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Operations research in the high tech military environment: a survey

C. Steven Griffin
University of Central Florida

OPERATIONS RESEARCH IN THE HIGH TECH MILITARY ENVIRONMENT: A SURVEY

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C. STEVEN GRIFFIN
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ABSTRACT

The use of operations research as a technology to solve many of the problems of government and industry has become a major field of study within the very short span of the last fifty years. In the paper entitled, "Operations Research in the High Tech Military Environment: A Survey," the reader is provided with a better understanding of the tenets of operations research through an examination of a representative sample of the latest operations research applications developed for the high tech environment.

Initially, this involves providing the reader with some fundamental insights into what operations research is, what its practitioners do, and how the state-of-the-art has evolved to its present form. It then involves providing a brief description of what is meant by the term, "high tech military environment." A survey, which constitutes the bulk of the material presented, focuses on how various operations research methodologies are being used within that environment. The paper concludes with a discussion of the possible directions operations research will take in the future, based on the present state-of-the-art.

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NOMENCLATURE

APPS	Army Personnel Planning System
CONFORM	Continuing Concept Formulation
DMES	Deployable Mobility Execution System
DOD	Department of Defense
FORTRAN	Formula Translation
GAO	General Accounting Office
ICBM	Intercontinental Ballistic Missile
IFORS	International Federation of Operational Research Societies
ISD	Instructional Systems Development
MILES	The Multiple Integrated Laser Engagement System
NATO	North Atlantic Treaty Organization
ORSA	Operations Research Society of America
PERT	Program Evaluation and Review Technique
PROM	Programmable Read Only Memory
SDI	Strategic Defense Initiative
SHAPE	Supreme Headquarters Allied Powers, Europe
TIMS	The Institute of Management Sciences
TIS	Training Importance Survey

INTRODUCTION

The purpose of this paper is to provide the reader with a better understanding of the tenets of operations research by examining a representative sample of the latest operations research applications developed for the high tech military environment. Initially, this involves providing the reader with some fundamental insights into what operations research is, what its practitioners do, and how the state-of-the-art has evolved to its present form. It then involves providing a brief description of what is meant by the term, "high tech military environment." A survey, which constitutes the bulk of the material being presented, will focus on how various operations research methodologies are being used within that environment. The paper will conclude with a discussion of the possible directions operations research will take in the future, based on the present state-of-the-art.

The diverse works of many individual authors are summarized in a serial format in this paper. Each summary being presented has been extracted entirely from a particular work by the author, or authors, whose names appear at the beginning of each synopsis. Repeated author citations throughout the numerous synopses presented have been purposely omitted in order to make the paper more readable.

DEFINING OPERATIONS RESEARCH

Before surveying the current state-of-the-art in military operations research it will be useful to develop an understanding of what operations research is, and how it has evolved to its present form. In the fifty years since operations research has become a recognized profession, it has had an increasingly important impact on how organizations are managed throughout the world. Today, the Operations Research Society of America (ORSA), and The Institute of Management Sciences (TIMS) each have nearly 7,000 members. The four journals published each year by these organizations contain over 3,000 pages of information about new research and new applications in the area of operations research. In the International Federation of Operational Research Societies (IFORS) there are 29 member nations, each of which publish journals similar to those found in the United States (Hillier and Lieberman 1986).

Fields involved the use of operations research techniques are widely varied. Some representative titles of organizational departments involved in operations research range from Operational Analysis and Systems Analysis to Industrial Engineering, Industrial Administration, and Market Research, to name only a few. While the type of decision problems to which each of these diverse disciplines is oriented may vary, their objectives and methods are all basically the same (Operations Analysis Study Group 1977). The generally accepted categories of operations research problems are provided by Ackhoff and Rivett (1963) in the following list:

- Inventory
- Allocation
- Queuing
- Sequencing
- Routing
- Replacement
- Competition
- Search

With these things in mind a definition of operations research can now be explored. An excellent foundation has been provided by Stoller (1964), whose definition traces its roots to the very beginnings of the operations research profession. He states that at the founding meeting of the Operations Research Society of America in 1952, the members described the activities performed by the practitioners of operations research by saying that, "Operations Research is a scientific method for providing executive departments with a quantitative basis for decisions regarding the operations under their control."

He indicates that it was not too long before professionals in other disciplines pointed out that the same definition could apply to themselves equally as well, if the appropriate title substitution was made for the term, "Operations Research." To correct this problem an attempt was made to define operations research by listing the techniques with which operations research was characteristically associated. Stoller says that a definition of that sort would have said, "Operations

Research is the application of the theories of probability, statistics, queuing, games, linear programming, etc., etc., to the problems of war, government, and industry." However, this is equally as inadequate as the previous attempt because it is analogous to trying to define the activities of the medical profession by listing all prescription drugs.

