailing force ratios, it was rather natural that an attempt be made to derive these functional relationships in an empirical manner. To do so, recourse was made to historical combat records from which were extracted the necessary data to compute force ratios, as defined above, and the corresponding casualty rate percentages. These data were "faired" to get the relationship between the two variables and information obtained in this manner was presented for several postures of attack and defense (i.e., attack of fortified positions, prepared positions, hasty defenses, etc., and defense in meeting engagements, hasty positions, etc.) These so-called Casualty Rate Firepower Ratio curves found their way into a number of division-level and theater-level combat models (Figure 2) as a rather direct and convenient way to treat by aggregation the total attrition brought about by heterogeneous forces as well as offering ways to disaggregate this attrition into losses by individual classes of weapon systems. However, even though these curves trace their origin back to historical data, the reduction of these data to generate the curves for use in at least one widely-used model (ATLAS) is open to serious question (Reference 1, DePuy, p. 17). Even discounting these difficulties, one tends to mistrust in a most fundamental way, the entire concept of using force ratios based on firepower indices, in the manner I have described. As a static indicator of force firepower potential, the index is a highly stylized, contrived entity. Ratios of these indices, when used iteratively in a complex, dynamic simulation of combat, even when embellished to account for posture, supply, etc., impart an air of desperation to the process as if a "solution" to the problem of heterogeneous force attrition *must* be found or forced by any manner of means.

Short of the aggregation technique afforded by the use of firepower indices and force ratios, there are two difficult (but hopefully more precise) alternatives for dealing with the problem of modeling the attrition for combat between heterogeneous forces at the division, corps, and theater levels. One, of course, involves the explicit simulation of every weapon-target engagement as is done at the company and battalion levels. This approach is precluded by the enormous amount of computation that would be required. The other, advanced by Bonder and Farrell for the Vector models[16], and alluded to earlier, decomposes the battle into classes of engagements on each side (i.e., infantry vs infantry, infantry vs tanks, tanks vs tanks, etc.), in which fractional allocations are made of the weaponry within a type of unit on one side against some or all types of units on the other side. Each class of engagement has associated reciprocal attrition-rate coefficients that are defined to include a variety of weapon performance and operational factors.* These are cast into a differential equation format similar to that used by Lanchester. While this approach is deterministic and aggregates attrition by class of engagement over time, it still requires a great deal of computation and a considerable data base for implementation. However, short of simulating each and every weapon-target pairing, the Vector approach is the most explicit method known at this time for modeling attrition in large-scale combat.

The brief discussion of firepower scores and indices and force ratios would be incomplete without mention of what could be described as an analytically imaginative approach to

*These are variable attrition-rate coefficients formed by the product of the allocation factor (fraction of a unit type engaging a similar or dissimilar type of enemy unit), an intelligence factor (fraction of a unit type actually engaging live targets) and an "inherent" weapon kill rate at which a single weapon kills live targets when so engaged. The kill rate, in turn, depends on engagement range and system characteristic times, such as time to acquire a target, time to fire, projectile times of flight and, in addition, on certain conditional hit and kill probabilities attrition; one that combines force ratio methodology with Lanchester methodology. This technique[26, 27] was developed by the Institute for Defense Analyses (IDA) for the IDAGAM series of theater models. It is based on the assumption for the ground war that the actual number of weapons lost in a battle, by weapon type, is proportional to the "potential" number of weapons lost, by weapon type. This "potential" loss number is derived from a computation using a Lanchester square law for heterogeneous forces with attrition coefficients based on firepower scores (hence, the "potential" descriptor). A second assumption is that the total number of personnel casualties in battle is basically equal to the actual number of weapons lost multiplied by their manning levels (number of personnel per weapon). Thus, it can be shown that the constant of proportionality, or scaling factor, between actual and "potential" weapons losses is equal to the ratio of total personnel casualties, determined in this approach from force ratio/casualty curves, to the loss of personnel associated with potential weapons losses (where the latter are derived from the Lanchester equations). This methodology mélange can, with variations, be used to compute the number of actual weapons losses either on a strict numerical basis or on the basis of the loss of ground weapon *value*. If, for example, one chooses the latter option, then the value of a particular Blue weapon is defined as the sum over all Red weapons types of products of the rate at which the Blue weapon kills each particular Red weapon type and the value of the Red weapon type. When working with weapons values, the technique that is used is known as the Antipotential Potential (APP) Method and at the heart of this method is the solution of the eigenvalue problem.

This is a very brief description of an analytical approach to attrition modeling that is quite complex, while at the same time demonstrating a high degree of mathematical ingenuity. There are, of course, many other computational options open to a user of IDAGAM, the details of which are beyond the scope of this overview.

Illustrated in Figure 2 are the cross-overs from the differential equation and the firepower index (force ratio) approaches to attrition modeling into the simulation approach. The later approach, of course, eventually provided the most flexibility in accommodating the modeling of all elements of combat and, as such, became the dominant technique used for this purpose and has remained so to the present. However, as indicated above, simulations have borrowed heavily from the differential equation approach and particularly from firepower scores and indices to aggregate the attrition (and movement) of large, heterogeneous forces in battle.

The dotted arrow show in Figure 2 connecting Approaches I and III reflects work performed by Taylor, outlined in Reference 8, to fit the curves of fractional casualty rate versus force ratio (as used, for example, in ATLAS[28]) by modified Helmbold-type differential equations that are part of the extensions of the Lanchester theory dicussed earlier in this chapter. Thus, in a sense, we have effected closure between Approaches I and III in being able to demonstrate a similarity in the form of the results produced in both cases.* More significant, perhaps, is the fact that the relationship between casualty rate and force ratio can be put into the differential equation approach with a more useful, meaningful set of variables when it comes to furthering our understanding of the combat process.

Before taking leave of firepower scores and indices (Figure 2), it is important to describe briefly yet another method of modeling combat that might be considered the ultimate projection and extension of the scores/indices concept. This method is purely empirical, deriving from a careful analysis of countless historical battles and is known as the QJM

*With a word of caution, however, regarding the questionable validity, mentioned earlier, of the casualty-rate curves that are presently in use

(Quantified Judgment Method[29, 30]).* Rather than building a model around cause and effect relationships in battle or, to put it another way, creating a large combat model that is composed of the logical assemblage of process submodels, QJM first identifies some seventy-three factors (see Appendix A) that, according to a judgmental consensus of experienced military people, affect the outcome of battle. It then strings these factors together in multiplicative or additive fashion, largely on an empirical basis, so that battle outcomes can first be reproduced and then, in new instances, be predicted with a significant degree of accuracy. Certain variables are expressed in terms of other variables through the use of formulae or by tables and the numerical values assigned to these variables are derived from weapons data, the historical records, or from the exercise of military judgment. What appears to be a reasonable degree of internal consistency is maintained throughout in the definition of variables and the range of values they can assume.

The first major objective with the QJM is to calculate the power potentials for both friendly and enemy forces (P_f and P_e). These might be regarded as highly modified, vastly extended forms of the firepower index previously described. The ratio, P_f/P_e, is, in some sense, an extension of the force ratio concept. If P_f/P_e is greater than 1.0, the friendly forces should be successful in the outcome; if less than 1.0, the enemy forces should succeed. The actual outcome of an engagement is evaluated on the basis of three factors. These are:

(1) The extent to which each of the two sides accomplished its mission (subjective assessment).

(2) The ability of the opposing sides to gain or hold ground (spatial effectiveness).

(3) The efficiency with which (1) and (2) were accomplished measured in terms of casualties, with losses viewed in relation to the initial strengths of both sides (casualty effectiveness).

If we sum the assessments and the prescribed computations of (1)-(3) for the friendly and enemy forces and identify them as R_f and R_e, respectively, then the difference $R_f - R_e$ is the outcome indicator. A positive difference indicates an outcome favoring the friendly forces; a negative one, the enemy forces. A difference close to zero reflects an inconclusive outcome. Using a plot (again, empirically derived) of $R_f - R_e$ vs P_f/P_e, we enter with the computed $R_f - R_e$ and obtain a new, *effective* P_f/P_e. The difference between the P_f/P_e originally computed above and the effective P_f/P_e is attributed to behavioral factors such as leadership, troop quality, surprise, etc., making the QJM the only model to treat such variables.

The existence of such a methodology prompts a few observations, even conceding the fact that the confirmation of its validity perhaps awaits further evidence in the form of additional testing against historical combat. The QJM concept is, in effect, an enormous static indicator of combat outcome. As such, it would appear to be completely independent of battle dynamics and therefore of the time dimension. If, indeed, one can assemble a set of effects and factors pertaining to weapons, terrain, weather, season, posture, mobility, etc., and assign values to them reflective of initial conditions for both sides in the engagement and the environment, and from these, through the exercise of a "method," determine the outcome of the engagement, then one is brought face-to-face with a paradox of sorts. For if this is a viable procedure, it contradicts the concept of engagement outcome dependency on "decision/event paths" as discussed in Reference 1, p. xvi, recognizing, of course, that such paths are tied inexorably to the time dimension. Thus, we come across an interesting question that warrants further attention; namely, are combat outcomes as sensitive as our intuition would

*The QJM is shown as a spin-off of firepower scores and indices in Figure 2 rather than a completely separate, independent development. This is because of an apparent connection between this methodology and some earlier work performed by T. M. DuPuy and the Historical Research and Evaluation Organization (HERO) under subcontract to the Research Analysis Corp. to provide historical data for the Force Ratio/Casualty curves subsequently incorporated incorporated into the ATLAS model.

indicate to the decision processes that occur over time during battle or can outcomes be conceived as locked in at the outset by relationships among the combat variables identified in the QJM that are, in many instances, static surrogates for dynamic processes?

The QJM is thus far unique among methodologies with the empirical, "design-to-correlate-with-history" approach taken in its development. However, it has been subjected to criticism particularly by members of the analysis community and it may, in some ways, be vulnerable to such criticism. Assuming that QJM could gain wider acceptance after closer examination, further application, and careful consideration of the options, then it might provide a most useful mechanism for the examination of tradeoffs between certain key variables (such as firepower and mobility, for example) within the context of a particular historical battle. Furthermore, some of the QJM ideas and structures as well as the values, historically derived, for certain behavioral variables might be incorporated into analytical models of combat and simulations.

Shifting to the simulation "mainstream" of Figure 2, a few observations are worth noting before proceeding with a discussion of the last class of models shown in the figure — the theater-level model. Much of the overview thus far has centered around ground combat considerations and models developed under the auspices of the Army. In combined arms operations, the air support of ground activities is, of course, an important element. However, in the simulation model developments that have been described thus far, we find early chronological preoccupation, in perhaps a "walk-before-you-run" way of thinking, with the modeling of small unit engagements that involve ground systems exclusively. As the scope of combat activities treated by simulation broadened, the importance of factoring air support into the modeling became increasingly apparent, resulting, ultimately, in air-to-air, air-to-ground, and ground-to-air combat modules in some simulations of land warfare that are as elaborate as those of the ground operations. Attack helicopters, being organic to the Army forces, appear to have enjoyed some slight priority over fixed wing aircraft in early efforts to incorporate close air support into models of land combat.

The pattern is somewhat different when viewing the combined arms modeling problem from the tactical air (Air Force) side. Here, there appeared an early appreciation of the fact that tactical air was a supporting arm and that its effectiveness could only be properly measured in terms of how it influenced ground activities. Hence, there were the pressures of logic and reason on the people who pondered the problems of air support in land warfare that impelled them, at an early stage, towards model concepts that were of division or theater-level in scope of operations, levels at which the presence of air support becomes a very significant factor. Of course, a highly aggregated approach to both ground and air system attrition (Lanchester-like) was all that the then-existing state-of-the-art in computer technology would permit. Even though analytical models (eventually followed by simulations) of "one-on-one" aircraft engagements or duels emerged in the late 1940s and early 1950s, they became channeled for the most part into problems of strategic and tactical air defense (fighters attacking enemy bombers, fighters vs fighters, etc.). There was a gap in high-resolution modeling of flight-on-flight, ground-to-air, and flight-on-target array engagements that was not fully addressed until rather recently (see Reference 1, Robinson, p. 134). Thus, there has been less of an orderly chronological progression of modeling from high resolution (low-level conflict) to low resolution (high-level conflict) when one compares the evolution of "air" oriented models with that of the "ground" oriented models. Examples of high-level conflict models that have resulted from this development trend are TAGS V[31] (a highly modified current version of the ancestral TAGS) and TALLEY-TOTEM[32]. On the other hand, FAST-VAL (Forward Air Strike Evaluation model[33]) and AGATE are examples of high-resolution, deterministic, ground combat models involving small units up to regimental size that were developed in parallel with and subsequent to the work on theater models. These latter models were designed to permit a detailed comparison of air support effectiveness against that of other ground-based combat support weaponry in small-unit operations. In short, all of these models, despite their wide variation in degree of resolution, attempt to model the impact of air operations* on the conduct of ground battles.

An important spin-off of the program of model development by Air Force activities was early recognition of the problem of air resource allocation in those instances in which aircraft were used multifunctionally. Briefly, the problem was to optimize the allocation of multipurpose aircraft among the various missions they could perform, and to this end the use of game theory and the multistage game (two-person, zero-sum) was introduced by Dresher and Berkovitz[35,36]. While significant simplifying combat modeling assumptions and constraints† were required to accommodate the mathematics of solving the game in this particular effort, it was noteworthy in that it opened the door to the possibility of treating an entirely new and important dimension in combined arms modeling, that of allocating air resources in a (mathematically) optimal fashion. The basic concepts were extended into the TAC CONTENDER simulation model, which was developed by the Air Staff (Studies and Analysis). The desire to incorporate more operational "realism" (i.e., more air missions, more allocation decision stages, better measures of air support effectiveness, etc.) prompted this development. Yet the attempts to model air/ground force interactions with greater fidelity, clashing as this does with the inherent mathematical complexity of game theory, created serious difficulties that were soon recognized, and a heuristic solution to the air allocation problem was advanced in TAC CONTENDER. This, in turn, led to the further development of algorithms for obtaining approximate game theoretic solutions to the resource allocation problem — such methods are exemplified by DYGAM (see Reference 1, pp. 163-160 and Appendix A) and the ATACM methodology (see Reference 1, pp. 161-168 and Appendix B). Conceptual and/or computational difficulties appear to persist, however, with these and other methods for obtaining approximate solutions (Reference 1, pp. 195, 196, and Reference 36) and at least one attempt to obtain exact game-theoretic solutions with models that treat air/ground interactions explicitly has met with failure[37].

TAC CONTENDER was superceded by the TAC WARRIOR theater model, which abandoned the allocation optimization procedures of the former on the grounds that multifunctional capabilities in tactical air support aircraft were not realized in practice to the extent that was originally assumed. However, the concept of optimal allocation, tied to game-theoretic methodology, has nonetheless persisted, finding its way into at least one of the major theater-level model developments.[40] To support TAC WARRIOR in hierarchical fashion, Air Staff saw to the development of a series of models such as TAC AVENGER, TAC BRAWLER, LCOM, Blue Max, TAC TURNER, etc. which, respectively, treated "one-on-one" engagements (using energy-maneuverability methodology), "flight-on-flight" engagements, the logistics support of air units, air-to-ground operations, and air base activities. Some of the inherent model interfacing difficulties experienced in using this kind of hierarchy are discussed in Reference 1, pp. 4, 5.

At this point, it is appropriate to round out the discussion of theater models, noting that there has already been considerable mention of such models in connection with developments described earlier in this overview. A set of selected campaign/theater models is shown in Figure 5. This figure includes, within the bounds of available information, models that are less than theater level in scope but from which, by virtue of extending the analysis technique

*Airbase attack, interdiction, close air support, air defense air-to-air

† The original closed form solution to the Dresher/Berkovitz game was based on the allocation of aircraft to three missions. close air support, air defense of air bases and counter air air base attack The game pay-off was simply the difference in the number of Blue and Red aircraft assigned to the close air support mission, and for three missions considered, aircraft mission effectiveness was assumed to be proportional to the number of aircraft assigned

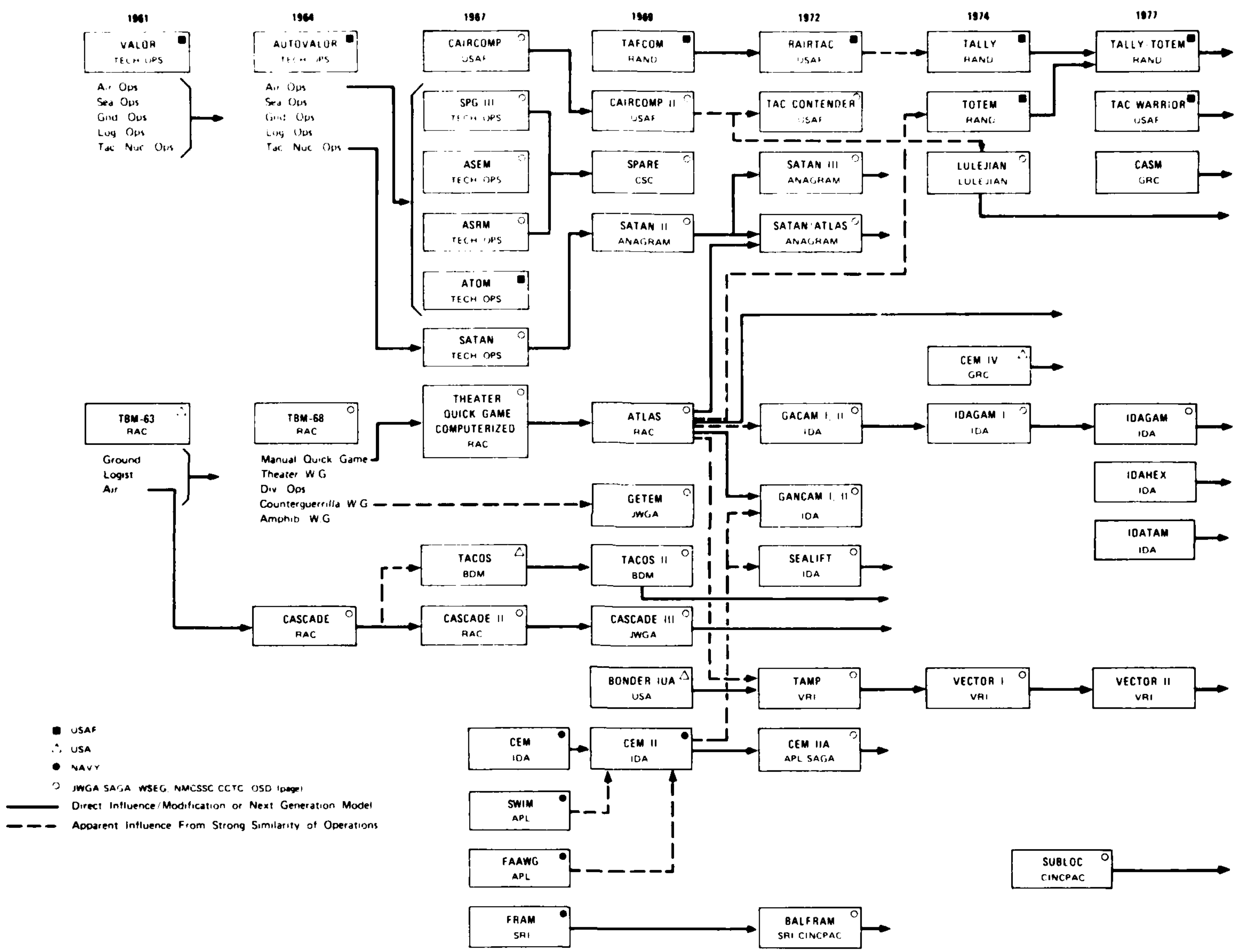

FIGURE 5 SUMMARY OF SELECTED MAJOR CAMPAIGN AND SUPPORTING MODEL DEVELOPMENTS

employed, a theater model evolved, or which served as a supporting model in the evolution of a theater model either alone or in combination with other models. The figure is not exhaustive in its identification of all theater models. Rather, it is concerned with those models that are documented and available and that have achieved a degree of utility with a major user activity within the Department of Defense. Table 1 is companion to Figure 5 and presents the full titles for each of the models that are identified in the figure by acronym.

There are generally three major, nonexclusive classes of functional activity that are directly involved in a model's life cycle: (a) proponent activites, (b) development activities, and (c) user activities.

Table 1
MODEL NOMENCLATURE FOR FIGURE 5

Acronym	Title
ASEM	Air Strike Evaluation Model
ASRM	Air Strike Requirements Model
ATLAS	A Tactical Logistical and Air Simulation
ATOM	Air Tactical Operations Model
BALFRAM	Balanced Force Requirements Analysis Methodology
BONDER IUA	Individual Unit Action
CAIRCOMP	Counter Air Computations Model
CASCADE	Computerized Air Strike and Counter Air Defense Evaluation
CASM	Combined Arms Simulation Model
CEM (IDA)	Campaign Execution Model
CEM (GRC)	Concepts Evaluation Model
FAAWG	Fleet Anti-Air War Game
GACAM	Ground Air Campaign Model
GANCAM	Ground Air Naval Campaign Model
GETEM	Guerilla Elimination Time Evaluation Model
IDAGAM	IDA Ground Air Model
RAIRTAC	RAND Air Tactical Evaluation Model (revised TAFCOM)
SATAN	Simulation for the Assessment of Tactical Nuclear Weapons
SPARE	Strike Planning and Aircraft Requirements Evaluator
SPG	Strike Planning Guide
SWIM	Sea Warfare Integrated Model
SUBLOC	Submarine Blockade Model
TAC CONTENDER	(same)
TACOS	Tactical Air Defense Computer Simulation
TAFCOM	Theater-Wide Tactical Fighter Combat Operations Model
TALLY/TOTEM	(same)
TAMP	Theater Analytical Modeling Procedure
TBM	Theater Battle Model
VALOR	Variable Local and Resolution

The proponent is normally a government activity that requests and supports the development of a new model to fill a particular need. If appropriately staffed, the activity may undertake the development "in-house". More often than not it becomes a significant user of the model.

The development activity may be a contractor facility, an academic institution, a government laboratory, or a military staff that undertakes the development of the model. In the case of government activities, a developer can also be a proponent (and a user).

The user activity consistently uses, or foresees a continuing use for, the model to support decision making at various levels in government. This attitude towards model utility is directly reflected in a commitment on the part of the user to generate or to have generated an appropriate data base for the model, to analyze and staff the results obtained with the model, and to modify and refine the model when it is deemed necessary. Alternatively, a user may request the developer (if a separate activity) or any other appropriate organization to perform the model modification and refinement functions. It should be noted that a model can often have more than one user.

In Figure 5 the model developer (most often a government contractor) is shown in the model identification block. These blocks are coded in the illustration to identify the department affiliation (Army, Navy, Air Force, JCS/DoD) of the proponent/user activity and in those instances where more than one user is or has been associated with a model, affiliation of the user in highest authority is indicated. The dates attached to the various models in the figure are not precise; rather, these dates, in association with their precedents on the figure, reflect periods of time during which the indicated models made their first appearance. Direct and apparent influences of one model on another are shown by solid and dashed lines, respectively.

No attempt is made here to describe the models in any detail; however, some general observations may be drawn from the material presented.

To reiterate, the fundamental difference between combat models at the theater level compared with those at the division or corps level is really one of scale. All of the elements in Figure 3 properly belong in the architecture of both types of models.

The mainstream developments in theater-level gaming had their earliest origins in manual gaming at the service level (i.e., Army and Air Force). But with the relentless swing towards greater use of computers (following developments in this technology area) and a growing appreciation for the power of simulation in addressing large, complex problems, it was only a few short years before these games had been "computerized." Firepower scores used in the refereeing of the manual games were incorporated into the automated games. These games in turn, gave rise to a series of higher resolution tactical air models to afford closer examination and evaluation of air-to-air, air strike, counter-air, and air defense missions in the context of theater warfare. Another spin-off of the automated games (in this instance, AUTOVALOR, developed for the Air Force) was the series of SATAN models exclusively concerned with the employment of tactical nuclear weapons on the battlefield.

Reference to Figure 5 shows a very early and continuing involvement of DoD activities in the theater games and their supporting models. The activities most directly concerned both as model proponents and users were JWGA/SAGA (Joint War Games Agency, replaced in 1970 by Studies Analysis and Gaming Agency) and NMCSSC/CCTC (National Military Command System Support Center, superseded by the Command and Control Technical Center). Others included WSEG (Weapon Systems Evaluation Group) until its disestablishment in 1976, and OSD (PA&E).

The first theater model to achieve significant visibility and widespread utility was the ATLAS model.[18] A direct offshoot of the RAC Computerized Quick Game, ATLAS, in turn, spawned a number of modified versions tailored to the specific needs of certain activities such as the SHAPE Technical Center, STAG/CAA,* ACDA, and CINCPAC. It also influenced the GACAM[39] and GANCAM[39] developments of IDA. ATLAS, as discussed earlier, was a "firepower scores" (FPS) model and the extensive use that was made of it tended to popularize the notion of employing FPS techniques, despite persistent expressions of concern over FPS shortcomings within the analysis community.

The advent of ATLAS ushered in a period of perhaps the greatest spurt of activity to have been experienced to that time in theater-level model development: this was the period 1969-1973. Significant impetus for this activity stemmed from a WSEG decision in 1972 to support the development of three new theater models that each took an independent approach to the modeling of large-scale combat. The three organizations that undertook this task were IDA, Lulejian, and Vector Research, and the series of models that eventually evolved from their respective efforts were IDAGAM 1, 2, and, from these, TACWAR, IDAHEX, IDATAM; LULEJIAN 1, 2; VECTOR 1, 2, VECTOR 1 NUC and the division/corps models DIVOPS and COROPS. The three basic theater models, IDAGAM,[26, 41] LULEJIAN,[40] and VECTOR,[26,42] represent significantly differing approaches to the same problem; so different, in fact, that one could scarcely hope for the three to produce comparable answers when applied to the same problem. IDAGAM and LULEJIAN are "aggregated" models that use firepower scores in differing ways for the calculation of attrition. On the other hand, VECTOR, by comparison, is usually described as a "detailed"† model.

The methods of treating attrition in IDAGAM and VECTOR were touched on earlier. A word or two about LULEJIAN is perhaps in order. It is unique among the theater models in having incorporated into its structure an optimization algorithm for the allocation of some major theater resources (tactical air and logistics). It also attempts to optimize the choice of sectors for the initial enemy massing of forces and attack. The structure of this algorithm is that of a two-person, zero-sum sequential game[43] and it makes use of certain approximations to keep the process computationally tractable that open to question the degree of optimality provided by the game-theoretic solutions.[36,44] The attrition computations in the LULEJIAN model are based on exponential equations, which are shown by Karr[44] to be related in approximate fashion to the Lanchester square law. FEBA movement is based on a concept of its being controlled by the relationship of actual to "acceptable" loss ratios for the attacker and defender, implying a behavioral assumption that a combat commander is willing to trade off higher casualty rates for position or territory.

Of the three models, IDAGAM, LULEJIAN, and VECTOR, LULEJIAN appears to have lagged the most in application, whereas IDAGAM has enjoyed the greatest frequency of use. The apparent popularity of IDAGAM undoubtedly stems in part from its relatively modest data base requirements and low CPU times which, of course, are related to its high degree of aggregation. VECTOR, by contrast, is blessed with the most direct, explicit logic of the three models and a global structure (i.e., a built-in "hierarchy of models") that averts those concerns for proper model interfacing that normally attend the use of a hierarchy of separate and distinct models. The price one pays for these features is the feeding of a voracious appetite for data, particularly low-level data (see Reference 1, Bednarsky, p. 214) that is a VECTOR hallmark. This, in turn, leads to longer input preparation times (at least for initial runs of the model) and in all probability higher CPU times (although I have not seen data to confirm this.)‡

*Strategy and Tactics Analysis Group (Army), superseded in 1972 by the Army Concepts Analysis Agency

†The terms "aggregated" and "detailed" are, of course, employed in a relative sense. VECTOR is very detailed and explicit in its treatment of all combat elements when compared to the other two models; however, it does involve some degree of aggregation compared, for example, with the usual simulation treatment of "one-on-one" weapon system duels.

‡At this writing, VECTOR 2 had not been used operationally and VECTOR 1 is purported to require approximately 11 seconds CPU time per combat day for a typical game.

In addition to these three model developments of conventional warfare at the theater-level initiated by WSEG, there are three models, which appeared subsequently and are not shown in Figure 5, that treat the theater employment of tactical nuclear weapons in mixed conventional/nuclear situations. Two of these, VECTOR 1/NUCLEAR and TACWAR (Tactical Warfare model,[45] as mentioned earlier, were essentially combinatory derivatives of VECTOR 1 with UNICORN and IDAGAM with SATIN.* The third model is COMBAT II[46,47], developed by BDM for the Defense Nuclear Agency (DNA) as the proponent and user activity.

It should be noted that the IDA TACWAR model is the only one of the above group that also treats chemical warfare (in addition to conventional and tactical nuclear), thus encompassing the entire conflict spectrum that could conceivably be encountered by general purpose forces. COMBAT II, which uses differential equations for the modeling of attrition, is highly transparent and highly aggregated. It is, in fact, envisioned as the top-level model in a BDM hierarchy of models that are under development† wherein it is anticipated that COMBAT II will identify driving processes and variables as well as critical time periods in the conflict that can be explored in greater detail with lower-level models in the hierarchy.

Two additional theater models that have had considerable impact in force planning are CEM (GRC CAA[48]) and TAC WARRIOR. CEM, widely-used by the Department of the Army in its force planning process (see Reference 1, Louer, pp. 10-11), evolved from ATLAS via the TCM (Theater Combat Model[17]), a model that sought to provide improvements over ATLAS by incorporating a command decision structure (consisting of "table look-up" contingency decision rules) at the theater, army, corps, and division levels. This structure was carried over into the series of CEM model developments (CEM I-IV)‡ along with other modifications. A major departure from ATLAS is the method used to determine engagement attrition. Instead of curves of percentage casualty rates as a function of force ratio, derived from historical data (as described earlier), CEM employs a series of exponential equations, somewhat similar to those of LULEJIAN, to compute losses to ground combat systems, air systems, and personnel. Firepower potentials are used in these equations to aggregate the various kinds of fire being brought to bear against a specific class of target, such as tanks. The main feature of CEM that distinguishes it from many of the other theater models is the aforementioned hierarchical decision structure, where the decision cycle time in days is varied according to the level of decision making (i.e., at the levels of theater, army, corps, division). FEBA movement is governed by weighted force ratio computations, which are compared with threshold force ratio values that are provided as inputs to CEM. From this comparison, FEBA displacements are determined from tabular values of movement that must also be provided as input. Both thresholds and movements are functions of terrain, force postures, and the possible presence of barriers or obstacles.§

TAC WARRIOR, a previously mentioned theater model, is part of a model hierarchy developed by the Air Force that permits analysis of combined arms combat from a detailed,

*UNICORN and SATIN (Simulation for the Assessment of Tactical Nuclear Weapons) are both models of limited scope (from the standpoint of unrestricted theater warfare) that are concerned with tactical nuclear weapons employment. UNICORN, developed by Science Applications Inc. (SAI), is a relatively detailed model that allocates conventional/nuclear indirect fire weapons to a target array to determine a least cost "one-salvo" allocation that produces a specified level of target damage. SATAN, on the other hand, is a two-sided, dynamic, stochastic model of theater ground/air operations but is restricted exclusively to the employment of nuclear weapons. For further information on VECTOR 1/NUCLEAR and TACWAR, the reader's attention is invited, respectively, to Reference 1, Spaulding, pp. 108-115 and Kerlin, pp. 47-55.

†This hierarchy consists of the COMBAT II model, the T-COR model (also at the theater-level), the CORPS-COMBAT, and the DIVISION COMBAT model. The logic behind this development, known as the Integrated Combat Assessment (ICA) methodology, is thoughfully explained in Reference 47.

‡More recently, the full title for CEM has been changed from CONAF Evaluation Model to Concepts Evaluation Model.

§See Reference 49 for a critique of the CEM methodology.

structured air operations point of view. The TAC WARRIOR model, itself, while stressing air operations, contains only a highly aggregated representation of ground combat. Use of TAC WARRIOR has been more or less restricted to Air Force force planning issues in much the same manner that CEM has been used by the Army.

Referring again to Figure 5, we make mention of BALFRAM[50], a methodology that can be used to construct a highly aggregated theater model that has the capability of treating naval forces and war at sea in addition to the more traditional treatment of the ground/air war. Developed by SRI International under joint ONR/CINCPAC sponsorship, its use has largely been restricted to the Pacific Command (PACOM) and governments in the Far East (Taiwan, Korea, Japan). BALFRAM differs somewhat from the models discussed thus far in that the user must construct or model a scenario of interest from a set of compiler-like routines. Thus the services of an analyst/programmer staff must be provided to actually create the model for subsequent use. Geography is simply abstracted in terms of nodal points and lines of access between nodes and there is no explicit treatment of terrain masking or weather. Lanchester-like differential equations with exogenous firepower parameters* are used to model attrition wherein aggregated attrition rate coefficients for heterogeneous forces are obtained by using a "base attrition rate" that is multiplied by the weighted, normalized ICEs† of the units in the force. Thus, with this attrition methodology, we find a mixture of both Lanchester and firepower scores for whatever that may be worth. However, the degree of resolution in BALFRAM is far too low to permit explicit accounting for weapon system effectiveness or the attrition to these systems in ground combat, and, in the modeling of air operations, exclusive use is made of notional aircraft rather than specific aircraft types. As one might expect, once the model has been assembled to the user's satisfaction, input preparation times and model running times are considerably shorter for BALFRAM than for most of the other theater models.‡

To complete the discussion of Figure 5, we should take note of CASM, a simulation model of the next generation currently under development by the General Research Corporation for the Air Force (AFSA). Beyond the fact that this development is to stress true modeling of command and control, there appears to be little other information available at present on the progress of this effort.

To summarize the current status of theater modeling in the United States, one might start with the observation that the front-runner models from the standpoint of general acceptability and actual or potential utility in the shaping of policy (at various levels) are:

- IDAGAM and variants
- VECTOR and variants
- CEM
- TAC WARRIOR.

In addition, perhaps to some lesser degree than with these models, the now-venerable ATLAS in any one of its many forms finds application.

Theater models should in some way address all of the circumstantial elements and processes of combat, as we understand them, if these models indeed are to be a reasonably

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*Reflecting firepower that is not organic to a ground, air, or naval unit as for example, close air support or naval gunfire support of ground units engaged in battle.

†See p. 24.

‡As a consequence, BALFRAM can be used in a single stage, matrix game-theoretic sense to investigate "optimal" allocation strategies for major resources as, for example, the way a theater commander might split his ground forces in a two-front war. Attempts to develop a multistage game using BALFRAM for the allocation of air power to the various theater air missions have not been successful see Reference 37.

faithful abstraction of what they are attempting to represent. The elements of combat are essentially the "givens" in the problem: the factors that are dictated by the circumstances of the conflict, the factors that define the combat environment, and the human and material resources and their organization with which the adversaries do battle. They can be listed as follows:

- Combat circumstances, and initial objectives and missions for both sides.
- Natural and man-made environments in the area of operations.
- Human resources; numbers, characteristics, and behavior.
- Material resources (all of the equipment and devices for waging and the support of war); numbers, characteristics, and performance.
- Organization and structure of opposing forces.
- Tactics, doctrine, and operational concepts.

Combat processes are concerned with the interdependent phenomena that occur on the battlefield; that is, with the functions that are performed by the combat and the support forces of the adversaries during the battle and their effects on the opposition. They are:

- Attrition
- Suppression
- Movement
- Command, control, communications and intelligence (C^3I)
- Combat support
- Combat service support.

In modeling warfare situations, one essentially feeds the combat elements (as inputs) into mathematical formulations of the combat processes that are tied together by appropriate logic to derive outputs which are, in effect, the outcomes of the encounter between the opposing forces.*

The theater models touched on in this brief review reflect about as many approaches as there are models to the problem of accommodating the circumstantial elements and combat processes described above. Intuition and experience tells us that these elements and processes are basic factors in determing battle outcomes, but we have little understanding of the relative importance of each. Which factors are indeed the drivers and under what conditions do they so become drivers?† The different emphasis that the various models place on these factors seems to reflect in part the confusion that is upon us in not having the answer to this question. Moreover, there are very real uncertainties about the validity of much of the modeling despite the remarkable analytic ingenuity that has been displayed in many cases. Finally, we come to the problem of obtaining appropriate data for the models, an enormous problem that has finally been recognized.‡ These data pertain to, and in many instances are, a quantification of the circumstantial elements of combat, listed above, that define and describe the basic inputs for the models.

Elements and processes whose treatment is notably weak, deficient, or totally lacking in the models of Figure 5 are:

*These combat elements and processes can be compared with Figure 3, and Reference 1, Figure 1 and Slide 10-1, which look at the taxonomy of combat in differing degrees of detail and from different points of view.

†This issue is discussed more extensively in Section 4.

‡See Reference 1, Bednarsky, pp 210-228, and Schneider, pp 208, 209, 243.

• Human behavioral characteristics under the conditions of stress and confusion associated with combat and their impact on combat processes as well as their possible influence on other combat elements.

• Flexibility of movement in the broad sense of the term that encompasses breakthroughs and nonintegral FEBA situations in general (flanking maneuvers, encirclement, etc.).

Factors that are perhaps less significant from the standpoint of their visibility (or lack thereof) in theater models, but which nevertheless continue to present extremely difficult modeling problems, are C^3I, combat support (signals warfare), and the dependency of human and material resources on combat service support (logistics and enemy interdiction thereof). These factors do, of course, involve a close interweaving of "elements" and "process" considerations, as discussed above.

In a broad sense then, one can state that the efforts to model land combat mathematically started with, and have retained, a strong "engineering" orientation through their evolution to the theater level. In these developments, expediency seems to have prevailed because, as mentioned earlier in the discussion, the performance of man-made machines in their operating environments is certainly easier to model (although by no means a trivial task) than is the performance of man himself. While weapons and combat support systems are blessed with a certain degree of predictability in terms of their expected behavior in a mechanistic sense, the impact on battle outcome of the characteristics of the human operators of equipment and their leaders in combat, for whom the machines are extensions of relatively meager destructive powers, are not nearly as well known. Of great significance here is the existence of strong evidence[30] that those human factors in battle having to do with command decisions, the choice and execution of tactical alternatives, and proficiency in the use of weapons are far more important in the true shaping of battle outcome than the attention given them to date in combat models would indicate. Partial alleviation of this problem may be found in the recent and discernible trend towards the use of player-assisted or interactive computer gaming* at the theater level and considerable experience with such gaming at division/corps levels. It must be recognized, however, that the human decision making in these games is constrained to certain hierarchical levels of organization and to certain classes of options by the very structure of the models themselves.

This overview would be incomplete without some mention of European gaming developments, particularly those of the United Kingdom (UK) and the Federal Republic of Germany (FRG). In both countries, the mainstream theater-level models (NATO Deployment Model[51] and RELACS,[52] respectively) would seem to reflect preference for an hierarchical rather than a global approach. Over a period of about ten years, the British have created a series of models known as the Battle Group Model, the Corps Model, the Central Front Game, and the NATO Deployment Model, which are somewhat similar in concept to the U.S. CARMONETTE/DBM/ATLAS hierarchy of models described earlier.

In the Battle Group Model, we find the high resolution simulation of a constrained set of scenarios (limited to eight) that are believed to typify battle group/regimental encounters. These scenarios (which, for example, cover such operations as forward battle group action, armored battle, withdrawal in contact, the encountering of water obstacles, etc.) form the basic building blocks for all applications of the model(s). Although structured to conform to specific types of operations along microscenario lines, these building blocks nonetheless afford considerable flexibility for their compatible adaptation to much larger conflict situations by allowing appropriate variations of weapons and weapons mixes, unit deployments, terrain characteristics, etc. Attrition in the Battle Group Model is computed using an

*At this writing, for example, IDAGAM is being used by JCS/SASA in an interactive mode extended form of Lanchester's equations that includes such factors as single-shot kill probability, weapon rate-of-fire, target availability, and target selection doctrine.

The Corps Model, the next model up the hierarchical ladder, is concerned with activities at divisional or corps levels. Resolution in this model is still down to the battle group and regiment, and such units are distributed along axial attack-defense corridors. Blue units (battle groups) and Red units (regiments) are separated by a FEBA that is "logically" constrained to retain a relatively smooth configuration across the various corridors. Attrition in the Corps Model is of the Lanchester form and is aggregated by a weighting scheme that is related to the kill powers of individual weapons in each battle group/regiment that, in turn, depend on range of engagement.* The main function of the model is to ascertain, for a given attack/defense posture, the casualties over time for each side and the rate of FEBA movement.

The Central Front Game is concerned with yet a broader front of battle than that of the corps. At this level, considerable interaction on the part of senior military people and scientific personnel (a Command Group) is called for in the game play, although it should be noted that military judgment is exercised fairly liberally throughout the entire hierarchy when it is applied to a specific problem. In the Central Front Game, however, the major concerns are with the commitment of reserves and the allocation of air power. In the latter, use is made of an Air Campaign Model that examines the air war as a whole and ultimately aids in establishing a feasible allocation of tactical aircraft sorties to the attack of ground targets. *It is in this manner that the link is forged between ground and the air-support-of-ground combat activities.* As Command Group decisions are made affecting the allocation of ground reserves or air to its various tactical missions, the impact of these decisions is assessed through new runs of the Corps Model and the Air Campaign Model. Thus, solutions to a problem that are generally credible to the military can eventually be reached through iterative cycles of decision, analysis, and computation. While there is much to be said in favor of this approach, the time required to play a game in the fashion described can be several weeks.

As a consequence, the NATO Deployment Model was developed to provide faster response times in solving a variety of force deployment problems. Briefly, this model operates on more highly aggregated outputs of the Corps Model than does the Central Front Game and is chiefly concerned with the defender's problem of dealing with *uncertainty* in the manner in which the attacker will employ his forces (how many and where) even when the attacker's total force strength is known. The defender's objective is to optimize, against a spectrum of possible enemy attack configurations, the allocation of defense forces, in depth *within sectors, between those committed to forward positions and those held in reserve.* The defender's measure of merit is, in a general sense, the imposition of the greatest delay in the time that it takes the attacker to reach his objectives. The model recognizes and accounts for trade-offs inherent in the employment of reserve forces, i.e., the greater flexibility they afford in the application of military force where it is most needed versus the time it takes to get them into position, the time they require to prepare their positions, and the attrition such forces may suffer en route.

Niemeyer[52] provides an overview of German thinking† in the development of war gaming models. Again, computerized war gaming in the FRG appears to have evolved from manual (and computer-assisted manual) war gaming, resulting by the early 1970s in a series of hierarchical models known as RELACS (theater-level),‡ KORA (Corps-level), and COFORKS

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*See Reference 51, pp. 294-295, for a more detailed description of attrition processes in the Battle Group and Corps Models.

†Largely, as reflected in the work performed at the Industrienlagen-Betreibsgesellschaft (IABG), Ottobruun.

‡Real Time Land Air Conflict Simulation

(brigade-level). These, in turn, are connected to a hierarchical set of corresponding command and control models, known as the TREND models, that afford the opportunity for closed simulation of the C^2 function. Through the TREND models, battle parameters can be varied rapidly and with relative ease. In a broad and general way, these developments parallel those with hierarchical models in both the U.S. and the United Kingdom, allowing, of course, for differences in the detailed treatment of combat unit representation, attrition, FEBA movement,* etc.

Of greater interest, perhaps, is a more recent shift (since 1976) in model development at IABG to the concept of a structure for the ground/air war wherein combat organizations and systems are modularized in a hierarchical fashion within a single global model. The modules can be thought of as minimodel building blocks that can be used to construct larger combat units at higher levels of organization. The degree of resolution within a module is inversely related to the organizational level, and the interfaces between levels are logically defined by the model software. In many instances, modules can be standardized and electronically stored in a module program "library." Replacement of selected modules, if so desired, by human beings results in an interactive or player-assisted simulation. Otherwise, the game can be played as a closed simulation with preset command and control rules.

The model that has been developed around this modular concept is known as TALCS (Tactical Air/Land Conflict Simulation), and its operating system is defined by a special gaming software package, BASIN. In addition to all the programs and routines for TALCS, this package contains those elements necessary for interactive gaming such as the graphic presentation of the battle situation for the players and the transformation and transfer of their instructions into the game. The TALCS model appears to stress command and control and the air war (including air defense). Air war interactions with the ground war are obtained through ground battle simulation at the brigade/ division level, using Lanchester equations for attrition. An idea of the structure and emphasis in TALCS can be seen in submodels that make up the whole.

- Air attack command and control submodel
- Air defense command and control submodel
- Air field activities submodel
- Air mission progress submodel
- Air surveillance submodel
- Antiaircraft artillery, missiles/aircraft engagement submodel
- Aircraft/aircraft engagement submodel
- Ground target engagement (by air) submodel
- Brigade/division engagement submodel.

The developers of TALCS/BASIN count it among the most advanced of today's gaming techniques, and well it might be, because, from at least a structural viewpoint, it contains a number of interesting and novel ideas, particularly with respect to accommodation of the command and control process.

The foregoing overview of ground/air combat modeling methodology was structured around the premise that a form of analytical engrossment with the attrition process gave rise to the sequence of developments that have been described. No proof of this assertion can be found. However, the manner in which the evolution of combat models and simulations has

*A comparison of FEBA movement rates, for example, between IDAGAM (U.S.), CORPS Model (UK), and RELACS (FRG) is presented in Reference 53.

occurred over a period of some thirty years would appear to support this hypothesis. If concern with attrition has indeed been a prime mover in the development of our combat modeling concepts, then F. W. Lanchester is the man who probably dislodged the first rock to start an avalanche.

4. Key Issues and Concerns

4.1 Introduction

The material presented in Volume I, "Proceedings," supports the assertion that the use of combat models and simulations in general, and those at the theater-level in particular, have become infused into decision making at the policy-levels of our government in varying degree and often in subtle ways. But that same material also points up the many recognized, yet unresolved, problems associated with the development and employment of such models and methodologies. The purpose of this section is to categorize the wide and highly diversified assortment of problems that surfaced at the workshop on the basis of their criticality and to place them in a perspective that permits the evolvement of a comprehensive, cohesive strategy of research that should be capable of addressing these problems. Product improvement is the ultimate goal. Within constraints imposed by the totality of knowledge available to us today and the state of development of the theoretical foundation of our discipline, the attainment of perfection in any scientific sense of the word is not possible.

4.2 Background Comments and General Observations

Some observations are in order that, perhaps, go beyond the boundaries of discussions in the workshop. However, they are fundamental to creating a more complete understanding of an inordinately complex problem that has organizational, societal, and behavioral components along with those of a technical or "hard" scientific nature.

Gaming and simulation are a part of operations research (OR). The wellsprings of OR were mathematics and physics, and the recognition of a few individuals of scientific bent during World War II that there was value to be gained by some practical "problem solving" to assist the conduct of military operations.* Since its spontaneous generation in the 1940s, OR has expanded dramatically in many directions.† Although the boundaries of OR today are somewhat fuzzy, the field is recognized to deal with "systems" and "operations" in the broadest sense, with emphasis on the quantitative measurement of their utility and behavior. The ultimate objective of OR is the optimization or improvement of utility, which implies a good understanding of those variables that are of "first order" importance in driving or controlling the process being analyzed.

Since OR is concerned with socio-technical systems and operations, it is broadly interdisciplinary, cutting across the boundaries of the traditional sciences to a degree unmatched in any other scientific undertaking. The main thrust of OR is quantification and the language of OR is the language of mathematics.

The problem-solving activities of the earliest practitioners of OR were tested in relatively tight, responsive, closed loops of paradigms, models, and experimentation. The experimental laboratory was the ultimate in realism and relevance — actual warfare. The experiments could not be controlled in any real sense but the calculations performed by the scientific analysts led selectively to new concepts for evaluating the effectiveness of missions and operations and for employing the equipment and weaponry at hand. With a trip to the "laboratory," it was possible to ascertain whether some proposed change in equipment or operating procedures was worthwhile or found wanting.‡ What is really important, however, is that these early analysts were immersed in sources of data (albeit requisite data were not always factual, discernible, or obtainable) and operated in an environment rich in

*These activities came under the heading of operations analysis in the U.S. and operational analysis in Great Britain. See the recollections of a pioneer in the field, P. M. Morse in References 54 and 55 for an early history of operations research.