Stoller contends that a better approach to the problem might be to examine and understand the two terms, operations and research, and glean from them an adequate definition. Research clearly indicates the use of the scientific method. In this case, the orientation of the research is toward the study of operations, where an operation consists of "an activity (or complex of activities) occurring in a man-machine system which is engaged in an established task, according to a set of rules." The final binding concept between operations and research is optimization. This is because the ultimate goal of operations research is to develop a methodology which will produce the best possible way to accomplish the activity being studied.

Additionally, operations researchers attempt to quantify the systems they study, and then use experimentation to deliberately alter that system in order to observe its induced behavior. Stoller brings together all of these concepts into a single definition, stating that operations research is "the use of the scientific method to provide criteria for decisions concerning man-machine systems involving repeatable operations." He points out that the actual list of techniques relevant to operations research is as long as the list of all scientific techniques.

Miller (1984a) points out that another important aspect of operations research, and one which is widely overlooked, involves the contributions made in the area of productivity, or the increase of outputs with fixed resources. He goes on to say that operations research aides in the measurement and analysis of input and output relationships through the use of the classical techniques of optimization, mathematical programming, combinatorics, and simulation.

A much more recent definition given by Hillier and Lieberman (1986) provides some final insight. They state that operations research is concerned with studying deterministic and probabilistic systems which occur in real life, and then modeling them to in order to reach optimal decisions concerning the allocation and use of scarce resources.

To summarize the contributing aspects of these definitions, it is clear that the essential characteristic of operations research is a systems orientation toward decision support through the adoption of the five phases of the scientific method, namely observation, definition of the problem, formulation of a hypothesis, experimentation, and verification of results (Levin and Kirkpatrick 1975).

The preceding discussion about what operations research is, and what its practitioners do, provides the foundation necessary to appreciate the scope of work which is being presented in the survey of operations research applications which follows. However, before examining specific applications it is necessary to discuss what constitutes the high tech environment.

THE HIGH TECH MILITARY ENVIRONMENT

The previous discussion has clearly shown that the field of operations research is very broad, and that its problem solving techniques are used in a wide variety of professions. However, as is the case with any technology, the continued advancement of the state-of-the-art depends largely upon the amount of money spent over time on the performance of research and development activities.

It is not surprising that the largest annual budget for research and development in this country has been that of the United States government. The 1987 federal outlay for research and development is in excess of $45 billion. What is somewhat more surprising, however, is the fact that over 75% of that figure, or roughly $33 billion, has been allocated for research and development for military-related activities being conducted under the purview of the Department of Defense (Greenburg 1987).

The military's seemingly never-ending drive to be at the very forefront of technology is well publicized. Many of the advancements made across a broad spectrum of applications used in civilian life have come about as a direct result of military spending, and the same is true concerning operations research.

One of the most notable and important contributions that have been made to civilian operations research by military operations research is that of the Program Evaluation and Review Technique, or PERT, developed as a project management tool for the Navy's Polaris program (Malcolm 1978). PERT has evolved into a standard project management tool for both military and civilian projects.

PERT is still required on most DOD programs including those in Space Defense Initiative (SDI). For example, recent Requests For Proposals issued to two major defense contractors by the Air Force for the Neutral Particle Beam Integrated Experiment included the requirement to submit PERT activity charts in their respective bids.

Another example of how the military has taken the lead in operations research lies in the Navy's recognition after World War II that there was an urgent need for operations research professionals in its ranks. This lead to the establishment in 1951 of a curriculum in operations research at the Naval Post Graduate School in Monterey, California. This was the first formal program of its kind among the military services, as well as one of the very first of such programs established anywhere (Operations Analysis Study Group 1977). Today, no major university is without extensive class offerings in operations research at both the undergraduate and graduate levels.

Therefore, for the purposes of this paper, the high tech military environment will be defined as the continuing technological interests of the armed forces. The remainder of the material presented will address the question of how this technology called operations research has been recently advanced through its application to military problems. This survey is an attempt to examine the latest work being done in military operations research by describing representative models being developed to solve particular problems. In the process it is intended that some insight will be gained into how military applications of operations research are continuing to shape similar applications in civilian areas of study.

MILITARY APPLICATIONS OF OPERATIONS RESEARCH

The following is a generally accepted list of the major military applications of operations research as categorized by Hoeber (1981). These topics will serve as a framework for the survey of specific applications being addressed in this paper. It is recognized that while this list may not include all possible military applications of operations research, it is capable of categorizing the vast majority.