†Even laying claim to certain earlier developments in mathematics and military sciences.

‡A rule of thumb for the operations analysts of the time was to reserve their talents for those problems where improvements by a factor of 2 or 3 could be expected.[54] Such a philosophy would of course be consistent with a prevailing situation of small scientific staffs faced with an overabundance of problems. On the other hand, one should perhaps not overlook the possibility of an intuitive rationalization that would seek the largest expected improvements as a hedge against the lack of experimental control inherent in wartime operations. This would be done in the hope of assuring the realization of *some* improvement in virtually any situation.

opportunity for feedback. Furthermore, they concerned themselves almost exclusively with the *technical* aspects of weapons, sensors, and delivery systems, allowing such aspects to shape new tactical concepts. The social or behavioral aspects of these problems were automatically factored into the experiments by the unique "laboratory of war" environment.

Postwar, OR expanded into nonmilitary activities, along with continued application to military problems. Here, again, in dealing with existing systems or ongoing operations, the utility of OR techniques could be assessed with little delay and reasonable accuracy. Mathematical models of problem areas deemed to be in need of analytical attention were constructed as abstractions of the conditions that prevailed in true-to-life situations, and the fidelity of these models could in many instances be established or verified by interaction with continuing real-world operations. At the same time, creation of the models provided a mechanism for identifying the areas where data were lacking or where better data might be needed. These and earlier efforts at modeling, in turn, led to developments in mathematics that were singularly stimulated by the kinds of problems that OR addressed. These developments gave impetus to the credibility and acceptance of OR as a scientific endeavor in its own right.

The earliest efforts in OR were then characterized by interaction and feedback model abstractions and an experimental base provided by ongoing, real-world activities.

However, these conditions were not destined to prevail. Following World War II much of the momentum behind OR came from continued military interest in the field, but the major focus was no longer on how to fight an ongoing war but on how future wars would or should be fought. As a result of this new focus, a branch of OR, known as systems analysis, emerged during the 1950s and 1960s (and still continues), nurtured by rapid developments in computer technology and a veritable love affair with the problem-solving technique known as simulation. At first, simulation was resisted by purists* but its powers were not to be denied. The main attraction of simulation was its enormous computational flexibility and capacity. Seemingly as if drawing strength and resolve from this new found capability, the practitioners of OR sallied forth to tackle ever bigger and broader problems.†

Since a "system" is a conceptual entity, hierarchical in nature, that embraces any collection of things that can be reasonably circumscribed in terms of behavior and support, it took no discontinuity in reasoning to progress from the contemplation of small systems, such as a tank or missile battery, to more majestic ones like armies or the defense resources of an entire nation. Now, supposedly, one could, with sweeping aggregation of cause and effect relationships, throw simulations of large-scale problems on a computer and reasonably expect the machine to grind out meaningful results.

Not quite so, for the road to this nirvana has always been obstructed by some serious difficulties. One difficulty was created by the transitory growth of modeling from "one-on-one" duals between machines of war (largely a technical or engineering problem) to combat between large military forces of heterogeneous composition over sizable geographic areas (a full-blown socio-technical problem). In the broadest and simplest of terms, models of human behavior comparable to those of machine or equipment performance have not yet been developed, nor are they ever likely to be.‡ Yet the performance of virtually every weapon, vehicle, and piece of equipment in a wartime environment depends in varying degree on human operation or control. How, then, can the human effect be factored into the weapons equation? How, in modeling large-scale operations, do we account for the brilliant strategic

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*Jacinto Steinhardt, another pioneer in OR, is known to have remarked that resort to simulation was an admission of failure to obtain a meaningful problem solution

†This trend can be observed in the discussion of the evolution of theater models presented in Section 3.

‡See Reference 56, pp 158-186, for an excellent treatise on this subject

or tactical insights that often set one commander apart from another, his skillfull rather than prosaic employment of weapons, his superior control over his forces in the attainment of objectives?

The truth is that we cannot account for these factors, with models alone. Yet there is considerable historical evidence to support the fact that these factors are significant enough to effect favorable outcomes in battles or wars despite advantages in numerical strength or weaponry enjoyed by the opposition. History, in fact, may have much to teach us that we have not, as yet, exploited to the fullest. In short, in seeking to provide answers or insights to the mainline problems, we have expanded the scope of the military operations we model to a point where human behavioral factors can exert significant influence on the outcome. And this we have done with precious little, if any, theoretical or experimental work to guide us.*

In modeling for future wars or conflicts (which, for planning purposes, often involves looking ahead some five, ten, or more years), the problem is compounded by the fanlike spread of uncertainties over virtually every aspect of combat phenomenology. On the question of "futures" and their impact on human factors, one can only observe that human behavior with all of its variations, is perhaps, the most unchanging over time of all of the variables of combat, if only we knew how to measure it in a meaningful way. Here, again, we have no theories to guide us, no access to experimentation, and no availability of hard data.

In summary, the analytical processes described here are clearly "open loop" (no feedback) and highly conjectural compared with the relatively "closed loop" conditions that prevailed (and the more circumscribed nature of the problems addressed) when OR first formally appeared. They are "open loop" because they do not interact with experiments (either "turn of events" or contrived) and because there is no recognized theory of war or combat that describes the phenomenon in the language of mathematics. It can be argued that, in these matters, the practice of OR or systems analysis has been pushed beyond the bounds of logic and reason and that not only are these exercises pointless, but, what is worse, perhaps misleading. There is little doubt that the procedures being discussed, although quantitative, are not rigorously scientific. On the other hand, can they in certain instances contribute information of some value to the totality of knowledge about war or armed conflict, recognizing that there are precious few options available (and none of them perfect) for the study of these phenomena? Whatever one's point of view, the important thing to note is the true lack of consensuality (Reference 56, p. 6) in the use of "open-loop" simulation procedures.

If one is indeed wedded to the concept of a mathematical model because one wishes to measure and hence, in some fashion, to tweak or optimize some system or operation, then the most serious shortcoming of the "open-loop" approach to complex problem-solving is the lack of scientific evidence as to what truly drives the process being modeled.†

In the absence of suitable scientific underpinnings, intuition and "expert judgment" are generally called upon to address the issue of what variables are important in a problem, and, at times, what their values should be. Here, the whole field of endeavor becomes vulnerable to certain idiosyncratic interactions within our societal system.‡

To many trained in the model-experiment-theory interplay of the natural sciences, feelings range from discomfort to disbelief that there are educated and seemingly intelligent people who have the temerity to create mathematical models of a phenomenon as grandiose and complex as "warfare." To some social scientists, on the other hand, where much of what is being explored is of a qualitative and classificatory nature, the intrusion of "mathematics"

*In making this statement, I in no way wish to make light of the difficulties inherent in such theoretical or experimental undertakings in the social sciences

†Some thoughts on this subject quoted from Reference 56 are presented in Appendix B

‡Several of the foregoing and following issues are addressed by Bonder.[52]

and "models," with existing developments as they are, seems premature and unjustifiable. Behind this divergence of viewpoints lies the fact that our system of higher education in the sciences has tended to stress a solid grounding in some particular established discipline to the exclusion of fostering an awareness of the state of knowledge or the shape of things in other science fields.

Only within the last two or three decades has a new scientific "middle ground" emerged in the form of research areas such as control theory, information theory, decision theory, bioengineering, artificial intelligence, etc., that seems to herald a gradual shift in scientific thinking to cut more dramatically across the old traditional disciplinary lines.

Coupled with the mind-set that is associated with the pursuit of a particular discipline, another set of factors affect the degree to which individuals trained in the sciences may tend to accept or reject something as heroic and "unscientific" as the modeling of combat. These factors are an individual's fundamental values and the standards of excellence by which he shapes his own work and judges the work of others, the impact of the culture in which he is reared, the intensity of his curiosity about the social and material worlds and his sense of reality as it pertains to each.

Thus, it should be easy to appreciate the variability in attitudes among individuals that can result from interactions with their social and educational environments as noted above. This is *particularly* true when they are assessing the validity or utility of a simulation model of theater-level conflict, which is without substantive scientific foundation.

If there is disagreement or a lack of consensuality among trained scientists in these matters, one might well imagine the misgivings and confusion the situation evokes in the minds of lay people, many of whom have responsibility for decision making in which models and their outputs play roles of varying importance. One can only begin to appreciate the doubts and uncertainty that emanate from a continuing drone of technical controversy as staffs attempt to explain the methods and results of their analyses to decision makers and to peer groups. Then, too, the touting of the use of mathematical models somehow gets coupled with the notion that a "scientific method" of some kind is being employed, creating still further confusion. In the end, the decision maker can only apply his own experience, intuition, judgment, and common sense to the problem solution.

In all of this, we confront a problem area with which is associated a definite body of knowledge that is anchored to reality through mainly an accumulation of historical evidence and the scattered pieces of data from other sources. There is ample room and good cause for open and honest questioning, discussion, and disagreement regarding the validity and utility of our analysis techniques, the limitations that should properly be placed on their application, and methods by which the techniques can be improved. That grave concerns and considerable controversy exist over these matters within the analysis and user communities is borne out by much of the discussion at the workshop. Still, and perhaps not surprisingly, there emerged from the meeting a strong consensus that the building and exercising of combat models has utility to the decision making process, albeit constrained. The upper limits on this utility are far less clear.* These would depend on the nature of the decision the model is supporting and how this is formalized into a problem for the computer. However, under any given set of conditions, there is unlikely to be consensus on the "hard" limitations of model utility. There can be no judge or jury in these matters because there exists no law. Instead, we find that as problems associated with the indeterminate aspects of this ambiguous subject appear, they are fielded and addressed in judgmental fashion. This, of course, is a "soft" and highly subjective procedure. Given this reality, the prevailing reluctance to accept the results of these endeavors without gnawing reservation is both legitimate and understandable.

*Model utility is most often described as "providing insights" into the innermost workings of a complex process.

An additional complicating factor has to do with the "advocacy" or "proponency" issue that was raised by several speakers at Leesburg* and is addressed by Stockfisch in Reference 58.† This issue is concerned with avowed attempts by activities (organizatious or people) within the DoD to use models and their data bases in manipulative ways to justify certain specific programs or procurements that an activity wishes to pursue. Thus, into what might be described as intuitive but unbiased "best effort" notions of what warfare is about (as formally depicted in mathematical models), we now introduce the possibilities for infusion of some preconsidered, deliberate legerdemain into the design of models, or the manner in which the models or their input data are used. Since, in a scientific sense, the fictional results in the former case can in no way be rigorously distinguished from those in the latter, advocacy possibilities and suspicions that are aroused serve to further lower the credibility of modeling. That combat simulation is particularly vulnerable to deliberate attempts to bias or distort gaming outcomes should be clear. It is not always easy to recognize such attempts unless they are outrageously flagrant, and it is even more difficult to identify precisely where and how in the process the mischief is being wrought. Since definitive and rational adjudication is not possible, attempts at resolution usually degenerate into argumentative debate.

Another factor is worthy of attention — the strong competitive spirit within the model building community. At times this spirit stridently manifests itself in the "selling" of a particular model's attributes over those of all rivals. Since there is no way to *prove* the superiority of one model over another, it is helpful in this environment to point out the shortcomings in a competitor's offering.‡ Unfortunately, this raises the noise level in what is already a disturbingly noisy background and may be damaging to gaming endeavors if only because the criticisms emanate from within the analysis community itself.

Accepting, then, the premise that most analysts do indeed recognize the limitations of their models, are these so severe as to obviate any utility that they might afford? The answer is generally "no." For example, the purposes to which games are put in connection with force planning are the following according to Goad (Reference 53, p. 194):

- Weapon systems analysis — e.g., what is the contribution to overall force effectiveness of long-range antitank missile systems?
- Development of tactics — e.g., what tactics should be adopted by the defense when employing remotely delivered mines?
- Force structures problems — e.g., what is the best mix of antiarmor weapons for defense against an armor-heavy threat?
- Studies of force deployment and employment — e.g., where should corps and army group reserve forces be deployed at the initiation of hostilities and how should they subsequently be employed?
- Determination of force levels — e.g., what NATO force levels are necessary in the 1985-95 time frame to deal with projections of Warsaw Pact capabilities at that time?

Most analysts would agree that the first four classes of problem in this list *can* be solved with a reasonable model, a valid data base, and the proper measures of merit.§ This is simply because *relative* measures can be applied to the outcome of model "experiments" that can be conducted in the first four cases. For example, for the first, a battle or engagement is run with

*See for example, Schneider (Reference 1, p. 209), Kapper (Reference 1, p. 239); Stockfisch (Reference 1, p. 236).

†See also Reference 1, Stockfisch pp. 236-237.

‡This statement is in no way intended to denigrate some of the more thoughtful critiques of models as exemplified by References 17, 44, 49.

§These requirements are far easier to state than they are to satisfy. The argument being presented is admittedly more conceptual than realistic.

and without a particular weapon system present in the rank and the differences in outcomes are noted. The same thing is done for the second case, trying different employment concepts for mines, while again observing differences in outcomes and similarly for the third and fourth cases where alternative weapons mixes and force deployments are respectively run in model exercises.*

In the last case, the force level problem, disagreement among analysts is likely on the applicability of models.† The first four cases are involved with selections in *kind*, while the last case involves a determination in *degree*. Force levels must be defined in terms of absolute numbers and, in this instance, all of the caveats previously discussed pertaining to the shortcomings of models come into play. Consensus on the greater acceptability of using heuristic models to measure relative differences in outcomes, as the models are used to examine varying procedures or configurations in a combat context, stems from an implied assumption that *unknowable* errors will equally effect the results being compared. In effect, then, these errors "wash out" in a relative comparison. While the absolute values of the outcomes have no credibility, the absolute value of the *differences* in outcomes might hold approximately in the real world (see discussion in Reference 1, Bracken, Goad, pp. 28, 29). We don't, of course, know for certain that this is true. It is only a hypothesis. But, at the same time, neither can this hypothesis be invalidated a priori on logical grounds.

In brief, then, through the use of appropriate gaming models, we can ascertain analytically with comforting assurance, the simple fact that configuration or procedure "x" is better than "y". A measurement of *how much better* "x" may be than "y" is riskier. Finally, a valid measure of the *value* of "x" or of "y", in some absolute context, is out of reach with the techniques discussed here. As purely intellectual activities, of course, all of the above three classes of questions can be tackled with gusto by analysts — and often are.‡

Relating to these matters was a significant exchange that occurred among several of the workshop participants at Leesburg (Reference 1, pp. 146-147). It was initiated by Helmbold who observed that analysts are known to believe (or act as if they believe) in the predictive powers (in some absolute sense) of their models. This issue caused a flurry of animated discussion wherein belief in absolute measures with models was stoutly denied by some of those present while others supported the validity of Helmbold's observation. Unfortunately, because of time constraints, the discussion was prematurely terminated.

There are, to be sure, examples of instances in which analysts who purport to know better seek to obtain absolute measures of important variables with models simply because there is no other way possible of estimating their values: Such an example was presented in the workshop in connection with the MCSSG study (Reference 1, Goad, p. 26) in which, among other things, the predictions of three theater models on the duration of a war in Europe were being examined in connection with the effective introduction of U.S. reinforcements. All participants in the study were well aware that a valid, absolute measurement of the time variable is no more possible than the measurement of any other combat variable. Yet, perhaps it was nothing more than curiosity that impelled the investigators in this direction to see how the results might compare with the only other option available to them — that of expert judgment.

There may be instances where analysts do indeed become beguiled with the power of simulation and the capacity for elaborate computation afforded by the high-speed computer (down to fairly-minute details of the combat process) to the point that their make-believe

*Because of the two-sided nature of gaming, the tasks outlined are not as trivial as they may sound. With changes in a defense posture, an enemy is likely to alter his mode of attack, and such changes should be properly reflected in the analysis.

†That is, the *formal* application of models, which is not to say that one cannot derive force levels (out of curiosity or for their entertainment value) in the privacy of one's own computer center.

‡See Reference 1, Goad, pp. 25, 26, for further comments on the issue of model utility.

world of modeling takes on a real world aspect. Hopefully, the number of people so afflicted is very small.

One would hope that the observations made here on the utility of gaming fairly represent the consensus of thinking in the analytical community. As one moves away from the community into various levels of the decision making hierarchy, the general awareness and understanding of these rather subtle notions appear to fade rapidly. It is as if the message concerning the true nature of these intellectual exercises and their explicit limitations (as we understand them today) has not been spread with enough energy, persistence, and consistency among those who are in any way involved with them; this, despite the publication of thoughtful papers and articles on the subject as exemplified by Reference 57. If one were to do so, some "unselling" of these gaming activities will more than likely be necessary, as much as this tends to conflict with the natural ebullience manifested by the model builder for his craft.

Another natural reaction among the model development community also stems from the unsettled, unproven foundations on which computerized war gaming has been built. This is the propensity for the introduction of more and more detail into combat models, usually at the suggestion or insistence of experienced military officers who might argue that without the treatment of some specific factor or other in the model, one does not have a proper representation of the combat process. Just how much of such material might be fundamental in shaping the outcome in a combat model and how much of it might merely go into immortalizing in computer code the reflections of an individual's combat experience is, of course, not known. The analyst may well argue that sensitivity analysis could provide the answer, but more often than not such analyses are not conducted. If the suggested additions seem reasonable, or if, perchance, contracts might hang in the balance, then into the model they go.

Of significance here is the almost subliminal pursuit of a goal which, in the absence of any other hand-hold on the problem, reflects the need to converge on reality through the eventual simulation of every finger on a trigger and every round of ammunition fired. As a result, models tend to become more and more complex and their appetite for input data increases commensurately. This, of course, is in direct contradition to the tenets of systems analysis in which the objective is ultimately to isolate and identify the parameters "that really matter"; those that have a first order effect on system behavior. Without a laboratory in which to conduct experiments and without any fundamental theoretical knowledge, the traditional systems analysis approach then appears to be unattainable, and we are left somewhere in mid-flight between two worlds, so to speak, without enough computational power, reliable data, or real knowledge about the dimensions of the problem to see us through to our destination. In the meantime, the opacity, complexity, and costs of the models that are being developed are great enough to cause frustration among those who support and use them.*

Nevertheless, it seems that pursuit of combat modeling is justified on the basis of some demonstrable measure of utility derived in the past — and some hoped-for display of it in the future. At this stage, it is important that we understand the state and condition of combat gaming — precisely where it stands as a scientific undertaking — to illuminate the fundamental methodological difficulties attendant to combat modeling and how these, in turn, can lead to further complications and bureaucratic commotion when the models are applied to problems of national defense.

*See, for example, Reference 1, Bonder, p. 28

4.3 From Reality to Abstraction: The Missing Link

Much has already been said about the absence of ties between computer war gaming and reality. It has further been postulated that this lack of significant coupling between the two fosters and abets much of the contentiousness that surrounds computer gaming activities. Under the circumstances, one might well ask why a serious, systematic attempt is not made to bridge this gap, or, putting it another way, to forge that missing link between the real world as we observe it and the abstract world we have created, populated as it now is with a variety of models representing our perceptions of war and combat. The answer to this may be simple in that to do so represents an undertaking of staggering difficulty, both as to the concept of the form that missing link should (or must) assume and the steps that must eventually be taken to shape it.

The problem of coupling our model abstractions with the real world is extremely important. But in three decades of combat model development little research has been performed that reflects an interest or even some semblance of continuing curiosity about what the relationship between the models and the real world of combat might be.

Among these efforts are the several attempts to verify Lanchester's equations of attrition (see Section 3.2). These attempts can be characterized as sporadic and inconclusive (it should be noted that the attrition process, as modeled by Lanchester, is only one of six combat processes identified and discussed in Section 3). While the enrichment and extensions of Lanchester theory, discussed, earlier still apply to the attrition process per se,* their apparent thrust has been towards representation of the remaining combat processes (at a local level) and the effects of these processes on attrition. In some sense, then, the extended forms of Lanchester's equation have the necessary ingredients to qualify as true models of combat in a broader context, although their flexibility in representing wide-ranging processes such as C^3I and combat support is sharply restricted when compared to the use of simulation techniques. In any event, the attempts to verify Lanchester's equations (usually in their simpler forms) constitute perhaps the most significant effort to date to explore the form and substance of the missing link.

Another effort, which approaches the problem from a unique but highly logical direction, is the QJM effort (see Section 3.2), which derives an empirical formulation of battle based on extensive study of military history. Being empirical and static, it seems to hold little in the way of a relationship with the dynamic cause and effect or process models, but the actual extent of such a relationship deserves further investigation.

An isolated primary effort to verify combat models† by field experimentation is the TETAM (Tactical Effectiveness of Antitank Missiles) experiments conducted by the Army's Combat Development Experimentation Command. The many difficulties inherent in this type of effort apparently forced a contraction of objectives to a comparison of line-of-sight or weapons intervisibility capabilities between actual terrain and the digitized terrain of the CARMONETTE model.

The attempt to calibrate our mathematical models against reality constitutes the process of model verification or validation.‡ It seems that this process should not be narrowly channeled to the search for quantitative verisimilitude between models and reality (although such an outcome would indeed be nice). Rather, our objective is to ascertain the difference

*Apparently in recognition of the fact that attrition is one of two primary processes occurring at the interface of opposing forces. The other, of course, is movement which in its broadest context has never been treated beyond "breakout" in an analytical model.

†DYNTACS, CARMONETTE, Bonder IUA

‡This particular subject did not receive earnest consideration at the Leesburg meeting (even though it had been specifically identified in the plan for the meeting as a topic for discussion). From the comment made by Bednarsky (Reference 1, p. 227), substantiating the observed behavior pattern at the meeting, one can only assume that in the minds of the participants, the problem was so difficult as to be unapproachable, making any serious consideration of it seem unreal

between outcomes as a calibration measure in a broader sense, noting whether such differences were small, moderate, large — or vast — and whether there is any consistency in the difference patterns emanating from various combat situations.

The intent to *measure* differences in any sense introduces consideration of an "error" concept that is borrowed from the natural sciences; that is, a breakdown of error (*or outcome* differences between models and reality) into the components of *systematic* error and *random* error.* Consideration of random error as it pertains to armed conflict in the real world, poses the first of several difficult conceptual problems that plague the type of effort being discussed — the problem of determining in some manner the statistical characteristics of warfare; that is, *some feeling* for the form of the outcome distributions. Considering that armed conflict represents a societal dislocation of severe proportions, which under a given set of circumstances comes (fortunately) in sample sizes of *one*, the notion of obtaining statistical data from the real world confronts us with a frustrating problem. Yet we must find a way to derive measures of mean outcome and outcome variability (always under the assumption of rational, although not necessarily optimal behavior on the part of the opponents) to isolate the randomness of the real world. Is it very large or is it very small?† At present, there appear to be proponents of both positions but we do not have any solid information on which to base an answer to this question. Without such information systematic errors cannot be separated from random errors and attempts to measure the outcome differences between models‡ and reality essentially become meaningless exercises. This problem is further addressed later.

Finally, we come face-to-face with evidence reflecting an astonishingly low incidence of sufficient thinking or concern (as reflected in the literature) about the broader concept of a combat *theory*, recognizing that were such a theory to materialize, we should in fact have found a substantial piece if not all, of our missing link. In an imaginative paper, H. K. Weiss[59] first put forth the need for a "theory of combat" in 1953 and outlined an approach to such a theory oriented about Lanchester's equations (these having been exhumed only a few years previously by Koopman, Morse, and Kimball from their quiet resting place of a quarter-century or more). Weiss also went on to address a theory of morale (!) in a unique way and to express the need for a theory of communications.§ The "theory" field then apparently lay fallow until very recently when another attempt[60] was made to investigate the dimensions of a theory of combat and outline some approaches to developing one. In the intervening years, the need for a theory has found expression many times with unfortunately little in the way of an approach or a procedural road map being offered in conjunction. In fact, at the Leesburg workshop, it was recognized that certain difficulties with the modeling of combat stemmed from the lack of proper theoretical underpinnings.** At the same time it seemed as if the enormity of the problem of developing a theory was duly appreciated.

In reflecting on a "theory" of combat or war, we are basically concerned with "a coherent group of general propositions used as principles of explanation, for a class of phenomena" †† in this instance the phenomenon of combat. Such a theory could assume an inestimable number of forms, and it might, but assuredly need not, be mathematical. Virtually all of the data available to us that defines a body of knowledge concerning armed conflict is the legacy

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*For a discussion of model errors, see Niemeyer and Reidelhuber[61].

†A large variability would seem to support the observation that ground combat is more of a sociological than a technical phenomenon, while the converse would be true if the variability were small.

‡Most models are "expected value" or deterministic models. What, one might ask, is the form and variance of the distribution to which the "expected value" solution pertains?

§Here, in reality, Weiss was addressing an embrionic form of the C^3 problem.

**See, for example, Reference 1, Welch, p. 7, Kapper, p. 20; Helmbold, pp. 140, 141; Niemeyer, p. 145; Stockfisch, pp. 233-234.

††Definition from The Random House Dictionary of the English Language.

of recorded history. From this body of knowledge have emerged certain patterns of occurrences in warfare that inspired military theorists such as Clausewitz, Jomini, Ardant du Picq, Fuller, and others to contribute collectively to a set of general principles known as the "Principles of War"* and to make various other qualitative observations about the art of warfare that have come to be regarded as "verities of combat." Lanchester's mathematical approach to studying a particular aspect of war (see Section 3) appears to have been the bellwether for a procession of mathematical models and simulations of combat that were developed over the past three decades.

Thus, we have histories of combat from which certain quantitative data have been derived (largely by Du Puy[30] in the United States), many essays on combat principles by military theorists and historians, some data from combat experiments and exercises, a variety of mathematical models of combat (unverified for the most part), and at least one empirical model (QJM) based on the study and analysis of history.[30] All of these contain measures, large and small, of those ingredients that go into the development of a combat theory.† But the many and varied pieces of this combat puzzle have not been systematically examined for compatibility and complementarity. This lack probably arose from the interdisciplinary barriers discussed above and the inherent difficulties (technical and conceptual) in such an undertaking.

Because there is constant pressure for sounder, more valid methodology reflecting the needs of those in the defense community concerned with force and weapon/support system evaluation and planning,‡ it would appear that the most salutary approach to theory development would be one that was intimately connected with model verification, discussed earlier. Thus, if one is to treat a theory of combat as a significant part of the model verification process, the selection of approaches to such a development become more sharply constrained. Since the models themselves are quantitative and mathematical in nature, the theory should likewise be mathematical in form. Furthermore, the models, whatever their shortcomings, do indeed stand as hypotheses; that is, as hypothetical and abstract representations of the structure of combat as it occurs in the real world. This fact cannot be emphasized too strongly, for the models that have been developed, all of which reflect a rather wide variety of approaches, are very much a part of the existing body of information and data from which a theory of combat might evolve.

Consequently, a model-centric approach, or one that treats an agglomeration, in some sense, of existing combat models as a point of departure, may constitute a judicious and rational procedure. With such an approach, one might look for commonality of combat structures as they are represented in existing models and simulations (see, for example, Figure 3) and correlate this common model structure (an abstraction) with structures that are suggested or implied by the conduct of battles as recorded in the annals of military history (reality). If the structure of combat employed by our models can be confirmed or verified to a reasonable degree, the entire combat operation will have decomposed (somewhat inexorably by the correlation process) into a series of cause and effect loops that are, to a large measure, interactive. To these loops one can then apply the concept of the elements, processes, and outcomes operators discussed in section 3.2, and Reference 60 (see Figure 6 and Table 2). The

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*The principles that are traditionally identified are those of objective, offensive, simplicity, unity of command, mass, economy of forces, maneuver, surprise, and security.

†The steps in the development of scientific theory are normally described as observation, identification of observable qualities, experimentation, data collection, data analysis (organization of expermental results and derivation of empirical laws) and formulation of general principles (theory construction).

‡Evidence of this can be seen in the unending (and perhaps increasing) use of models in studies that are used to support decision making at all levels, despite recognized model imperfections. Short of the pure exercise of judgment, there often are no other means of addressing or supporting some of today's complex decisions.

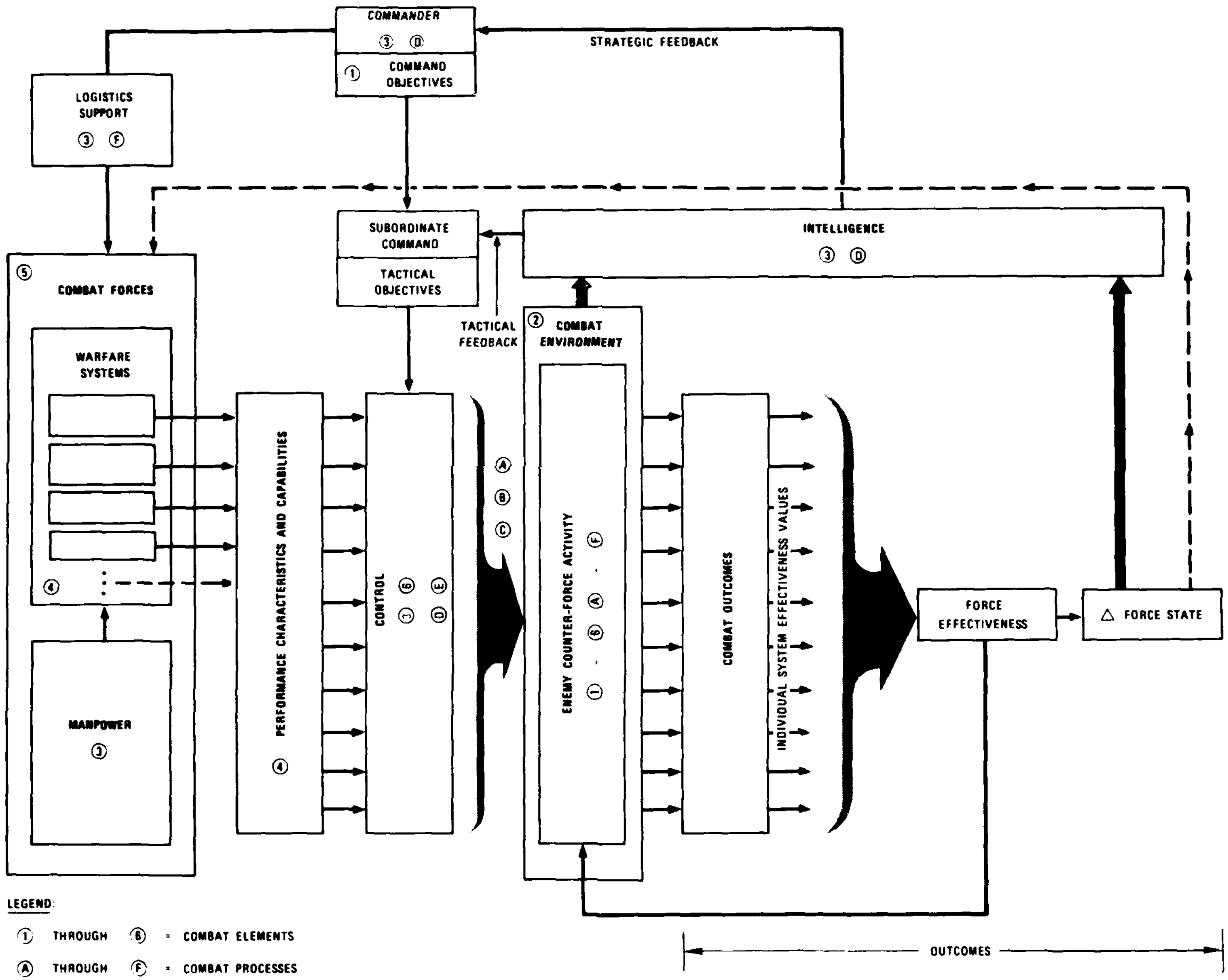

FIGURE 6 STRUCTURAL CONCEPT OF COMBAT AND RELATIONSHIP TO ELEMENTS, PROCESSES, AND OUTCOMES

Table 2

ELEMENTS AND PROCESSES OF COMBAT

Elements

(1) Combat circumstances; initial objectives and missions (both sides)

(2) Natural and man-made environments in the area of operations

(3) Human resources, numbers and characteristics

(4) Material resources,* numbers and characteristics

(5) Organization and structure of opposing forces

(6) Tactics, doctrine, and operational concepts

Processes

(A) Attrition

(B) Suppression

(C) Movement

(D) Command, control, communications, and intelligence (C^3I)

(E) Combat support

(F) Combat service support

*All of the equipment and devices for the waging and the support of war.

employment of closed form, analytic expressions (to the maximum extent possible) in representing the process functions that relate elements to outcomes is to be recommended for, aside from the computational transparency it affords, the effect of the elements (independent variables) on processes and outcomes can be assessed directly. In this manner combat operations of varying size can be treated piecemeal, hopefully permitting some or all of the mathematical "pieces" to be compared with their historical counterparts as well as affording a means for some form of cross-correlation with empirical methodologies such as the QJM.*

Note again that, in the context of the above approach, the Lanchester laws only pertain to the attrition process (Table 2). There remains, of course, the task of determining the effects on attrition of the other five combat processes (i.e., suppression, movement, C^3I, combat support, and combat service support) and, what is more important, the impact of all of these processes on "outcomes", defined in some meaningful way. Here, in fact, is an excellent example of what might be considered the point of the entire exercise outlined above; namely, what are the interactions among variables and processes and which of these are drivers of the outcomes under what particular set of circumstances?

*A broad formulation of this concept in mathematical terms is presented in Appendix C

Other approaches to the development of combat theory* may offer the same or greater promise. Clearly, the matter presents a challenge that requires further careful thought. It should benefit greatly from the exchange of ideas and concepts among concerned researchers. Consequently, any extended discussion of the "approach-to-theory" issue is premature here.

But whatever approaches are taken, they will be constrained by data that are or can be made available. The possible sources for data (pertaining to the past, present, future) germane to the analysis of combat are:

a. National archives

b. Official military histories

c. Field/fleet/air exercises

d. Combat experiments

e. War games, models, and simulations

f. Operational test and evaluation (OT&E)

g. Proof tests

h. Engineering laboratory tests and design studies.

As noted by Taylor (see footnote p. 33), (a) and (b) are sources of real combat data while (c), (d), (e), and (f) are sources of simulated combat data. Data for the *technical* characteristics and performance of military equipment are represented in (g) and (h).

Sources (a) and (b) provide data from the past; (c), (d), (f), and (g) with data reflecting present and near-term future capabilities; and (e) and (h) identify data sources that can provide a window into the more distant future. Considering the range and sweep of data required to model ground combat (and the depth to which such data must be defined), it comes as no surprise that all of these sources collectively are unable to provide complete, consistent information in sufficient detail to meet the needs — and this quite irrespective of whether interests are focussed on the past, present, or future. Thus, for example, if one wishes to use historical data in developing a theory of combat, or in deriving inputs to a combat model, there will be disheartening discrepancies between what is needed and what is actually available.† So one is forced to structure problem-solving procedures and techniques around the data that are or can be made available.

Data sources (a) and (b) are, of course, historical. Generally speaking, data from the national archives are voluminous but patchy and disconnected in their coverage. These data gaps are revealed only after one sifts through mountains of the material. Official histories, on the other hand, rarely address areas of combat or treat levels of detail that are the major concerns of modelers and analysts (i.e., combat weapons and equipment, troop lists, etc.). Whatever our sources of historical data, our information of enemy force characteristics and activities should be comparable in detail with those of friendly forces. This, unfortunately, is not always the case.

McQuie[62] aptly describes the difficulties inherent in extracting data from historical records that are appropriate for application to mathematical modeling. Extracting the information from historical records for both sides in a conflict is an arduous, time-consuming task that, according to McQuie, should be entrusted to *professional historians* who (if they are so inclined) can often conjecture and make reasonable guesses to fill holes that are discovered in

*For further discussion see Reference 60, R. K. Huber "Approximating a Theory of Combat," Appendix C, and J. G. Taylor "A Review of Some Previous Attempts to Establish a Theory of Combat," Appendix D

†It is doubly unfortunate that the chroniclers of warfare through the first half of this century were unable to foresee the future needs of operations analysts and that even in more recent conflicts when these needs were better known, the exigencies of combat operations mitigated against attempts to meticulously gather data in the field.

the data.* This introduces an element of judgment in building the yardstick with which we would hope to calibrate our models, but there are no other alternatives open.

Since historical combat data are the only form of *real* (as opposed to simulated) combat data, greater efforts are needed in archival research and the analysis of military history, difficult and time-consuming as these activities may be. Without such expenditure combat modeling will probably remain little more than Bonder's "intellectual activity" with minimal ties to reality.

McQuie makes the following observation about ground combat, which corroborates earlier statements made in this paper:

> "It has been remarked that Army problems would be easier to analyze if only battalions had rudders. Since they do not, more variables have to be considered than with Navy problems which are essentially those of a few large pieces of equipment.
>
> In ground combat, too many people are going [in] too many different directions for the traditional tools of statistical analysis to provide much insight. The implication is clear: the study of ground combat is essentially a social science like economics or sociology, and not a branch of engineering like the study of air warfare."

He notes that mathematical techniques have been developed in the social sciences for analyzing this type of problem, citing linear programming, the discriminant function, multiple regression, factor analysis and network flow analysis, but further observes:

> "The shortage of data about actual operations is so acute that these tools generally cannot be used in a meaningful way. No matter how complex a method of analysis is employed, it will not compensate for information that is not there."

Data source categories (c) and (d) are complex, cumbersome, and costly if one views them solely from the point of view of combat modeling support. The problems here arise from disparities of immediate purpose and lack of realism (relative to actual combat). Combat exercises (see Reference 1, pp. xv, xvi) are conducted to train personnel and to evaluate combat readiness, while combat experiments are performed largely to evaluate equipment performance in an operational environment or to develop tactics. In the face of some rather well-defined objectives, then, there is an unwillingness in the military to tolerate interference with these activities by having to accommodate additional requirements to gather data in support of combat model development or verification. This is particularly true if these requirements are poorly conceived or scattershot and are furthermore incongruent with customary or routine objectives and data gathering procedures. Ironically, guidelines for establishing meaningful data requirements are best provided by having access to a proper model; yet, in this instance, the development of the proper model depends to a degree on having access to the very data we seek. Thus, in a sense, we face a 'chicken and egg' situation.

In addition, combat exercises or experiments can never quite capture the true 'life or death' flavor of actual combat. This, of course, affects the authenticity of the human behavioral factors that derive from a simulated combat environment.

While these difficulties are not altogether insurmountable, the extensive use of field experimentation in the future to support combat modeling is unlikely. This is particularly true of the upper levels of conflict (theater, corps, division) in which the scale of the exercises is so large as to make them unwieldy in the extreme. Even at the lower levels, service attitudes towards the importance of obtaining data for combat models (for their inputs and

*With the exception of the work done by Du Puy, there is a dearth of historical analysis in the United States, where there appears to be a general disinterest in history and the information it might hold for the operations analyst. This is in contrast to the Soviet who "appear more concerned with the quantitative aspects of military history".[62]

their verification) must change significantly before anything meaningful can be accomplished.*

In summary, we can look to (c) and (d) to provide us with some sorely needed data and information at the lower hierarchical levels of combat only if the participants can be psychologically induced or motivated to react more nearly as they would under real combat conditions and if there could be a careful, well thought out program of experiment design with the clear delineation of those data elements being investigated. At best, field exercises and experiments would appear to be capable of providing some distinctive (yet spotty) support to the model verification process.

Data source category (e) affords the most flexibility and accessibility for obtaining input information for models of higher level combat. However, it becomes readily apparent that war games, models, and simulations do not in themselves constitute adequate techniques for generating input data; unless the games and models have been verified or validated in some manner, they will suffer from the very same deficiencies that plague the larger combat models they presume to support. War games (free-form) as a separate and distinct category of technique must use a set of rules derived from subjective, empirical, or mathematical "models" of force/counter force activities to enable the referees to establish an outcome for such activities. Here, again, the verification of the outcomes obtained in this manner is an important consideration. When we think about data sources described by category (e) we are, in effect, moving towards the concept of a model hierarchy, and it goes without saying that *all* models in such a hierarchy must be verified if a validation of the entire process is to be realized. This hierarchical structure, however, affords us a ray of hope in seeking support from combat experimentation because it is far more manageable and feasible to verify models and constructs at the bottom of the hierarchical ladder than it is at the top.† At least, under such circumstances, we are certain to gain greater confidence in our data bases even though we may never be able to verify our models of *large-scale* combat with field exercises or combat experimentation.

With data source categories (f), (g), and (h) we have crossed a threshold where the emphasis is on *systems* effectiveness and performance and *systems* engineering rather than on *combat* operations and outcomes. In fact, the "engineering" orientation becomes more pronounced in going from (f) to (h). Operational test and evaluation (category[f]) is presumed to provide some measure of the overall effectiveness of a particular system against stylized threats in an otherwise benign environment. Category(g) produces for us, by actual testing, the realizable performance envelopes for military hardware under varying climatic and battle conditions irrespective of an enemy presence. Such characteristics as the maximum speed or rate-of-climb of an airplane, or the muzzle velocity, trajectories, or target-dependent single-shot kill probability of a howitzer are examples of performance data that can be obtained in this manner. Finally, we have recourse to category(h) whenever our interests are focussed on future systems or systems concepts in advance of prototype hardware availability, for it is from engineering studies and laboratory testing that estimates of future system characteristics can be derived. The "verification" of this type of data by proof or operational testing can only await subsequent developments in a systems program.

From the foregoing discussion, it should be clear that no single source category of data can possibly satisfy the verification needs of high-level combat models. In fact, even when one considers all sources — (a) through (h) — in combination, serious deficiencies are found in the coverage and quality of the data that are available today. Even more disheartening,

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*Data gathering for modeling purposes must be given reasonable yet comparable priority with the evaluation of systems and tactics, the conduct of training, and the assessment of readiness.

†Remembering, of course, the aforementioned caveats that apply in general to exercises and experimentation.

however, are apparent shortcomings in the combined ability of these sources or techniques to ever provide us with what we truly need (from a scientific standpoint) in the way of confirming data and input information for our models. While some of this information, then, may forever elude us, there do remain additional large measures of data but whose acquisition will require the expenditure of enormous effort.

How then, to proceed on any quest to find the "missing link"? The most straightforward approach, and perhaps the most promising, appears to be to decompose the problem into a series of steps. In this process, one first must recognize, as a point of departure, the position of history as *the* source of *actual* combat data, and exercises/experiments as a useful secondary data source limited only by the extent to which such exercises/experiments reflect simulated rather than actual combat. Additionally, in the world of modeling, two fundamental classes of model are acknowledged: analytical or mathematical models, and simulation models. For the most part, both are dynamic, cause and effect types of models. Finally, a class of empirical methodology developments (exemplified by the QJM) exist that are derived from combat histories and are generally static constructs.

Within this framework of models and data, research might start with a methodical comparison of prominent simulation models of combat at several levels of combat scope or size of engagement. The same reference data bases (commensurate with the scope of conflict) and reference scenarios (derived from historical battles) would be employed in the comparison studies with particular emphasis being placed on the various ways that different models treat the elements, processes, and outcomes of combat (see Section 3.2) and the relationships among them. The differences in such treatment among the models should be noted and analyzed.

As a parallel effort, an attempt should be made to derive an analytical combat model (or models) of conventional ground/air warfare at a level of force aggregation corresponding to the division level*. Again, the relationship of combat outcomes to elements and processes should be the focus of attention and the results of this work should be compared with those from the study of the simulation models.

Again, paralleling and keeping pace with the above developments should be historical research to derive the best data bases attainable for all levels of combat and to provide a basis for validating or modifying the *structure* of combat established for the modeling activities (as hypothesized, for example, in Figure 6). It would seem important in the work devoted to the development of data bases that factual information be clearly and carefully differentiated from the researcher's estimates, judgments, and hypotheses — to the maximum extent that this can be done.

A final logical step in this approach would be to relate all of the analysis and simulation work outlined above to the combat process and battle outcomes of the real world (however imperfect our data may be). It is interesting to note that some form of the empirical/judgmental QJM, attempting as it does to qualify the phenomenon of armed conflict through information derived directly from historical records, could serve as a methodological meeting ground (in effect a "half-way house") for coupling the analytical and simulation models with some of the harder facts and figures that history has to offer. Here, again, any comparison or correlation of process models with purely empirical models (implicit in the preceding statement) must involve the recognition and identification of the "hard" and "soft" aspects of both types of models. This is particularly true in the specific instance of the QJM, in which substantial portions of the methodology depend heavily on historical interpretation, enlightened estimation, and various other judgmental factors, as distinct from historical records of "factual" information.

*This is suggested for reasons of analytical tractability and furthermore happens to correspond with a level for which historical combat data appear to be most readily available

From the foregoing discussion, it would appear that only an incurable optimist could ever hope for complete and rigorous scientific closure in this problem area of linking models of combat to the events and happenings of the real world. Rather, we might reasonably expect through some procedure, such as the one outlined above, to obtain a more precise picture of how our models compare with one another and how close or how far off the mark our modeling techniques happen to be with respect to reality. Quite apart from the fact that it is long overdue, working one's way through a convoluted maze of methodology and data, such as described here, should help us define with far greater precision than we now enjoy those areas that stand most in need of further research. Needless to say, this research will undoubtedly take us into remote, unexplored regions (from a traditional modeling point of view) in the social and behavioral sciences, historical analysis, field experimentation, and into other science areas that will inevitably be caught up in the complex web of our subject.

To lend better definition to what the results of such an undertaking might be, attention is invited to a solution concept advanced by Huber.[60] Recognizing what are perhaps insurmountable difficulties in obtaining "rigorous verification (of models) in the sense of the physical sciences," Huber proposes a relaxation of verification criteria. He suggests that models need not reproduce the results of an historical battle with fussy exactitude for his concept of verification to obtain, but that if the actual historical outcome happens to be "an element of the set of possible outcomes within the significance bounds of the simulation,"* then we will have achieved a relaxed form of 'one-case-only' verification. If this process can be repeated with numerous historical engagements, a quasiverification of the model will have been effected. While concepts such as that advanced by Huber are deserving of further careful thought, the major consideration for this discussion is the fact that "less-than-rigorous" verification may be the best that we can ever hope to achieve.

For an area of endeavor as vast and complex as the one addressed by this paper, it should be clear from the foregoing arguments that there is much "homework" to be done, and that it is long overdue. The remainder of this section will be devoted to the identification and discussion of other modeling issues that surfaced at the Leesburg workshop. Many of these must await some effort to forge the "missing link" before we can have a frame of reference that will permit the use of evaluative terms such as "worse," "worst," "better," "best" to describe the alternative approaches to analysis.

4.4 Gaming Management and Organizational Issues

In Section 3.2 we addressed an issue which surfaced a number of times at the Leesburg meeting — that of "advocacy" in the bureaucratic sense, which involves the misuse of models, the manipulation and, at times, the suppression of data to influence decision making. This can occur at all levels within the Department of Defense (DoD). Even if the extent of this practice may never be known precisely, the provision of any theoretical underpinnings to what is at present the art form of combat modeling would serve to curtail such activities in the future. If we could somehow manage to place sizable segments of the modeling process on consensible and consensual footings (to use the words of Ziman[56]), the latitude for mischief that has prevailed in the past would be reduced significantly. With no intent to minimize the pervasive, damaging effects that these practices have had on the credibility and acceptance of ground combat models in general, we might pass on to a discussion of issues that are more closely related to the management of modeling activities in the DoD and the dissemination of knowledge about the models within the community of model builders and users.

The management of models of large-scale combat, to the extent that it is to be found, usually takes the form of guidance and direction in three domains. These domains are (1) the

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*It is presumed that a stochastic model or simulation is being addressed here.

overall structure of the modeling, (2) the weapon systems to be modeled, and (3) the combat situations or scenarios (including the threat) that the models should accommodate.

Responsibility for such management has traditionaly resided in the three services (Army, Navy, Air Force) although, in the past decade, there has been diffusion and spillover into OSD activities such as WSEG,* SAGA, CCTC, PA&E. Such a trend should not be surprising in that the models, in response to certain decision-making needs, are concerned with a scale of conflict that involves the forces of all three services. Sooner or later, one would expect the focus of attention on models of joint land/sea/air operations to levitate above and beyond any single service activity and to coalesce at some level in OSD. This is what seems to be occurring, particularly with respect to theater models (Figure 5).

However, there is no nesting place within the OSD in which can be found formal stewardship responsibilities for model development and use, nor is there a "clearing-house" for the collection and dissemination of information on the inner workings of models presently in use. The development of data bases for the models,† while representing a monumental undertaking, does fare somewhat better from the standpoint of having a distinct OSD point of focus (CCTC). Yet the increasing numbers of service-generated data bases being developed for various purposes, which are particularly concerned with weapons performance, are tied into a mainstream data gathering effort such as the WCPDB only in a tenuous way. There is a distinct need for the designation of an OSD activity to monitor and guide the research necessary to establish the validity and improve the acceptability of large-scale combat models and to provide direction for the development of new models and their data bases. Responsibility for the dissemination of information pertaining to the strengths and weaknesses of existing models might also be assumed by such an activity. Lastly, but certainly of major importance, is the need for a certain amount of coordinated guidance leading to the more uniform consideration of potential trouble spots, *world-wide*, in scenario development in recognition of U.S. global commitments. This guidance should also be a function of this OSD activity.

The documentation of complex simulation models of combat presents a subtle and thorny problem in communicating the underlying, fundamental assumptions made in model design. Most models are designed and developed to solve specific problems. Unanchored as the subject is to scientific moorings, the model designer, in treating a specific problem, makes certain assumptions in his model about the variables to be included, the emphasis and the degree of resolution required to accommodate the problem, and the algorithmic representation of the combat processes. Once such a model is developed, particularly if it represents a complex undertaking, it is retained for more widespread application. When the model is applied to a new problem (other than the one for which it was designed), it is often necessary that *all* the assumptions made in designing the model be known to properly assess some possible new-found application. Unfortunately, the model documentation is such that one can hardly trace the layering of the assumptions that have been made in creating the model because, despite formal requirements (see, for example, Reference 63) for model specifications and manuals, the type of information alluded to here usually resides in the head of the individual who develops an algorithm or creates the model. Unless voluntarily recorded for all the world to see (and, perhaps, criticize) there is no formal mechanism in model documentation procedures for extracting information at this level from analysts or model developers. More often than not, this type of information can only be obtained through personal contact with the model designer, and should he or she have moved on it is unlikely that this information can ever be uncovered.

*Disestablished in 1976

†See Reference 1, pp 208-229, for a description of two major data base development efforts, the Force Planning Data Base and the Weapons Characteristics and Performance Data Base (FPDB, WCPDB)

The few general purpose models that have been developed pose the same difficulties regarding the identification of underlying assumptions. However, with these models, there is another form of difficulty that stems from gaming being uncoupled from reality, as discussed earlier. Without a focussing mechanism, such as is usually provided by a model having to address the dictates of a specific problem, the model designer is instead trying to accommodate *all* conceivable problems related to a warfare area. With no theory to guide him and in trying to satisfy the anticipated needs of everybody, his model is likely to fall short of meeting anyone's prerequisites ("an all purpose model is a no purpose model").*

Thus, there is a distinct problem with the manner in which "scientific computer programs" are documented in DoD having much more to do with the "whys" of a program than the "what". This constitutes a fundamental failing.

Additionally, when applied to different specific problems, models are frequently modified or revised but such revisions are not formally documented. Thus, several versions of a model may be in circulation at any particular time, some documented and some not (see Reference 1, p. 230). Consequently, complex models are readily "transferrable" without a great deal of deep probing and questioning, despite the ponderous (though ineffectual) formal structure imposed on the defense establishment for model documentation. As a consequence, the model developer is often tasked to run his own model in its application to a new problem on the grounds that he is the most familiar with all of the subtleties and assumptions in the construct. Deficiencies in documentation have, in turn, led to new investigatory areas of endeavor exemplified by References 27, 44, and 49.

Large-scale combat model development has been a competitive field, particularly those efforts involving nongovernment activities such as contractor organizations and FCRCs. Model builders vye among themselves to develop the "better" product with little more than intuitive perceptions of "realism" to guide them. Analytical ingenuity and mathematical cleverness are almost perceived as an end in themselves and, in some instances, strong proprietory feelings are associated with these developments. These factors, coupled with the inadequacies of documentation discussed above, tend to inhibit or impede communication among members of the model building community. Yet much of the testimony in Reference 1 suggests that there are synergistic benefits to be derived from closer working relationships and exchanges among modelers. A central overlook activity within OSD could serve a useful function in encouraging and coordinating such exchanges.

4.5 Issues Related to Model Users†

Recurring terms appear in the model user's lexicon such as "transparency", "playability", "realism", "validity". These terms, frequently heard at the Leesburg workshop, all have in common the fact that "more" of what each of them represents is regarded as "better" from a user's point of view. While they do not appear ever to have been subjected to rigorous definition, they aptly describe the factors that enhance the credibility and intimate understanding of a complex model in the mind of a staff analyst. With this confidence and understanding, the staff, in turn, can better communicate to the decision maker (with conviction!) the results obtained with the model. And, ideally, the decision maker should have a better appreciation, a sense of perspective, as to how these results should be factored into his decision.‡

Model transparency refers to the clarity of model logic and structure and the ease with which the model algorithms can be understood. One would hope for a degree of model

*See Shubik, Reference 1, p. 148

†See Dunnigan, Reference 1, pp. 136-141

‡See Dobieski, Reference 1, pp. 173-187, Tuan, pp. 187-194

transparency that would achieve this clarity and understanding in individuals that have a reasonable knowledge of military matters and who are not necessarily involved with mathematics in a professional way. Unfortunately, such is seldom true in computer gaming.

Playability is jargon for a subtle characteristic of games, whose importance is difficult to over-emphasize.* It establishes the degree to which a game player or someone who is experimenting with a gaming model becomes inexorably immersed in the game process itself. The stimulus for doing so may be purely intellectual, in that, in some sense of living the game, the individual *must* find out what has happened or is next about to happen in his game world. Unless there is visual or "mind's-eye" clarity of perception of the workings of the game and its progress, *it is not possible to create that feeling of personal involvement with the gaming event.* Map-board exercises, as in manual war games, with their visual stimuli and their relatively clear difinitions of "rules" are very strong in this respect, while automated computer games are notoriously weak. In the latter, playability can be greatly enhanced by CRT graphic displays that selectively depict the progress of a battle or engagement, and, with player-assisted computer gaming, we again can capture a large measure of human involvement in how the game is played.† With respect to playability, "One picture is worth 10,000 lines of computer printout."

Realism, as used with respect to models and gaming should be, but unfortunately is not, concerned with "correctness." Rather, it reflects the degree of success the model developer has in answering queries on whether his model treats this or that combat function, operation, or variable. Such questions are invariably based on trendy, state-of-the-art considerations and practices, on individual combat experiences, or on someone's perceptions of combat. If the factor in question is not treated by the model, then perhaps it should be added, or so goes the thinking. Of course, it is impossible to realize complete fidelity in modeling everything that actually occurs in combat. Thus, a plethora of "detail" will always remain as candidate material for incorporation into models.

The concept of realism just described is purely intuitive, subjective, and arbitrary in a "hit-or-miss" fashion. We should be concerning ourselves with selective detailing to enhance realism in those modeling areas that truly dominate the shaping of combat outcome in the real world. Thus, model realism is logically coupled to model validity and should be treated in this light.

Validity, in turn, has been the concern in much of this paper. We remain unable at this time to assess model validity. Since this problem appears to be at the root of so many of our difficulties, it literally begs for early attention.

Attempts to add realism to models adds to model "clutter".‡ Farrell has observed that clutter also results from an explicit rather than an implicit treatment of combat phenomena in modeling, in which the explicit form of modeling enhances "visibility". Transparency and playability tend to be mutually supportive concepts but clutter (and hence realism in the restricted sense of the term) works in opposition to both. Visibility, through its handmaiden clutter, also tends to detract from transparency and playability.

Yet another user concern that must be superimposed on those discussed above is the *issue of the time and costs involved in the development, operation, and maintenance of* models and data bases. Both model proponent and user activities would, of course, prefer that these expenditures be minimal. Model and data base development are protracted, highly-specialized activities with model "debugging" ranking as one of the most unpredictable of human endeavors and the acquisition and updating of data bases perhaps the most frustrating. Model operation and maintenance brings one face-to-face with documentation

*Model users are defined in the broad context to include decision makers and their staff analysts and advisors (see Section 1.2).

†See Dare, Reference 1, p 79

‡Farrell, Reference 1, p 94

issues, discussed above. Furthermore, model documentation, with its inherent shortcomings, has invariably been looked on as a model development "afterthought." It generally takes longer and costs more to produce documentation according to specifications than is ever anticipated by user or developer.

All in all, then, the use of large complex models in DoD represents a time-consuming and relatively costly undertaking. The user, in seeking the best of all worlds, would make them even more so, without, perhaps, a full understanding of the trade-offs involved among the model attributes that are believed to enhance the acceptability and credibility of model output. The key attribute is, of course, validity. But the attributes discussed are assuredly helpful in promoting a better understanding of model content and logic among developers, users, and decision makers.

Lastly, there is the user-related problem, alluded to earlier, that pertains to models and how they are affected by differences in defense planning for the different geographic regions of the globe. Much of theater-level modeling in recent years has been tied by model structure to a Central Europe and NATO-Warsaw Pact conflict. In fact, virtually all of the models discussed in Reference 1 are concerned with such conflict. Of course, the United States does have military commitments in many other areas of the world: the Pacific and Indian Oceans, the Middle East, Central and South America, the African and Asian continents (to name a few). Such global interests imply a need for model aids to decision making that would be expected to vary significantly from those that are applicable to conflict in Europe. This is largely because the concepts of military operations can change drastically from area to area. Emphasis on sea and airpower, for example, may well be called for in areas of the PACOM to replace the emphasis on ground operations in EUCOM. A forum for the periodic exchange of planning study methodologies and modeling techniques among the analysis staffs of U.S. and allied commands and the JCS/SAGA would undoubtedly prove extremely useful in fostering a far better understanding of global military planning problems and possible ways of solving them. Monitoring and coordination of such exchanges should be the function of the hypothetical OSD activity described in Section 4.4.

4.6 Modeling and Methodological Issues

In this review of the issues and problems associated with model design and development and model application, an attempt has been made to structure their presentation to permit a graphical depiction of their interrelationships. It is not possible here to assess or evaluate in truly meaningful terms the appropriateness of a specific combat modeling methodology or technique. However, one can comment on the pros and cons of those that have been employed in models, the trade-offs they entail, and their apparent fidelity in portraying actual combat.

As were the sessions at the Leesburg workshop (Sessions II and III), the discussion of modeling issues is organized into two major interdependent groupings that are each hierarchical in nature. One group concerns model and gaming structures in the broad sense of model concept and design; the other concerns combat operations and process modeling.

Figure 7 illustrates the interrelationships among structural issues in combat modeling (at the theater-level, in the instance shown). At the top of the figure is an abbreviated representation of the spectrum of armed conflict as it is observed to occur in the real world. With the support of the military planning process being a major concern of this treatise, one must recognize and accept the need for some form of analysis of the real world as the enabling adjunct to planning. This analysis (of unspecified form) must be shaped and constrained by existing or anticipated world conditions (political, economic, military), national and military objectives, budgetary considerations, etc., as shown in the figure. In the broadest of terms,

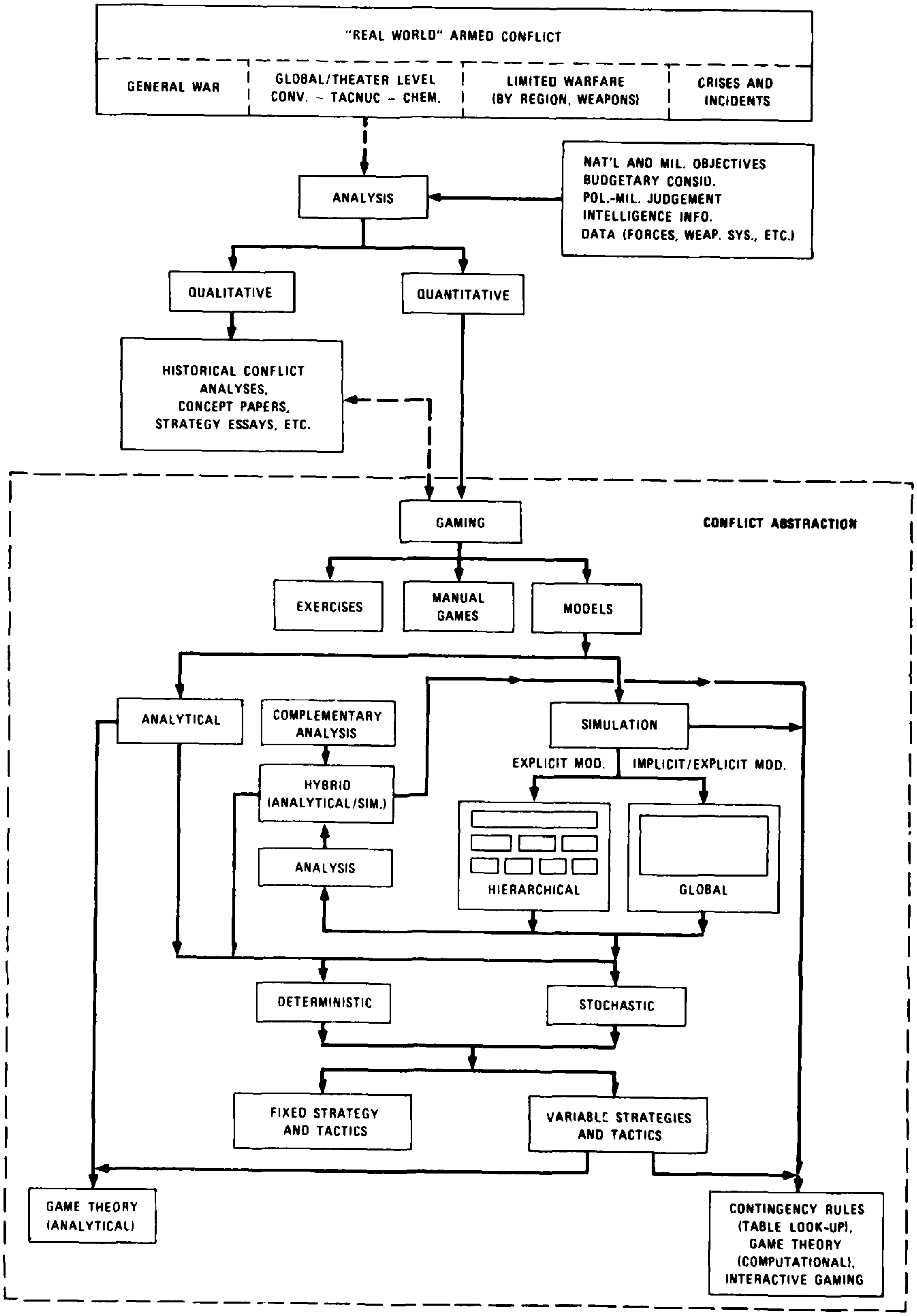

FIGURE 7 ANATOMY OF THEATER-LEVEL MODELING: I--GAMING STRUCTURES

the analysis to be performed can be qualitative or quantitative.* While the major focus of interest here is on quantitative methods, it is not to the exclusion of those elements of qualitative analysis that play a proper role† in the shaping of quantitative methods (indicated by the dotted arrow in Figure 7).

In pursuing quantitative methodology, it is by this route in Figure 7 that we enter into the realm of conflict abstraction. Unfortunately conflict abstraction is a world unto itself, for the coupling between it and the real world of armed conflict is exceedingly "soft" and can, in fact, be described as the "missing link" discussed in Section 4.3. Nevertheless, one can be assured that as long as we have a commingling of complex problems, inquisitive humans, and high-speed computers, there will always be further attempts to build models.‡

If one follows the route of quantitative analysis, it is the activity of gaming that dominates all of the efforts in conflict abstraction. Of the several forms of gaming (discussed in Reference 1, pp. xv-xviii), the primary interest here is in gaming models. However, it is apparent from the comments of several participants at the Leesburg meeting§ that gaming models should not be divorced entirely from certain aspects of other forms of gaming such as use of the game board from manual gaming to depict temporal and spatial relationships in battle (playability), or, borrowing back the human from manual gaming to play various decision making roles.

As shown in Figure 7, there are two fundamental forms of modeling: analytical modeling and simulation.

The power of analytical modeling lies in the closed form mathematical expression of vastly simplified combat equations that permit open observation of the interactions among variables and, to the extent that the models are valid, a rather quick determination of how the variables drive battle outcome. The crippling weakness of the analytical approach, however, is the tremendous rate of increase in mathematical complexity that is experienced unless extraneous detail is studiously avoided and the models are held to relatively stark levels of simplicity. The problem here, of course, is that we are not sure of our ability to identify what can be considered "extraneous detail" in the modeling of combat.

Simulation, on the other hand, affords enormous computational flexibility, opening the door to model developments of ever-increasing complexity. Unfortunately, the practitioners in simulation are no more privy to those elusive fundamentals of combat than are their brethren who are analytically oriented. Then, too, as simulation models move towards higher resolution and greater detail, their need for supporting data bases outstrips the capability to provide them. Finally, simulations (particularly new developments as opposed to modifications) are both labor- and computer-intensive undertakings and, as such, are extremely costly. But they are not nearly so costly as the cost of a bad hardware decision that the proponents of simulation claim can be averted by dint of their efforts and activities.

As a technique, simulation dominates virtually all efforts to model combat. As shown in Figure 7, two fundamental modeling structures are built around simulation techniques: namely, structures that are either hierarchical or global. There appears to be a pronounced preference at present for the hierarchical approach in simulation among models for the three services in the U.S. defense establishment and in British and German modeling.

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*Six methods for solving problems (analysis) are advanced by Chase in Reference 64. These are: appeal to the supernatural (prayer), appeal to wordly authority (the older the better), intuition, common-sense, pure logic, and the scientific method. The reader will recognize that none of the above is particularly alien to the process of analysis for planning purposes.

†We are, of course, unable as yet to define what "proper" really means in this context. Note also, that the QJM referred to several times previously represents an unusual undertaking that attempts to relate qualitative and quantitative methods in a manner that is not addressed by Figure 7.

‡At least two significant modeling efforts (e.g., STAR/TREM and CEM V/CAA) have been initiated since the Leesburg workshop.

§Reference 1, Kent, p. 81, Dunnigan, pp. 136-140, Taylor, p. 143.

Simply stated, the hierarchical approach involves a "stepping-stone" build-up of information from "one-on-one" models up through "force-on-force" models with increasing levels of aggregation. The output of a lower order model in the hierarchy serves, with proper manipulation and aggregation, as the input for the next higher level model in the hierarchy.* Here, then, is a complex train of models, one supporting another, by which we are cumulatively developing a large part of the system performance data base for the entire exercise as we proceed up the model ladder. The process of modeling at each level in the hierarchy can afford to be (and usually is) *explicit*, as indicated in Figure 7. However, the major problem with model hierarchies lies in the interfacing between models in which, as aptly described by Welch in Reference 1, one has to ensure that the data derived from one model as input to the next higher model were obtained under compatible simulated conditions. The interfacing process between models can be quite tricky to effect properly as can the process of aggregating the lower order model output to serve as higher order model input. Sometimes the latter function is performed by special processor satellite models, such as COMANEX (see Section 3.2). All in all, the use of a hierarchy of models is an elaborate process that involves more time and effort than many of its global counterparts. However, this form of modeling provides a degree of transparency — a reasonable audit trail of cause and effect — as one creates atoms from nucleii, molecules from atoms, and matter from molecules.† Also, each model in a hierarchy can play a multipurpose role by either supporting other hierarchies of models or by serving as a stand alone analysis device, thus affording significant flexibility of use.

The structure of the global simulation, by contrast, incorporates complete hierarchical sets of combat activities and operations in a single model to whatever extent one wishes. At the theater-level, for example, we can either simulate highly aggregated "force-on-force" encounters with model inputs appropriately aggregated, or we can simulate to a high degree of resolution, working with small combat units to assemble a mosaic of combat operations at theater-level. "In-between" variations of this capability are possible and perhaps useful — for example, with the so-called "zoom" concept in which a combat unit of interest and its adversaries are modeled in detail (with high resolution) while other units and battle or campaign activities are simulated in aggregated fashion (low resolution) to provide a form of combat backdrop. The global model overcomes the model interfacing difficulties experienced with sequential runs of hierarchical models in that the global model has internal to it consistent connecting logic between levels of organization and/or activity. However, it undoubtedly sacrifices some of the transparancy ascribed to hierarchical models. Thus, the modeling in global simulations can vary between implicit and explicit, depending largely on the degree of resolution employed. This is noted in Figure 7.

An "intermediate" class of model structure is also shown in Figure 7: the hybrid analytic/simulation model. This type is perhaps a more apt descriptor of many of the large-scale combat models in use today.‡ For example, models that employ differential equations of a Lanchester form to compute attrition between engaged units but that resort to simulation for modeling most other aspects of combat fall into this category. Of significance is that continuing experience with simulation may permit the expression of subroutines or certain recurrent results in closed analytic form (empirical or theoretical). Furthermore, advances in analytic modeling of processes in conventional or unconventional warfare may continue to provide mathematical algorithms that can be incorporated into simulation structures. This is shown in Figure 7 by the box labeled "Complementary Analysis." The long-term trend (as seen by Bonder) may, in fact, be back towards the development of "compex analytic" models (see Section 3.2) with the improvement in transparency that this class of modeling affords.

*See Reference 1, Welch, pp 3-73, Underwood, pp 102-107, and References 28, 51, 52

†An analogy from physics advanced by Fain, Reference 65

‡See Bonder, Reference 1, p 37-38

The next issue is deterministic versus stochastic modeling, as shown in Figure 7. Obviously the waging of war fully qualifies as a stochastic phenomenon and hence, ideally, the stochastic modeling of combat would be preferred. However, two major difficulties are inherent in this approach, alluded to in Section 4.3: the absence of suitable statistical data for combat variables that are of interest to the modeler, and the complexities associated with modeling (analytic) and the analysis of results (simulation). The paucity of data for modeling in any form has already been discussed. The added requirement for statistical dimensions to these data to be used with either stochastic analytic modeling or simulation (Monte Carlo) places additional burdens on a data-gathering system that is hardly adequate in meeting lesser demands. In stochastic analytic modeling of combat, noteworthy efforts include those with stochastic duels and stochastic attrition processes (Lanchester type). Extending the work with duels to engagements involving "few-on-few" or "many-on-many" combatants becomes extremely complicated, while the work with stochastic Lanchester attrition is generally in need of better data for refinement and application. On the simulation side of the matter, the inadequacy of available data for stochastic modeling looms large, most particularly with respect to those variables that are nonbinomially distributed. Additionally, one confronts the age old unsolved problem of ascertaining in complex stochastic simulations how many replications or runs with a model are necessary to obtain estimates of the mean and variance of the results to within certain confidence limits. In some sense, then, one is forced to ponder the wisdom, at this juncture, of the stochastic representation of combat with all of its added complexity in view of the disarray that prevails in the modeling of ground combat. If such modeling were to provide a realistic picture of the variability in combat outcome, it would be invaluable; however, with model structures that are suspect and data that are inadequate, the exercise appears to be pointless. Deterministic models and solutions, on the other hand, possess the attribute of reproducibility* and, considering the present state-of-the-art in modeling, are perhaps all that warrant serious consideration.†

The next issue area addressed in Figure 7 is the modeling of strategy and tactics. This area encompasses the introduction of human "behavior" in operational decision making and weapons employment into models of combat. In actuality, strategic and tactical considerations are strongly hierarchical and pervade the entire structure of warfare from its highest level of conflict objectives down to its microcosm of the individual combatant. In modeling these phenomena, tactics and rules for engagement at the lower levels of combat structure are generally aggregated over organizational entities on the battlefield that are usually set by the degree of resolution selected by the model designer. This level of resolution, in turn, is established by dictates of the problem to be solved, as discussed later. Obviously, it would be extraordinarily difficult to model the activities of every soldier in battle even if we had reliable sources of behavioral data for this level. This fact has given rise to the concept of "doctrinal" units‡ in modeling activities of dismounted infantry in combat; that is, in those rare instances in which one attempts to model infantry. Within the organizational entity that constitutes the smallest ground combat unit down to which a model can resolve, all members behave in some prescribed fashion as a bloc. In this manner, when considering McQuie's earlier observations (Section 4.3) about the modeling of combat for the three services, we find that ground warfare modeling is constrained or forced to conform more closely to that of naval and air warfare.

In Figure 7, a sharp, clean dichotomy is implied in model structures by the two boxes labeled "Fixed Strategy and Tactics" and "Variable Strategies and Tactics." In actuality, this

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*See Reference 1, p. xviii.

†That there can be disagreement on this point is shown by the comment of Goad, Reference 1, p. 27.

‡As in CARMONETTE (see Section 3.2).

is not quite so. Remembering that tactical considerations, in particular, are infused throughout the combat structure down to its lowest levels, it is impossible to conceive of a simulation model at the theater level in which every action is foreordained and fixed in the model design. There must be provisions made in the modeling for contingency actions to be taken at certain levels in combat that depend on local outcomes at these levels — outcomes that cannot be ascertained a priori. This is why one cannot categorize any theater model as being truly of a fixed tactics design. However, Figure 7 more importantly attempts to reflect broader, higher level strategy and tactics issues and their impact on model structure. Such issues are concerned with whether friendly and enemy objectives, allocation of resources, and plans of operation are fixed in a single play of the model game (regardless of enemy counter-activity or battle outcomes) or whether they are permitted to vary according to actions taken by the opposing side and the fashion in which the war progresses. It is in this manner that we attempt to define more aptly the context within which the issues of strategy and tactics are considered in Figure 7. Note that this area of model architecture encompasses modeling of the operational function of command and control.

With fixed strategy models, the attack and defense objectives and plans, the weapons to be used, and the allocations of manpower and weapons to specific roles are decided beforehand (based on intelligence estimates and knowledge of friendly force postures and doctrines) and become a matter of input to the model (constituting the conditional elements of combat discussed in Section 4.3). Within the constraints of model structure, many types of "what if" questions can be answered by repeated runs with the model and appropriate variations of the input. While the lack of realism with this approach may be readily recognized in the abstraction of a complex operation such as that of a corps or theater-level conflict (in which, in reality, many fundamental decisions are usually made on both sides during the battle that deviate from original operations plans), the approach has some compelling features in analyzing combat of lesser scope; for example, a single engagement. With the hierarchical nature of theater-level conflict already established, it is clear that an engagement is very much a part of the whole. If there be errors in the formulation or application of the engagement model, these errors may, in fact, be magnified many-fold as one moves up the hierarchical ladder and the output from one level becomes the input for the next. While the fixed strategy and tactics approach is attractive by virtue of its relative simplicity, it can entrap the unwary into a serious logic error. For instance, if at the engagement level, one were to fix the Red attack or defense plan and tactics (as is often done) and one were to make sequential exploratory model runs with a series of varying Blue weapons and tactics in an attempt to maximize Blue combat effectiveness, one would clearly be violating the two-sided, "action-response" behavior patterns that are characteristic of warfare. As one varies the nature of Blue force operations, one is also obliged to allow for a rational response on the part of Red. The fixed strategy selected for Red at the outset of our hypothetical exercise may not constitute such a response.

In treating variable, adaptive strategies and tactics as integral parts of the game structure, three basic techniques have been advanced (Figure 7):

- Contigency rules (table look-up)
- Game theory (analytic and computational)
- Man-machine interactive or player-assisted gaming.

Contingency rules are widely used in ground combat simulation models to ascertain changes in posture, state, and movement of combat units during the battle. Units of interest, of course, vary in size, depending on the aggregation and resolution characteristics of a particular model. The rules are primarily tactical and are generally imposed on a unit during game-play when the threshold value of some specified, measurable battle parameter is crossed. Examples of such parameters might be force ratio (via-a-vis the opposing unit), casualty rate, or "break-point"* and the threshold values for such parameters can be specified as input to the model. The rules governing the change in condition or activity of a unit are generally drawn from a constrained, stylized sampling of a larger number of possible tactical alternatives in the real world and yet they afford enough fidelity and sufficient flexibility to permit the battle to continue in reasonable manner. These rules are of a form that impose a change in a unit's posture, for example, from attack to defense, or its movement from advance to retreat. They are all programmed into the model beforehand and their implementation is simply a matter of table look-up in the computer routine. Contingency rules that are in use at present are almost entirely restricted to the combat tactics portion of the decision making spectrum in warfare and tend to provide only a coarse, somewhat stilted, representation of fluid conditions that generally prevail on the battlefield.

Game theory encompasses an extensive, rather unique intellectual activity that is concerned with the description, in mathematical language, of certain sociological phenomena arising from adversary, coalition, and bargaining situations.† Game theory had its origin in the economic and social sciences‡ and has been lurking in the wings, so to speak, with apparent strong potential for application to problems of armed conflict. As already noted, it is after all the sociological aspects of the combat phenomenon that are so frequently neglected in our modeling. So why should there not be some sort of marriage effected between the mathematics of equipment behavior (computer gaming, largely as we know it today) and the mathematics of human behavior (game theory)? Of course, in a broad sense such application for game theory has occurred to mathematicians and analysts and a number of attempts have been made to incorporate it principles into gaming models.§ However, the progress made in the more than two decades that game theory has been out of the "curiosity box" for military applications has been less than breathtaking — and one might well wonder why.

Philosophically, the most compelling quality of game theory, when contemplating its application to behavioral problems, is that with such application, one "drinks his rational behavior potion pure." There is no need "to fake spurious human parameters"** that have not been rigorously defined, much less measured (as is frequently done to accommodate human behavior in more conventional process modeling and simulation). However, full attainment of this worthwhile and relevant application potential using game theory has been thwarted by an admixture of the following factors: (1) the subtleties of the theory concepts themselves and the somewhat restricted exclusive nature of their dissemination,†† (2) continuing debate on the applicability of specific categories of game theory to military operations research,‡‡ (3) the apparent (but largely unexplored) high sensitivity of theory structure to variations in approximating pay-off functions and strategy sets and to changes in game parameters, and, finally, (4) the inordinate mathematical complexity involved in a rigorous game theoretic solution to any but the most rudimentary formulation of a combat game.

Figure 7 draws a distinction between rigorous, analytic game theory, applied to aggregated analytic models of combat (lower left side of figure) and rigorous or approximate

*The casualty threshold for a unit which, if exceeded, causes the unit to be removed as an effective entity from the game

†A large body of literature on the subject includes such works as: R. D. Luce and H. Raiffa, "Games and Decisions," John Wiley & Sons, Inc. (1957), G. Owen, "Game Theory," W. B. Saunders Co. (1968), M. Shubik, "Games for Society, Business, and War: Toward a Theory of Gaming," Elsevier (1975).

‡See J. Von Neumann and O. Morgenstern, "Theory of Games and Economic Behavior," Princeton University Press (1944)

§See Shubik, Reference 1, pp. 147-152, for an excellent overview of these activities and the role that game theory should play.

**Reference 1, p. 145.

††Lucas, Reference 1, pp. 152-153.

‡‡Mayberry, Reference 1, pp. 194-201.

game-theoretic solutions using mathematical programming algorithms,* applied with simulation models of combat (lower right side of figure). Within the context of combat gaming, the traditional applications of game theory to problems of strategy and tactics generally have been restricted to two-person zero-sum theory. One of these applications, strategic in nature, has had to do with the two-sided, optimal allocation of highly mobile, multifunctional resources, such as tactical aircraft, among the various missions the resources are capable of performing during a campaign. In this instance, use is made of multistage or recursive games but with questionable efficacy and validity.† Other attempted applications to problems of ground/air warfare are more tactical in nature, dealing with duels and games of search and pursuit at lower "one-on-one" levels of aerial combat. Few, if any, such applications have made their way directly into higher level conflict models. However, the effect of such considerations can always be appropriately accommodated in broader modeling efforts through the mechanism of the model hierarchy, discussed earlier.

In summary, game theory seems to have great potential for application to the human decision and behavioral aspects of combat modeling (command and control). It brings to the analysis of the subject a rational structure with a compelling logic governing the determination of behavior. Yet, in applying game theory to military applications, we find a stagnation in activity that is surprising and disappointing. This is due to a certain frailty and lack of continuity in communications among game theorists and practitioners who might apply the theory, the difficulties in relating game theory structures and pay-offs to the structure of combat as we understand it, and the enormous computational difficulties associated with game theoretic solutions. As noted by several speakers at the Leesburg workshop, a significant amount of continuing academic research in game theory can be cited, but very little of it is defense-inspired or defense-oriented at present. However, much of the work is judged to have potential application to defense problems.‡ Also noted at Leesburg is the purported emphasis placed on game theory research in the USSR. Under the circumstances, it would appear that reversal of present trends in military game theory application is called for, particularly in those areas in which investigation could involve the use of relatively simple, analytic models of combat (closely related, perhaps to those of the "throw-away" variety addressed by Shubik in Reference 1). Much is yet to be learned about the identification of the relevant variables in combat, as already discussed in Section 4.3, as well as the sensitivity of the behavioral factors treated by game theory to changes in these significant variables. These considerations alone would justify that continuing attention be given to game theory developments and their possible applications to combat and conflict modeling.

Whatever might be the ultimate merit in each of the methods shown in Figure 7 for the modeling of human decisions and behavior in combat, it is quite clear that the one receiving the lion's share of attention at present is that of man-machine interactive, or player-assisted, gaming. After accumulating experience with the limitations, difficulties, and shortcomings of the methods already discussed, it was perhaps natural and easy to relax somewhat the concepts of the all-computerized gaming model and make room again for man to participate directly in the game play. Stated simply, provisions are made in the game program for appropriate interrupts and the display of outcomes at interrupt points so that the human

*See Reference 66, Lansdowne, Reference 1, pp 153-160, Miercort, pp 161-171

†Use of a rigorous, analytic solution, working with a simplified model of ground/air combat[34, 35], failed to include any effects of the ground war in the pay-off. Additional attempts to solve this class of problem with computational techniques have likewise met with the need to restrict the problem (because of mathematical complexity) and, furthermore, have caused questions to be raised concerning the validity of the computational algorithms.

‡Continuing research in two-person general-sum games, n-person games and recursive games with incomplete information are cited as examples in Reference 1

decision maker can enter into the game at these points with interactive inputs.* This, of course, represents a direct, heuristic approach to the accommodation of decision/behavior phenomena in the modeling of warfare. Decisions are made by real human beings as game-play scenarios and situations unfold. Aside from complexities associated with man-machine interfacing, the concept is utterly straightforward in its representation of human decision processes. Once having made the proper hardware and software provisions for interactive gaming, feasibility is afforded for incorporating hierarchical decision making structures into the gaming program, which in theory, at least, can be quite elaborate.

Some trade-offs are associated with the employment of man-machine interactive gaming in lieu of other techniques for addressing variable strategies and tactics. Such gaming can generally be expected to enjoy greater playability and transparency, because of some measure of game path determination by the participants. This can be particularly helpful with technique credibility if the game player(s) are also involved in the decision process that the game seeks to support. For it is under such circumstances that the "decision maker" can inherit from his "analyst" alter ego a much finer appreciation of the merits and limitations of the analysis tool being used than is usual.

On the debit side, there is a philosophical issue worthy of some discussion. If the model is to be used as an adjunct to the planning process, which it is most frequently, then it is important in our modeling to factor the behavioral characteristics of leadership and command/control without necessarily carrying the imprimatur of a specific leader or commander. This is on the strength, of course, that in planning for the future, we cannot with any degree of assurance identify friendly or military leadership. Therefore, military force planning in any of its aspects can only proceed on a conservative basis of matched rational behavior for both sides (within the limitations of the military capabilities, for each side). Paradoxically, this abject rationality is not necessarily *realistic* in the true conduct of warfare. Yet, this is what planning seems to prescribe for its supporting analysis, and it is a paradox that game theory concepts accommodate to very nicely, although, as discussed above, there are difficulties in implementation. A straight heuristic approach such as interactive gaming, on the other hand, is largely subjective in its treatment of the human behavioral aspects and can be expected to produce different results, as players change. General Kent indicates an awareness of this issue† and goes on to endorse the advisability of seeking alternative results with many runs of player-assisted theater-level war games in order to develop greater appreciation for "the results of alternative decisions." This entails a great deal of work, and it is interesting to speculate how, in the limit (with a game run often enough), this approach would tend to converge, in some sense, with the concepts of game theory.

Another interesting concept is advanced by Pugh‡ that might be categorized as a formal analytic heuristic method to automate the human decision processes of interactive gaming. To do so, it makes use of values assigned to outcomes in the short-, mid-, and long-term periods of combat, these values being derived judgmentally. The judgmental value criteria are indeed the decision criteria that are used within a simulation to select the "best" outcomes among possible alternatives in the various combat time domains. They can be derived by a sampling of military judgment or experimentally by experience with repeated plays of a

*While perhaps sounding deceptively simple, this type of effort most assuredly involves nontrivial excursions into the computer sciences. See Reference 1, Tuan, pp. 187-194, Dobieski, pp. 173-186 for insight into hardware and software problems associated with interactive gaming.

†See Kent, Reference 1, p. 81 in which he states: ". . . We should not try to model decision makers. I think it's a will-o-the-wisp. Who are you going to model? A particular decision maker? Or a typical canonical decision maker? If you do that you've violated one of your precepts of detail. I'm against modeling of decision makers. I am for having models that tell the results of alternative decisions . . . ."

‡A description of the concept is presented in Reference 1, pp. 72-78.

game. This value-driven *weighting factors method* (as it is sometimes called) is companion to the concept of the automated computer game. Thus, while we might stand to gain a better understanding of the hierarchical nature of decision making in combat and the use of judgmental value criteria with this method, we perhaps lose considerable game playability in taking leave of the man-machine interactive game. As a compromise technique for planning analysis purposes, however, the value-driven weighing factor methodology would seem to show considerable promise.

It should be clear from the foregoing that modeling of tactical and strategic decision-making constitutes the very heart of portraying behavior of the command and control that largely embraces the sociological and human behavioral aspects of warfare which, as we have already noted, have been neglected in computerized war games when compared, for example, with the emphasis placed on the modeling of hardware systems. Much more work is needed to develop a better understanding of our modeling of command and control, particularly the overall validity and sensitivity of the scattered, fragmented methodology described above, which has been advanced but has never been evaluated with any degree of thoroughness nor disseminated widely throughout the model user and development communities. There does not appear to be any way short of rigorous (and, in all likelihood, extended) investigation to further our understanding of these methodologies and the trade-offs they entail among considerations of model structural complexity and logic and modeling fidelity to the real world.

The discussion of Figure 7 has been restricted to factors that directly affect gaming structure; its form, size, and complexity. Next to be considered in Figure 8 is the modeling of combat missions and functions within the context of the broader classification of gaming structures, developed in Figure 7. While it is true that the combat modeling of Figure 8 also impacts gaming structure, it is at a more local level than the general methodology level addressed by Figure 7. Drawing on an art analogy, one might look on Figure 7 as the sketch or roughed-in outline for the canvas, wherein the scope of the art work and the style of its execution are laid down in preliminary fashion. the combat modeling of Figure 8, on the other hand, is analogous to detailing in a painting as it is allowed to develop in both form and color. This is, of course, done within the outline previously defined.

This hierarchical view of relationships is reflected in Figure 8, in which the upper part of the figure repeats some of the classification material of Figure 7, indicating that the structure of the model selected (in the instance shown, a simulation) should properly depend on the nature of the problem being addressed. Most sensitive to problem structural dictates is the matter of the required degree of resolution to be provided by the model. Considerations of aggregation resolution should in turn uncover additional necessary or desirable characteristics for the model(s) in a particular application. Whatever model structure is deemed appropriate, the figure indicates that ideally it is this structure that should shape the function modeling of combat and combat support within the context of the theater-level game. In practice, however, it can well be that interests in combat model simplicity or in ease of computation or that constraints imposed by lack of appropriate data may have a greater conditioning impact on overall model structure than do the dictates of specifics in the problem being addressed.

The balance of Figure 8 is concerned with relationships among various military functions and operations of a direct combat or combat support nature whose treatment would be called for by intuition and common sense in any modeling of conflict at the theater level. These factors are presented in the figure as intuitive requirements for the functions that are germane to, and properly belong in, abstractions of theater conflict. At the same time, it can be flatly stated that there are no models in existence that address them all. Instead, one will find a varied treatment of the factors shown in different models, which ranges from highly

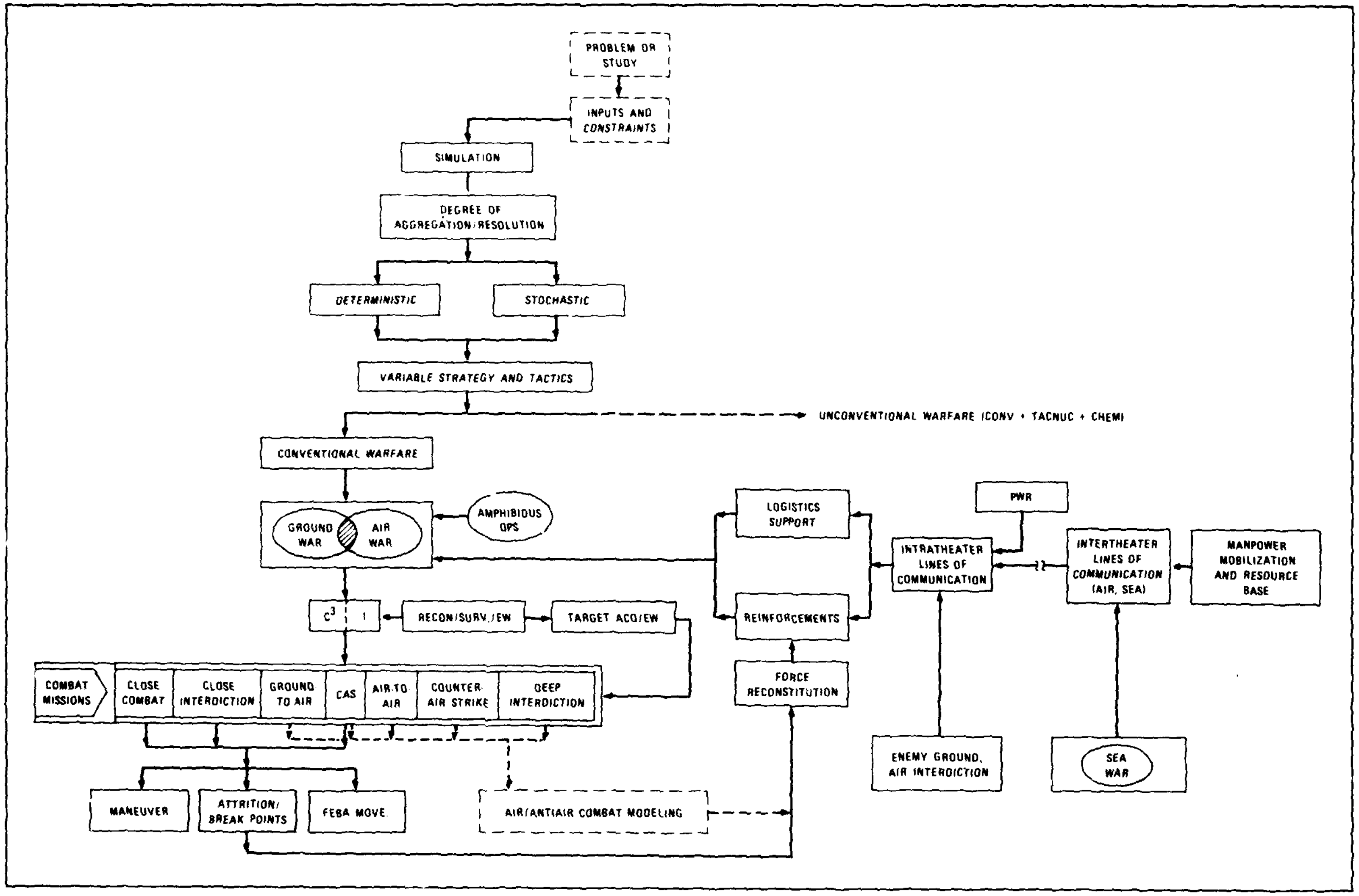

FIGURE 8 ANATOMY OF THEATER-LEVEL MODELING: II--COMBAT MODELING

explicit, to highly implicit, to regrettable and conscious, yet unavoidable, omission.* Thus, in effect, the combat modeling factors of Figure 8 encompass a number of problem areas that were identified and discussed in papers presented at the Leesburg workshop and by the panelists. We will briefly review these problems in the context of their presentation in the figure, recognizing that in our present state of knowledge (as previously emphasized) we can perhaps do little more than speculate on their true importance in the quantitative shaping of conflict outcome.

A major branch point appears in the breakdown of Figure 8 where a distinction is drawn between the traditional designations of "conventional" and "unconventional" warfare. Whether such a split can be justified as a conceptual discontinuity in conventional warfare when tactical nuclear and chemical munitions are added to the weapons menu is, in itself, an appropriate topic for debate.[67] But from at least a U.S. point of view, there is sharp break with traditional tactics and doctrine when the employment of nuclear weapons on the battlefield is contemplated. The use of such weaponry carries with it strategic implications of possible escalation to general all-out nuclear war. Consequently, decisions in these matters are the purview of government levels that transcend the theater and extend well into the upper structure of the National Command Authority. They call for the imposition of elaborate command and control procedures for the release of nuclear and other special weapons for use in the field and for the possible control of their employment. In modeling unconventional warfare, it seems quite clear that we have a better grasp of the physics of weapons effects than we do of exactly how, and when, these weapons will be used in combat and what their expected impact might be.†

Without belaboring this point further, we can turn to the conventional warfare aspects of Figure 8, recognizing that within this warfare category is a not altogether dissimilar situation when it comes to modeling tactics, doctrine, and command and control. This, too, was duly noted and received considerable attention in the papers and discussion at the Leesburg workshop.‡

The major classes of conventional warfare (ground, air, sea, amphibious) are designated by elliptical enclosures in the figure to map how and where in theater modeling these classes of warfare would most directly influence the conduct of theater operations. As noted earlier, modeling aspirations may strive for complete coverage of the theater problem approaching that shown in Figure 8, but no modeling effort has yet been known to attain it.

Ground and air warfare are shown as overlapping entities, conceivably supported in certain contingencies by amphibious operations. The figure emphasizes the importance of command, control, and communications and intelligence (C^3I) in the conduct of the ground/air war. The intelligence function is further broken down into its dependence on reconnaissance, surveillance, and electronic or signals warfare which, in turn, serve to fuel the target acquisition function on which engagement and attrition within the various combat missions rather strongly depend in our model abstractions. The combat missions shown are the classical ones associated with conventional ground/air warfare. While air and ground activities are closely interrelated in actual combat, an attempt is made in the figure to dissociate the combat missions into activities that are primarily ground (solid lines) and air/anti-air (dashed lines). This was done to show that there are problems in the modeling of ground combat having to do, among other things, with the proper representation of maneuver and the movement of the FEBA as well as the correctness of the attrition algorithms that are used, or

*See Section 3.2 for a background discussion of these matters

†This is discussed in varying degrees of depth in Reference 1, Kerlin pp. 47-55, and Spaulding, pp. 108-115

‡See, for example, Reference 1, Bode, pp. 61-72, Pugh, pp. 72-78, and Robinson pp. 129-135

the handling of force break points and the treatment of engagement termination.* It may be inferred from the figure that these problems are perhaps more troublesome than any encountered in the modeling of air/anti-air combat for which no particular problems have been called out in the illustration. The intent is not to make light of the difficulties inherent in the modeling of air combat but to suggest that on a relative basis this observation appears to be valid.

As shown in Figure 8, another problem encountered in ground/air combat modeling is that of the treatment of force reconstitution, or the reassembly of surviving force units (emerging from Red/Blue combat mission interactions) into new, viable combat organizations to join the pool of manpower reserves and reinforcements. Force reconstitution is possibly more a problem of doctrinal definition than one of modeling. It is not nearly as formidable as some of the others that appear in the figure, having been incorporated into a number of existing theater models.

The entire problem of logistics and manpower support of the theater-level game starts at the far right of Figure 8 with the manpower mobilization and resource bases for the adversaries in the conflict. There are likely to be asymmetric intertheater lines of communication for supply and resupply that could, for example, involve sea and air transport for Blue and ground and air transport for Red. It is the naval mission of sea control to retain for Blue open intertheater sea lines of communication that sets the stage for sea war if this Blue objective is to be challenged in any way by Red air or naval forces. Likewise, ground and air intertheater LOCs may be harassed and disrupted by enemy action (although such successfully pass through the intertheater pipeline are combined with prepositioned war reserves (PWR) to flow along intratheater LOCs to their final destinations in support of the ground/air war. Enroute they may be subjected to enemy ground and air interdiction (of the "close" and "deep" variety) as shown in the figure.

To put Figure 8 into proper perspective, it should be noted that the combat and combat service support (logistics) missions and functions shown are vastly simplified representations of inordinately complex activities.† Treatment of these problems, particularly those concerned with the modeling of logistics support in theater-level conflict, leaves much to be desired. A particularly troublesome aspect of the support problem is our inability to express mathematically the dependency of the effectiveness of the various forces engaged in the combat missions of Figure 8 on the availability of POL, food, ammunition, and spares that must make their way through the pipeline defined by the inter- and intra-theater LOCs, with these in turn, being subject to disruption by enemy action. Also to be noted in the figure is the location of the bloc labeled "sea war" which, significantly enough, is to be found some distance removed from that representing the ground/air war. In fact, in virtually all instances in which any sea war modeling is even attempted in connection with the simulation of a theater-level conflict (and these are very infrequent) modeling of the sea war is totally removed from the modeling of land combat shown in Figure 8 and is executed separately (but not altogether independently).‡ It can be appreciated that in concept, at least, naval campaign models can be run separately, yet parametrically, in support of theater modeling. This is done in a manner in which any or all of the various naval force level, force composition, or

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*These matters surfaced frequently at the Leesburg workshop. See, for example, transcripts of panelist and audience comments, Reference 1, pp 142-146, pp 171-173.

†See Reference 1, Hess, pp 55-60 and Hurford, pp 115-122, for some appreciation of the magnitude of the problem involved with the modeling of theater logistical support.

‡See Underwood, Reference 1, pp 102-107, for a description of the hierarchical approach traditionally used in naval campaign modeling. Naval models, run in isolation, generally employ "local" outcome measures such as ships, submarines, or aircraft destroyed. Such measures require transformation to the more global outcomes that affect a ground/air war, such as tons of supplies successfully delivered to the theater, if the naval models are to be run separately but in parallel with the land campaign in a theater conflict. Tons of supplies delivered must then be translated into some measurement of land campaign effectiveness.

tactical parameters are varied to optimize naval mission performance with respect to land battle outcomes. A theater model that integrates the sea war and intertheater LOCs into a global simulation of theater conflict is BALFRAM, briefly described in Section 3.2. Covering the wide scope of military activity that it does, this model is more aggregated in its treatment of the land/air war than many of its contemporaries. However, in instances in which naval forces ultimately become more involved in the support of land combat, as in delivering carrier-based air support, it becomes increasingly incumbent on the model builder and analyst to integrate the activities of such resources into the simulation to permit an accounting for their contributions — and their vulnerabilities — in a meaningful way. In short, this kind of battlefield support must be folded into the modeling of ground combat in much the same way that the entire tactical air support and related air war picture is handled in current models of theater conflict. Problems involving trade-offs among constrained naval resources that might prevail, for example, in simultaneous execution of sea control and power projection missions truly require the integration of sea war and land/air war activities in a single model structure. This is to ensure that all force contributions consistently relate to an outcome reflecting overall ground force effectiveness in the campaign.

A final observation is in order concerning relationships among Figures 6, 7, and 8, which represent at least three morphological cuts (out of perhaps a larger number of possibilities) through the structure of conventional warfare. A brief discussion of their interrelationships should prove useful in further clarification of prevailing thought concerning the structuring and classification of models and simulations of large-scale combat. This, in turn, should be of assistance in the conduct of further research.

Figures 6 and 8 are closely related through the logical connection between combat processes and outcomes and combat missions and operations. The former (as concepts that are primarily methodology oriented) do, of course, occur within settings established by the latter (for which Figure 8 is a "map" postulating the flow of military operations in a theater conflict).* Figure 7, on the other hand, is mainly oriented toward *analysis and modeling* technique while attempting to depict the fundamental relationship between the real world of conflict and the abstract world of modeling.

Taken together, the figures generally portray in three dimensions (or from three perspectives), the present state-of-the-art of our approach to the modeling of combat. Actual accomplishments, however, have not kept pace with all modeling aspects of Figures 6 and 8, as already noted, particularly in the areas of C^3I and the many facets of logistics support. Furthermore, there are doctrinal considerations, particularly the employment of tactical nuclear and chemical munitions, that are in need of further investigation and clarification. Finally, a caveat that bears repeating (only because it is so easy to overlook) is that little if any of the heroic modeling activity addressed by Figures 6, 7, and 8 has been substantiated historically or experimentally. For the present, this activity must stand as a class of intellectual exercises (albeit with recognized utility) in that universe of conflict abstraction.

4.7 Supporting Data Base Issues

Of all the issues that surfaced at the workshop, the problems associated with the data bases that support combat modeling and analysis were generally conceded by those in attendance to be the most critical. Model development, it was agreed, was far ahead of data development.† When one considers the multifaceted and multilayered aspects and complexity of the problems associated with the modeling of ground/air combat, as have been

*The reader will notice the presence of certain "processes" in Figure 8 (i.e., C^3, attrition, movement, etc.). These are shown because they persist as problem areas in the modeling of combat.

†Schneider, Reference 1, pp 208-209, 243

discussed in preceding sections of this paper, one can then appreciate the implications of this description of the problem of data bases.

That model development should properly take *some* precedence over data collection and organization is recognized as a sensible way to sequence research activities. This is based on the premise that one hardly knows what data to gather, not to mention how it should be assembled or in what forms it should be stored, unless one has available the model that the data is to support. *In short, the model is used as a guide in establishing the data base.* Unfortunately, much of the modeling of ground/air combat — particularly that at the higher levels of aggregation encountered in corps or theater modeling — has proceeded somewhat cavalierly with respect to the existence or nonexistence of the kinds of data that are specified as inputs to these models. Even the feasibility of ever acquiring such data through further research and experimentation is not often considered with much care. As discussed earlier, there can be considerable trade-off in model design (particularly at high levels of aggregation) *between the use of input data to represent or to model implicitly certain combat* phenomena and the use of process modeling algorithms that treat such phenomena in explicit fashion.* It should be noted, however, that at quite another level, explicit modeling also imposes certain requirements for input data of greater specificity that are generally more rigorously defined. Thus, we find that, depending on the level of aggregation one wishes to consider (and other factors, to be sure), models and data become inexorably interfused. In practice, the representation of combat in one fashion (data) or the other (process modeling) is *highly varied and largely a matter of data availability and the model designer's choice.* There obviously does exist, however, a hierarchy of data that is closely related to and parallels the hierarchy of military organizations. This hierarchy, in turn, is a determining factor in establishing the resolving power and hence the level of a model in a hierarchy of models.

There are, then, levels of data that generally correspond to the hierarchical levels in modeling, the limits of which are described logically enough as "low-level" data and "high-level" data.† Low-level data might include such factual pieces of information as the thickness of T-62 tank armor or the average muzzle velocity of a 90mm antiaircraft gun. High-level data, on the other hand, is concerned with aggregated information such as the firepower index of a Warsaw Pact mechanized division. Often, one or several models, computational routines or, at the very least, trains of logic are employed in relating low-level data to high-level data. As the data progress from narrow but specific and factual information to broader measures of performance or behavior, circumstantial and environmental factors have increasingly significant influence on data values and format. For this reason, the form of high-level data for a particular model is largely determined by that model's structure and the manner in which it treats combat operations and environment. Thus, while data at the lowest levels are characterized by a certain universality, high-level data must be tailored to the model which they presume to support. As a consequence, a somewhat awkward situation is perpetuated in which the same basic information that defines much of the high-level knowledge embodied in data bases must be expressed in several different ways to conform to each of the different theater models that may be in user demand at any point in time. In general, this tailoring of high-level data to fit a particular model is best performed by individuals who are completely familiar with the assumptions made in the model coding and structure. Unfortunately, the people who construct data bases and the people who design and develop models are not one and the same. We frequently find that members of the latter group are not disposed or generally available to perform the data conversion work for which they are perhaps best qualified.

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*It will be recalled that use of the former tends to enhance model "transparency," whereas the latter increases "visibility" in modeling at the expense, perhaps, of added "clutter."

†Bednarsky, Reference 1, p. 215.

Apart from the problem of *structuring* data bases, which in itself is formidable enough, there is also the matter of gathering or developing the data that the models require. Possible sources of data were discussed in Section 4.3, and it should be clear from the foregoing that the extraction of valid information from histories, exercises, experiments, etc., for incorporation into data bases represents a difficult and complex undertaking with its attendant set of special problems.

In Reference 1, Bednarsky describes the breakdown of theater model data needs into a requirement for two major data bases: the DoD Force Planning Data Base (DFPDB) and the Weapons Characteristics and Performance Data Base (WCPDB). He defines the contents of both data bases in considerable detail, and from this information it is readily apparent that the concept of low- and high-level data, as discussed above, applies in both instances. There is little doubt, however, that compilation of the WCPDB and the conversion of its information from low- to high-level data presents a much more difficult problem than in the compilation of the DFPDB. There are many more pieces of information in the former data base, pertaining to the characteristics and performance of myriads of friendly and enemy weapon systems. Many of these pieces, in turn, must be logically linked to environmental factors (weather, terrain) and the types of targets with which the systems are likely to interact. In addition, the weapons must be linked to the forces with which they are associated in the DFPDB. That there are conceptual difficulties associated with the design of such data bases is borne out by the fact that there appears to have been relatively slow progress with WCPDB development since the Leesburg workshop, compared with progress on DFPDB. Also to be noted is the parallel, but perhaps independent, proliferation of force and weapons data bases among service activities that make use of combat models to support their decision making and planning. At this time it seems that these are not in any way coordinated with the DoD data base developments in CCTC.

Another hurdle that must be surmounted in developing valid, useful weapon system data bases for theater level models is that of overcoming a recognizable degree of service paranoia when it comes to the release of "hard" weapon systems data. In the bureaucratic environment alluded to in Section 4.4, there is the ever present risk of suffering setbacks in the struggle for a proper share of the defense budget if one's "advocacy" guard is dropped and one admits to realistic weapons performance data that may be considerably less spectacular than that advertised in other quarters for program promotion and justification. It is interesting to note that in this respect both models (Section 4.4) and data become merged into a single entity for consideration, thus further supporting the notion, already expressed, that at some level of abstraction, models and data are truly inseparable. Fundamental, of course, to any successful "standardization" of data that is essential to effective defense planning in the United States is a greater degree of openness and cooperation among the services and the OSD in the matter of information exchange.*

Other difficult problems are associated with the management and development of data bases in addition to what has been mentioned thus far. One is the problem associated with the validation or verification of data to within reasonable limits, however this process may be prescribed. On perhaps a less grandiose scale, this is analogous to the model verification problem that has already been discussed at some length. Others have to do with the enormous task of assembling data bases as weapon systems, employment doctrines, and force compositions change over time; the resolution of conflicting data obtained from multiple sources; and the maintenance of data base security, an extremely important factor considering the awesome information content present in data bases for models of large-scale conflict. There is

*This theme, expressed by Stockfisch in Reference 58, is unfortunately one that surfaces all too frequently when problems associated with combat models and data are addressed.

little doubt, indeed, that the array of problems associated with data bases qualifies this subject area for high-priority attention. The criticality of these problems, as we understand them at present, stems in part from an excessive lag in formal data base development behind that of the models (with which the data are so intimately connected).

Of further concern (in the more distant future, perhaps) are problems that could arise from the fact that the structure and content specified in the design of today's data bases are tied to models that are admittedly unverified in any meaningful way. Any research directed toward model verification and improvement could indeed have its ripple effect on the supporting data bases, particularly on their high-level data components. While such matters are clearly conjectural, the changes that might be called for as a result of model improvement efforts will probably constitute more of a shift in data gathering emphasis to fill emerging information voids* than any large-scale abandonment of information already collected. Of utmost importance, however, is the necessity for much closer working relationships between model and data base developers than has been observed in the past. The two problems are essentially one and the same, and the split in responsibilities has been largely an artificial one, necessitated by the staggering magnitude of both tasks and the inclinations and interest of the individuals engaged in both types of endeavor.

Finally, we might again return to the question of data verification or validation for some additional comments. Note that the issue of validation (as it concerns both models and data) was an agenda topic for the Leesburg workshop.[†] The importance of this issue had been forcefully expressed by Stockfisch in Reference 25, and he reemphasized it at the meeting.[‡] Yet, elsewhere throughout the meeting, the topic of validation was generally avoided or, when mentioned, was treated with a measure of casual disbelief. For most, the subject was apparently too staggering to contemplate ... too "far out," to be worthy of serious consideration or discussion, other than in highly modified form.[§]

Models and data are again one and the same when it comes to the issue of validation.** The complex tangle of information sources to be found in the real world that conceivably can be used in the validation process has already been discussed in Section 4.3. That the task of validation may appear to border more often than not on the impossible is difficult to deny. However, this particular issue is key to the future health and welfare of the entire process modeling approach to the study and analysis of combat, as will be discussed in Section 5.

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*New emphasis might center, for example, on data pertaining to certain aspects of human behavior in combat.

†See Reference 1, p. xxi.

‡See Stockfisch, Reference 1, pp. 232-235.

§See Bednarsky, Reference 1, p. 227 (mid-page).

**A model may be conveniently looked upon as a construct that defines certain mathematical operations to be performed on one or more pieces of data at one level that will produce a piece of data of a higher level.

5. The Requirement and a Concept for Research

5.1 A Requirement for Research as Defined by Workshop Issues — Overview

The general preference for the use of computerized gaming to provide quantitative information in support of high-level planning and decision making is attributed to the convenience and accessibility that such gaming affords and the reproducibility of the output or the outcomes that are obtained with any given set of inputs. However, the "open-loop" nature of computerized gaming and combat modeling leads to a host of problems for which there are most certainly no easy solutions. Primary among these problems is the lack of verification. Existing models, or perhaps more precisely the mathematical equations and algorithms used to describe component combat processes within the models, have been subjected to only a few scattered, disconnected attempts at verification, with inconclusive results.

This lack of verification is not as widely known as it should be through the higher policy and decision making levels of government. Because mathematics and computers are involved in these gaming activities, some people at these higher levels look upon them as "scientific" endeavors. Many analysts and model users in government, of course, know better. However, if complex, yet altogether heuristic, analysis constructs are used as instruments of advocacy in a competitive environment such as that in the DoD, then considerable mischief can be wrought with defense plans and policies, particularly if the techniques being used appear to bear all the trappings of a scientific methodology.

Two ways to remedy this situation come to mind that could be explored singly or in combination. One is to change the environment of the bureaucracy,* by ameliorating the competition for programs and budgets among the services and promoting a persistent and genuine concern to find objective answers to defense problems.† Paralleling this thought is the recommendation made in Section 4.4 for an OSD activity to serve as the proper nesting place for problems relating to the research, development and application of gaming models, techniques, and data that are used as an aid in formulating high-level plans and policies. It is envisioned that such an activity, apart from providing the stimulus for exploratory work, the coordination of gaming efforts and data bases, and the orderly exchange of information that is so sorely needed, would be elevated organizationally above prevailing interservice contention.

The second way to improve the utility and validity of gaming in defense planning is to "close the loop" in the model and analysis domain, thus putting these endeavors on firmer scientific footing. Ideally, once the latter were accomplished, with consensus in the analysis and user communities, the misuse of models and analysis (deliberate or inadvertant) should be sharply curtailed. Moreover, the quality of the information made available as an aid to our decision making processes in the defense area should be markedly improved.

Most fundamentally, we find that combat modeling is beset by two classes of problems where the second class exists as a direct consequence of the first. These are: (1) the absence of any verifiable connection between reality and the abstractions of combat modeling and (2) the uncertainty in selecting "proper" techniques for the modeling of combat phenomena in the absence of these links or ties with the real world. In strictly rational terms, there can be no dealing with the latter in a meaningful way without first coming to grips with the former. Accordingly, attention in this section is directed to the first class of problem, recognizing that under the conditions that exist today, the debate can perhaps continue forever as to the

*As advocated by Stockfisch in Reference 58

†Unfortunately it can be argued that within the existing defense environment one can always find some motivation to let matters pertaining to models and data remain just as they are. The obfuscation of issues that accompanies the somewhat free-wheeling, inappropriate use of techniques and information, in whatever fashion, can often be used to short-term advantage in a competitive environment.

merits of hierarchical versus global modeling or how to correctly represent FEBA movement or command and control in our models of combat.

One can only wonder at the surprising lack of curiosity persisting over some three decades that has allowed the development of a large number of combat simulations at a total cost that cannot even be reckoned* (but most certainly in the hundreds of millions of dollars) while causing the investment of relatively miniscule amounts in such areas as the historical verification of Lanchester's equations or FEBA movement rates. Even these modest attempts at establishing ties between models and reality have met with difficulty. So it is easy to surmise that under the pressures of generating quantitative information for studies and decisions, it has been expedient to comply with these demands using heuristic constructs and to worry about sorting out the far more difficult tasks of model verification at a later date — if ever. Yet analysts and model designers have at times performed research and exploratory work† in the hope of obtaining better insight into particular problems with which they were confronted while practicing their craft. While falling short of the mark of model verification as envisioned here, this work was nonetheless performed to enhance knowledge and understanding of the modeling processes rather than to crunch numbers and generate answers. How much work has been performed of this nature is difficult to estimate.

Despite the difficulty of verification, it would seem that the gross imbalance of effort and money spent for model building and application over that for understanding the phenomenology being modeled would most assuredly mitigate in favor of a concerted, cohesive, multidisciplined attack on the problem. Once such an effort was undertaken, the discovery of impenetrable barriers (should there be any) to a final solution could be duly noted along with the knowledge of the exact form of scientific attempt that had been made. On the other hand, given at least a reasonable degree of success, we would be able to calibrate our combat models so as to eventually bring about their improvement. This, in turn, should provide us with a credible, unambiguous methodology to be used as an aid in weapon system and force planning. Furthermore, a methodology should be forthcoming from this type of effort that affords a better understanding of elusive C^3 processes and permits the evaluation of C^3 system alternatives (since the C^3 function is embodied in the broader construct of the combat model). Many further advantages would derive from this model improvement program (if it is successful) by no means the least of which is the guidance that it would provide in the restructuring of supporting data bases. Also worth noting is the measure of support potentially available from such a program in the planning and evaluation of combat experiments and exercises. In summation, there seems to be little doubt that research in the area under discussion is extremely fundamental and necessary if the most meaningful improvements to the models of combat are to be realized.

5.2 A Research Concept

A key underlying problem to many of the other problems identified at the Leesburg meeting is the lack of coupling between our models of combat and reality. The obvious question that immediately comes to mind is: how does one effect the coupling between abstraction and reality? How does one close this gap or forge the "missing link"?

The problem of finding the missing link is in effect synonymous with the problem of model validation; this, by definition. Let us allow for the introduction of yet another concept, that of a theory of combat, and consider what the relationship between it and model validation might be. If one were to attain a validated combat model, this model would constitute the mathematical expression (whether in program code or in closed form) of a combat theory.

*See Shubik and Brewer, Reference 68.

†Some examples may be found in References 44, 49, 59; Farrell, Reference 1, pp 89-94; Bode, Reference 1, pp 61-71

Thus, the forging of our missing link would be tantamount to the development of a theory of combat. However, the hypothetical, validated model that finally closes the gap need not greatly resemble any of today's models in either form or substance.

Several approaches seem, a priori, to be feasible for the development of combat theory. In attempting to visualize the final product, one can imagine a spectrum ranging from the highly judgmental, empirical type of construct that is represented by the QJM to perhaps any one of the more traditional forms of process modeling using mathematical programming techniques. The final form may indeed reflect some combination of elements from both ends of the spectrum.

It is clear that the research should proceed along broad interdisciplinary lines. Military theoreticians have, over the years, contributed to a body of knowledge that identifies qualitatively in essay form certain "great truths" or "timeless verities" of combat derived from extensive study of military history. Although these truisms about warfare do indeed appear to have withstood the test of time to have been formalized (in part) into a set of "principles of war," they are usually described as isolated, independent entities that appear to prevail given that "all other things are equal." From our combat modeling activities in the past, we know that many of the factors we treat in the models are and have been of concern to the military theoretician. These factors interact with or "trade-off" against one another in a complex way. Because an ultimate goal in theory development should be the identification of the controlling factors in combat and the conditions under which such factors prevail, it will be necessary to *measure* in some systematic way the interactive behavior of military theories. This necessity for measurement compels the use of quantitative techniques, and for this reason it is assumed that the theory of combat will involve some form of mathematical modeling.

The theory of combat should ultimately embrace all forms of warfare (land, sea, air). Ground combat is the oldest and most traditional of all the forms of warfare and is one that depends the most strongly on characteristics of human behavior (Section 4.3). If combat is recognized as a sociotechnological phenomenon that has received undue technological emphasis in past modeling, it seems prudent to select ground warfare (with appropriate "combined arms" support) as the main object for investigation. Any theory resulting from this approach should be applicable in more than just a general way to all other forms of warfare.

Some additional observations of a general nature pertaining to the research task being discussed should be mentioned. For one, the pursuit of such an effort will be extremely difficult, constituting an undertaking of high risk. It will be protracted in duration relative to any of the traditional model building or study endeavors of the past — surpassing, perhaps, even the most ambitious of these in the time required to achieve worthwhile results. Moreover, the investigators should have expert knowledge in a variety of disciplines that culminates in an appreciation for military history and theory, the importance of human behavior in the combat equation, the physics and engineering of military systems and their performance in a combat environment, the significance of data (historical and experimental) to theory development, and the proper application of mathematics and quantitative techniques to the type of problem at hand. Furthermore, communication among investigators must not be hampered by differences in points of view stemming from differences in background disciplines. In addition to a certain level of innate broadmindedness necessary in each member of the group, it will be helpful if each member's past professional contributions are known to all other members and are such to engender mutual respect. The smaller the research group, the more likely is one to find such an environment.*

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*The author wishes to note that such a group, small in size, has coalesced. It consists of academic, government, and contractor representatives that conform with the principles described above. It has, in fact, met informally on two occasions to discuss a theory of combat

Finally, a strong sense of purpose, a high level of motivation and determination is required on the part of those who approach this task, along with a measure of intellectual curiosity and objectivity that are so important to scientific inquiry. The problem under discussion has been recognized for a long time. This knowledge has been accompanied by scattered observations that the problem ought to be investigated. Yet its very size and complexity, coupled with the ad hoc pressures that characterize the conduct of affairs in the defense arena, have thus far militated against a concerted effort to address the problem squarely. Under such circumstances, then, determination on the part of those interested in exploring the issues is obviously a virtue *provided* that is tempered with knowledge and good judgment that signals when the investigator should "cease and desist" because a solution to his problem in no way appears to be possible. While conceding the enormity of the problem, the author does not believe that its tractability to solution has ever been afforded a careful evaluation. This clearly should be done in view of the importance of the issue to the combat analysis community-at-large.

Many approaches could serve as possible candidates to be used in pursuing the development of a combat theory. Only when we take stock of the constraints imposed by the real world in the form of the information and data that it can conceivably provide us (Section 4.3) do we find that the number of feasible approaches shrinks quite rapidly.

On reflection, it appears that one can decompose the feasible approaches to research in combat theory into the following classes of endeavor:

(a) Historical and military theory research, historical data development and analysis

(b) Analytical experimentation

(c) Behavioral experimentation

(d) Combat (phenomenological) experimentation.

These fundamental research activities would never constitute a viable overall approach to theory development if taken singly. But, a synthesis of our findings, using whatever combinations of endeavors (a) through (d) that are deemed appropriate, would be incorporated into a model improvement program out of which would come improved model(s) that would constitute the quantitative or mathematical expression of a theory. Such, then, is the overall strategy for research, recognizing that significant changes (up to and including abandonment of the effort) can be made at any point in the work as dictated by the accumulation of knowledge. A brief description of each of the activities is presented below:

- Category (a) concerns all research of an historical nature; the careful review and analysis of archival material, military histories and theory, records of exercises and experiments in the search for significant cause and effect relationships among the variables of combat (technical and behavioral). Also included are those efforts to uncover new sources of combat information and data to fill identifiable gaps in our knowledge of warfare.

- Category (b) covers experiments conducted with relatively small, simple models that can either be expressed in closed form or involve mathematical programming or simulation techniques. Furthermore, they can be either stochastic or deterministic. The purpose is to explore relationships among variables, to investigate and evaluate various methods of measuring combat outcome, to establish bounds on combat outcomes under varying battle conditions, and to ascertain those variables that are the significant drivers of combat outcome along with the identification of the battle conditions that allow them to so prevail. Also included is the use of mathematical optimization models (game theoretic) that may afford some study of optimal strategies and tactics. In short, the models under discussion will probably conform, for the most part, to those of the simple, "throw-way" variety espoused by Shubik (Reference 1, p. 148). They can, however, run the entire gamut of structural complexity.

• Category (c) activities are predominantly focused on the decision making aspects of human behavior under combat conditions and, as such, are oriented toward problems of command and control. Involved are the techniques of manual gaming, computer-assisted manual gaming, and player-assisted (or man-machine interactive) simulations. The purpose of this experimentation is to attempt to capture, through the observation of human players in a gaming environment, the fundamental characteristics of player behavior either by algorithm or by contingency rules for surrogate use in fully automated games.* Also included would be other "laboratory" techniques used in the social and behavioral sciences to measure human responses in crisis or stress situations reflecting those encountered in a combat environment.

• Category (d) represents what is undoubtedly the most elaborate and extensive of all the activities listed and pertains to full fledged experimentation with combat at virtually any level on instrumented ranges or in field, fleet, air or joint exercises. As such, it embraces both the systems and human behavioral aspects of the combat phenomenon.

Progression from category (a) to (d) generally involves an ascending degree of human participation and material support. An approach to a theory of combat is more likely to draw on the first three categories of activity — at least in the earlier stages of such an effort —with the possibility of eventually calling for information to be provided, as necessary, by activities in the fourth category. Clearly, the activities in category (d) are very complex and costly and recourse to them is to be made only after careful consideration and planning. Furthermore, it is to be remembered (as noted in Section 4.3) that these activities are likely to lack the realism of actual combat that is manifested in historical records of warfare.

Some examples of approaches to research and an overall structure into which they might fit are discussed below, noting that further *careful consideration* of approach strategy is most assuredly in order. Perhaps of greatest importance is the need for consensus among a group of experts (which need not be large) as to what constitutes a reasonable, intelligent —and, above all, feasible — approach to the problem.

A possible overall structure for the conduct of research is shown in Figure 9. The figure illustrates that military theory evolves from combat history. It is, of course, from the study of both, that the verities or truths of combat are established, recognizing that such so-called truths are based on repeated observations made in the "laboratory" of actual conflict. This information, along with the "principles of war" that ultimately evolved from military theory,† constitute the main body of empirical evidence available for theory development. Careful study of this evidence should suggest qualitative combat hypotheses. To these hypotheses can be applied various quantitative techniques of the types described earlier under categories (b) and (c) (for which some examples will be presented below) and by means of this procedure certain quantitative hypotheses can be developed. Once these are validated against military history and theory and (as necessary) against combat exercises and experiments, they are established as laws of combat. The incorporation of such laws into combat model structures constitutes the major thrust behind a model improvement program. The model configurations created in this manner are, in effect, an expression of a combat theory.

The dashed lines in Figure 9 pertain to activities that are primarily concerned with data base development which, it will be noted, supports the quantitative research and testing

*Note that there is a lack of unanimity on the value of such procedures as indicated by Kent, Reference 1, p. 81.

†According to T. N. DuPuy, the principal modern military theorists contributing directly or indirectly to the Principles of War are Napoleon, Jomini, Clausewitz, Mahan (D. H.), Moltke, Ardant du Picq, Mahan (A. T.), Goltz, Schlieffen, Foch, Fuller

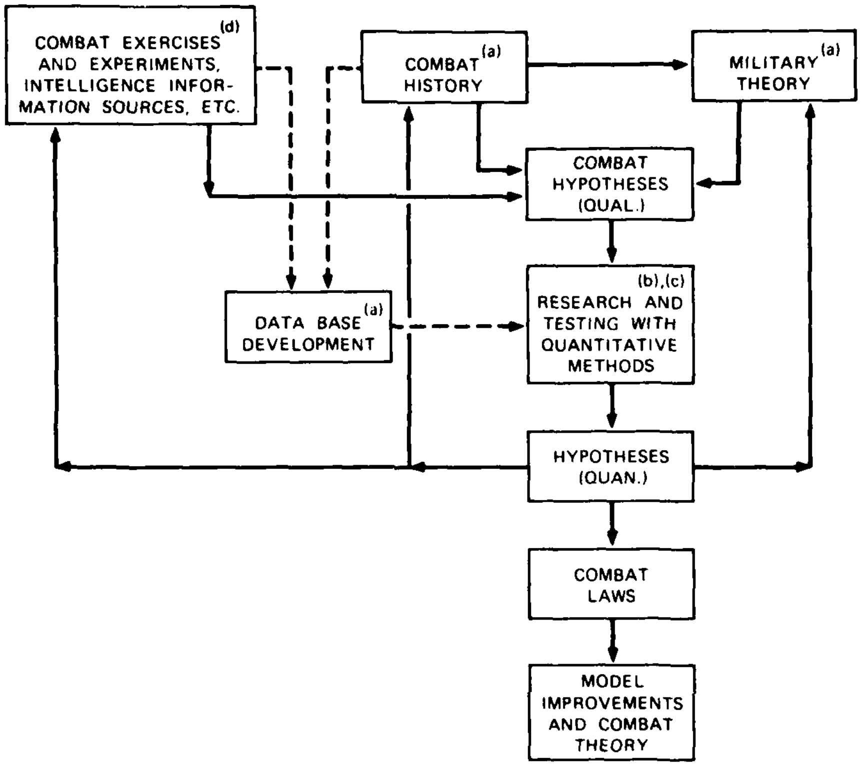

FIGURE 9 RESEARCH ACTIVITIES FLOW CHART

phase of the program. Certain activities shown in Figure 9 are keyed to categories (a)-(d) in the upper right-hand corner of particular blocks in the figure.

The process described by Figure 9 is iterative and requires careful orchestration of its major components. Crucial is the "quantitative methods" block in which procedures are called for that require considerable analytical ingenuity, yet with the conscious avoidance of undue complexity. Some examples of the quantitative methods that might be employed are described briefly below.

At the outset, it should be recognized that a long-standing example of the type of activity being considered in the "quantitative methods" block of Figure 9 is that of the original development of Lanchester's equations and the subsequent attempts to validate models of combat that are based entirely on forms of these equations. Lanchester (Reference 3) hypothesized the form of sets of differential equations to represent the attrition rates to both sides in combat, solved the equations, and developed what are now his famous linear and square laws. In his original papers, he refers to both combat history and to military theory (see Figure 9) in identifying, respectively, Nelson's tactics in attacking the combined naval forces of France and Spain at Trafalgar, and the Principle of Mass or Concentration, demonstrating that his square law was indeed compatible with both.* This somewhat primitive "validation"

*Lanchester, it seems, does not freely refer to his equations as "laws" until *after* his validation efforts attempt was probably appropriate enough for its time. However, it is particularly useful in illustrating the process that is charted in Figure 9. In their attempts to validate Lanchester models of combat against history (as, for example, in References 9, 11, 12, 14, 15) subsequent investigators have generally followed the same procedures.

In the quantitative methods block of Figure 9, some examples come to mind of what are seemingly viable and promising research activities to support the development of quantitative combat laws. The first example is one that is concerned with deeper, more extensive analyses of select historical data than heretofore and that will be used to help support or refute certain combat hypotheses; hypotheses that may be of sufficiently long standing to have found themselves adopted as doctrine or tactical rules of thumb. This type of effort would entail an intensive review of particular historical records, many of which may have already been subjected to analyses of one form or another. In addition, a search for new sources of historical data would be instituted, particularly for data pertaining to small unit engagements.*

During such study, one would look for persisting relationships between combat variables and task or mission outcomes. To do so, recourse to statistical methods or to the development and use of relatively simple cause and effect models must be made (the quantitative methods block in Figure 9). Thus the research involves categories (a) and (b). The study results would contribute both to the data base for some particular hierarchical level of modeling and to a better overall understanding of combat phenomena.

A second approach was presented in detail in Section 4.3, is illustrated by Figure 6, and expressed mathematically in Appendix C. What is suggested is a universal decomposition of combat model structure into a set of interdependent routines for explicit combat processes and their "local" outcomes, which, in turn, are related to overall outcomes of the conflict, defined by adversary objectives. The hypothesis is that *all* models of combat regardless of the level or type of warfare (hence the descriptor "universal") must conform to this structure† even though the character and form of the process loops or routines may change with warfare level and type and, accordingly, their influence on the outcome of an encounter. As an example, the nature and influence on outcome of command and control at the company engagement level is vastly different from that in conflict at the theater-level. Yet, in both instances, there are explicit, definable processes that properly fall under the heading of command and control and furthermore fit neatly into a C^2 hierarchy.

The decomposition of combat models in this manner should lay the groundwork for the development of analytical structures (models) for the various combat processes along the lines suggested in Appendix C. These are then to be reconciled with appropriate historical data so that, in effect, we achieve a piecemeal validation of the modeling process. If successful, the modeling should provide us with the means to determine the most significant process routines and the driving variables that shape the outcome in combat and the conditions under which they do so. In this instance (granting success of the effort as described) our theory of combat becomes the identical equivalent of an improved combat model that tracks with historical data.

Yet another approach to combat theory development is illustrated in Figure 10 and derives from the approach just described. Figure 10 is fundamentally similar to Figure 6, even though this similarity may not be immediately apparent. Several aspects of this new approach, however, are antithetical to the previous one. Briefly, it involves starting with the microstructure of combat or with the organizational elements of smallest size that confront

*Very little information exists for such engagements

†Needless to say some existing models have assumed away, or treat implicitly, the presence of certain combat processes in the formulation of their structures

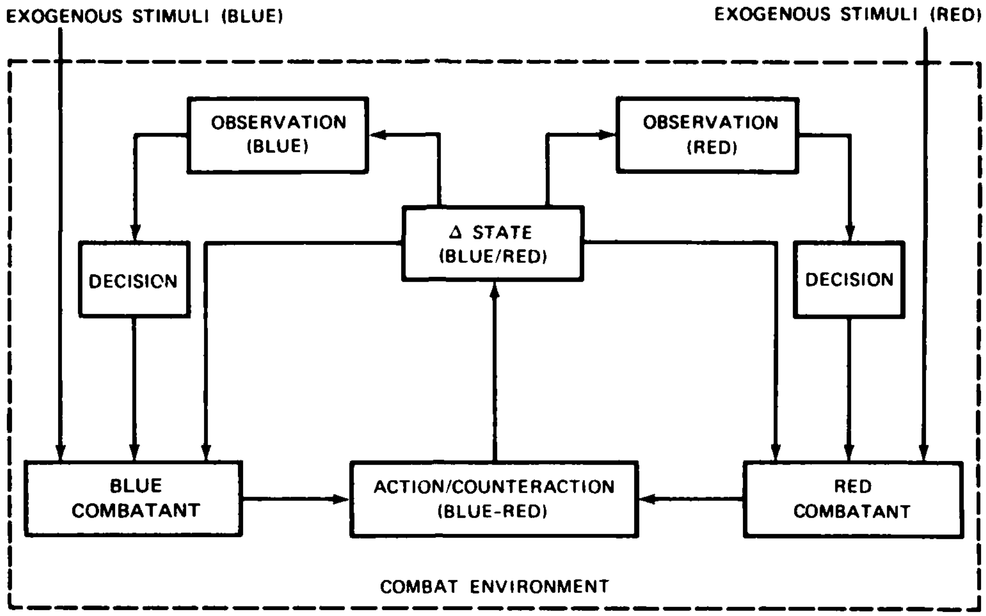

FIGURE 10 CONCEPT OF COMBAT MICROSTRUCTURE

each other on the battlefield. As shown in Figure 10, the individual combatant (Blue) is exemplified as a microcosm of combat and has imposed on him exogenous stimuli such as an assigned mission and a knowledge of tactics and doctrine derived from training. He is allowed to proceed on his mission (which, for example, might be to advance from point A to point B on some prescribed path) until he is opposed by an adversary (Red), who has *his* assigned mission. There are actions and counteractions taken by both antagonists that result in an altered state for each. There are, in effect, two sets of state changes: one real, the other perceived. Both the Blue and Red state changes perceived or observed by Blue are based on information derived from his sensory organs with or without the aid of sensing devices. The same pertains to the observations made by Red. Based on these observations, both Blue and Red make decisions about what further action each will take and, in this manner, the dynamic action loops for Blue and Red are closed. All of the above activity, of course, occurs within some specified combat environment that impacts on virtually all blocks in the figure.

One would wish to model the Blue/Red interaction just described in the simplest manner possible commensurate with a certain "first-order" realism (relative to actual combat). Even so, it may be necessary to define rather elaborate sets of contingency rules to cover a reasonable number of alternatives within each of the activity blocks portrayed in Figure 10.

Simulation techniques would be employed in such an exercise and numerical values for such characteristics as Blue and Red mobility, weapons effectiveness, observation accuracy and delay, and perhaps even resolve or determination (specifically, their effects on combat performance) would be varied over an appropriate range in two-sided gaming situations.

After developing some understanding of the one-on-one duel, additional combatants would be added to both sides, with each combatant modeled discretely. In this manner a building block technique is used to develop models of combat between forces of increasing size. Obviously, the levels of C^3I that are modeled must expand accordingly. Quite possibly, statistics of group behavior might be incorporated into such modeling activities, which would provide a measure of force cohesiveness based on the degree to which individuals in the force act in concert. Again, varying the numerical values of parameters used in the modeling, over appropriate ranges would give us sensitivity analyses from which we could hopefully derive tentative, quantitative combat laws. A review of historical data would be instituted to provide corroboration.

This approach is largely one of analytical experimentation (category [b]), discussed earlier. To the extent that we lack necessary behavioral data, elements of behavioral experimentation (category [c]) might be involved. It should be noted that this is a "bottom-up" approach to combat theory, while the second approach discussed can be characterized as "top-down." Furthermore, the approach under discussion is built around simulation techniques and the earlier approach is based on closed-form analytical modeling with historical validation. There is some merit in the simultaneous pursuit of both approaches for a degree of synergism they might afford in an attack on the problem.

A fourth example of an approach to the development of quantitative laws of combat consists of a way to address what is perhaps the central or core issue in combat theory: command and control. The approach represents category (c) and employs artificial intelligence (AI) techniques. The approach consists of man-machine interactive or player-assisted games which observations are made of the behavior of different human players (each of which is an avowed expert) as repeated plays of the game are run. Computer algorithms are, of course, used to generate the outcomes of decisions made by the players, permitting assessments to be made of the decisions — whether they are "good" or "bad." "Good" decisions are then captured in sets of contingency rules that are developed and can subsequently be used in automated games or at "unmanned" decision nodes in interactive games when the availability of game players is limited.

This AI approach seems to be a straightforward, obvious one when considering how to better represent the command and control function in combat modeling. The technique described also has utility if one attempts to select a preferred C^3I structure or systems from among several alternative concepts. In the latter instance, the "correctness" of the combat process algorithms or the input elements used in modeling outcomes may not be significant issues if our selection is to be based on relative comparisons of gaming results. For developing a theory of combat, however, this approach presents us with a "chicken and egg" situation. If good command and control should derive from the application of combat theory (if such theory existed), can we successfully seek a theory of combat by experimenting with command and control in the manner described? It is highly unlikely that this alone would suffice. Clearly, the combat theory issue is broader than that of just command and control, yet most would agree that a good understanding of the command and control process is of utmost importance to theory development. Thus, the above approach is germane, albeit obliquely, to the development of a combat theory.

Philosophically there is little doubt, when considering combat theory, that the concept of optimizing decision making on both sides afforded by applications of game theory is more appropriate for the purpose than the behavioral experimentation described above. Unfortunately (Section 4.6), many difficulties are associated with such applications. However, this should not rule out the possibility of experimenting with simple game theoretic models as advocated by Shubik in Reference 1.

In summary, the research challenge posed by a quest for a theory of combat is indeed enormous. The extent to which success can be realized in such an undertaking is impossible to foretell. Yet, any effort to develop a better understanding of the combat phenomenon, if planned and executed intelligently, can only prove to be beneficial to the diversified community that is involved with the development of combat models and the application of their results. Should the effort run into truly unsurmountable obstacles, even their identification can serve as an important research finding. Lesser difficulties, on the other hand, will define further research tasks to be undertaken so that the mainstream effort may proceed. In general, the effort would ideally involve a small, multidisciplined team of motivated researchers and thus, in a relative sense, would be a protracted one. Accordingly, the expenditure rates in such a program would in all probability be low. Furthermore, it is difficult to imagine that total costs would ever exceed those associated with the development of a small fraction of the more ambitious computer models that exist today. For those engaged in the research work, it is clear that patience, resourcefulness, and analytical ingenuity are called for in large measure.

Appendix A
COMBAT VARIABLES FOR QJM

The following variable effects are considered in the Quantified Judgment Model (QJM) (Reference 30).

A. Weapons Effects
- 1. Rate of fire
- 2. Potential targets per strike
- 3. Relative incapacitating effect
- 4. Effective range (or muzzle velocity)
- 5. Accuracy
- 6. Reliability
- 7. Battlefield mobility
- 8. Radius of action
- 9. Punishment (vulnerability) factor
- 10-13. Armor performance factors (4)
- 14. Helicopter
- 15-21. Special weapons effects factors (7+)
- 22. Dispersion factor

B. Terrain Factors
- 23. Mobility effect
- 24. Defense posture effect
- 25. Infantry weapons effect
- 26. Artillery weapons effect
- 27. Air effectiveness effect
- 28. Tank effect

C. Weather Factors
- 29. Mobility effect
- 30. Attack posture effect
- 31. Artillery effect
- 32. Air effectiveness effect
- 33. Tank effect

D. Season Factors
- 34. Attack posture effect
- 35. Artillery effect
- 36. Air effectiveness effect

E. Air Superiority Factors
- 37. Mobility effect
- 38. Artillery effect
- 39. Air effectiveness effect
- 40. Vulnerability effect

F. Posture Factors
- 41. Force strength effect
- 42. Vulnerability effect

G. Mobility Effects
- 43. Characteristics of mobility
- 44. Environmental effect

H. Vulnerability Factors
- 45. Exposure consideration, general
- 46. Environmental effects, general
- 47. Across beach
- 48. Across unfordable river
- 49. Across major fordable or minor unfordable river

I. Tactical Air Effects
- 50. Close air support damage and casualties
- 51. Close air support morale effect*
- 52. Interdiction logistical movement†
- 53. Interdiction delays on ground movement†
- 54. Interdiction damage and casualties
- 55. Interdiction disruption effect*

J. Other Combat Processes
- 56. Mobility effects of surprise
- 57. Surpriser's vulnerability effect
- 58. Surprised's vulnerability effect
- 59. Other surprise effects†
- 60. Degradation effects of fatigue and casualties†
- 61. Casualty-inflicting capability factor
- 62. Disruption†

K. Intangible Factors
- 63. Combat effectiveness‡
- 64. Leadership†
- 65. Training/experience†
- 66. Morale*
- 67. Logistics‡
- 68. Time*
- 69. Space*
- 70. Momentum*
- 71. Intelligence*
- 72. Technology*
- 73. Initiative†

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*Intangible; probably individually incalculable.
†Probably calculable; not yet calculated
‡Sometimes calculable

Appendix B
A COMMENT ON MODELS OF SOCIAL BEHAVIOR

The following excerpt is taken from Reference 56, J. Ziman, *Reliable Knowledge: An Exploration of the Grounds for Belief in Science*, Cambridge University Press (London, 1978).

> "... the dream of making a working model of social behaviour continues to grip the scientific imagination. It is conceded that such a model cannot be so simple as those conceived by past social theorists, but should nevertheless (so we are told) yield to the number-crunching power of a high-speed electronic computer. The aspiration of *general systems analysis* is to provide an instrument by which economists, businessmen, administrators, and politicians can make sound practical predictions. It has shown its value in the efficient management of material objects, such as the supply of components for the manufacture of motor cars, or the targetting of nuclear weapons on hostile cities; eventually it might help to reach less tangible goals such as national social development or personal health.
>
> We must regard these latter claims with considerable scepticism. There is, as yet, no evidence that any progress at all has been made by such means. Even the most elaborate economic models have failed to solve the problems of inflation, unemployment, exchange rates, etc. However detailed the mathematical computation, however many factors are supposedly taken into account, such an analysis is completely at the mercy of the assumptions that are made in setting it up. These assumptions, both as to the boundary conditions and constitutive equations, are subject to all the doubts and uncertainties discussed above. In many cases, the crudity and unreality of these assumptions are hidden under a mass of mathematical formulae, thus mercifully rendering a dubious argument completely opaque. Even when there is no claim to quantitative verisimilitude, the model usually contains doubtful qualitative relations between vague categories or hypothesized hidden variables which have never been shown to have any operational invariance. Such work must therefore be approached with a very cool eye. There is no reason why a piece of formal reasoning should be regarded as persuasive just because it is impenetrably complicated, when it does not satisfy in detail the elementary canons of scientific credibility.
>
> Indeed, what is often so puzzling about this sort of work is the status that is being claimed for the outcome of the calculations. The model can never be said to be so well founded that its predictions could be taken as seriously as those, say, of the performance of a newly designed aircraft. Nor are arrangements made to collect sufficient material evidence to confirm the predictions in detail, hence validating the assumptions of the model. On the other hand, the model itself is usually much too complicated to exemplify a general principle or to demonstrate a hypothetical phenomenon. It is thus difficult to decide what has been added to the archive of scientific knowledge by such investigations."

Appendix C

MATHEMATICAL EXPRESSION OF RELATIONSHIPS AMONG COMBAT OUTCOMES, ELEMENTS, AND PROCESSES

Stated in the simplest and most fundamental way, the relationship of combat outcomes to elements and processes can be expressed as:

$$\Omega = G_B(\lambda)$$

where

Ω = Engagement outcomes, dependent variables, expressed in terms of annihilation, territorial conquest and/or stalemate (see Reference 1, p. xiv, third footnote)

λ = The combat elements or the independent variables of the problem (see Section 3.2)

G_B = The battle process function that relates the dependent variable (outcome) to the independent variables (elements).

Also:

$$\Omega = f(\omega)$$

where

$\omega = \omega_a, \omega_s, \omega_m \ldots$, the outcomes of the various internal or component combat processes of attrition, suppression, movement, etc. (see Section 3.2) and, as such, are components of the vector, Ω

Furthermore,

$$\begin{aligned} \omega_a &= g_a(\lambda,\omega) \\ \omega_s &= g_s(\lambda,\omega) \\ \omega_m &= g_m(\lambda,\omega) \\ &\vdots \end{aligned}$$

where

g_a, g_s, g_m, etc., are the process functions of attrition, suppression, movement, etc.

There is no concealing the fact that we are addressing an inordinately complex problem in which any of the internal combat processes are functions of all other combat processes. This fact suggests iterative methods of solution, but such considerations are beyond the scope of the present paper. One should remember, however, that there exists an example of this concept in the body of analytical effort that has been devoted to just one of the "internal" combat processes; that of attrition (ω_a). In this particular instance, when working with the Lanchester equations, an attempt has been made to accommodate (for the most part, implicitly) the effects of the other combat processes in the attrition coefficients. In effect, attrition models of this type implicitly assume that $\omega_a = \Omega$, in the notation introduced here.

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