- Procurement and Acquisition
- Costing
- Strategic and Tactical Combat Operations
- Combat Support Services
- Force Structure and Sizing

Procurement and Acquisition

The proliferation of material concerning the procurement and acquisition of systems and materiel for the military has been quite extensive in recent years, and almost exclusively negative. The media regularly points out the deficiencies in the procurement systems used by the various Department of Defense agencies (DOD), and the apparent lack of control that exists within them. It was mentioned earlier that the majority of the federal government's expenditures for research and development are allocated to the military. This has been a trend that has evolved over the last two decades. An accompanying trend during that same time period has been the fact that the responsibility for managing military research and development has gone from civilian operations research professionals centered at prominent universities, to relatively untrained military officers with short tenures based within each of the services (Johnson 1978).

Probably one of the single biggest problems faced in the procurement and acquisition process are the changes in military strategy and planning brought about by the turnover in the political hierarchy in both the legislative and executive branches of the government (Agapos 1975). This causes frequent shifts in the priorities of long range research and development, which has lasting implications on the ability of the nation as a whole to meet and finance defensive needs. However, significant progress is continually being made by operations researchers within the DOD to turn the unfavorable trends around.

This section will be an examination of the various ways operations research is being utilized in the procurement and acquisition process. Once the examination of the process has been completed two specific applications will be presented.

Unlike the material which is being presented under some of the other major topics, the operations research analysis being performed to solve procurement and acquisition problems tend to concentrate on the process as a whole, rather on specific applications. This is because operations researchers are striving to understand the tremendous complexity of the process, in order to formulate feasible improvements in its efficiency, effectiveness, productivity, and cost (Sink 1984). Furthermore, despite all that has been written to the contrary, significant gains in the procurement efficiency of the DOD have been made. Possibly the best example of this has been the savings realized by the actions of the Defense Resources Board established in 1984. Their function has been to insure the interoperability of tactical command and control systems, the efficient allocation of resources for the acquisition of conventional weapons, and the integration of the various planning functions for munitions acquisitions. This has been done to better assess options for attaining a proper and affordable mix of systems in the proper quantities for all of the services. This interservice inititive has been in direct response to congressional requests for greater economy and enhanced effeciency in DOD procurement practices, and has resulted in nearly four billion dollars of savings in multiyear procurements for the present administration (Kozicharow 1985).

Since World War II the increased emphasis among the tri-services to acquire the most current and sophisticated battlefield technology has been well documented. While it is beyond the scope of this paper to examine all of the trends associated with military procurement cycles, one trend which has continued to be a major problem in DOD procurement efforts has been addressed by Stubbing (1986). He claims that, in an effort to make every procurement the best that it can possibly be, the process of requirements generation is dragging down the fielding of new systems. This is primarily the case where trying to get "the most bang for the buck" has resulted in what is called the "Start-Stop-Restudy Syndrome."

This is the process of continually rejecting current solutions to examine increasingly complex alternatives in an attempt to squeeze the most state-of-the-art technology as possible into a given system. This results in an escalation in product cost rather than resulting in the desired goal of cost minimization. Obviously at some point, the optimization process must stop and the hardware built and fielded. To better understand this problem an examination of the unique process of procurement and acquisition within the DOD is in order. This will provide for a basic understanding of how the DOD and its suppliers are organized to do business.

In order to understand the principal differences between a firm involved in traditional industrial capitalism and a firm involved in production for the military, the military industrial firm has been modeled by Gorgol and Kleinfeld (1972). This model provides an excellent explanation of the behavior of the military industrial firm as an increasingly important portion of the economy of the United States. Central to this model, which includes a computer simulation, is the premise that military industrial firms do not operate in an autonomous, cost-minimimizing, profit-maximizing manner as is the case with traditional firms in a free enterprise economy.

In a traditional firm, autonomous means that the management of a firm is responsible to determine product type, quantity to be produced, method of production, price, and marketing strategy. Competition requires the traditional firm to minimize its costs, so that their product can be sold for maximum profit accumulation. This in turn spawns new capital investment. In the military industrial firm, however, these decisions are made largely by the Pentagon, which uses competence rather than cost minimization as the production criteria. Five hypotheses are used in this theory of the military industrial firm.

The first two hypotheses deal with the marketing activities of the military industrial firm. The first says that the principal product of such a firm is technical competence. Military industrial firms often allocate substantial resources to respond to the technical proposals of the Pentagon decision makers. The second hypothesis says that since competitors are often able to display equal technical competence, it is necessary for them to further influence Pentagon decision makers by convincing them that, in the long run, their firm's particular emerging technology will be better in the future than that of the competition.

Hypothesis three states that, unlike firms in the civilian market, product pricing in military industrial firms is accomplished through negotiation rather than market competition. Inherent in this is the fact there is a binding relationship between the negotiating parties involved, which in turn taints the process and results in excessive product cost.

The fourth hypothesis states that an essential strategy of the military industrial firm is to accumulate as much government owned equipment as possible in support of ongoing contracts. This, in effect, adds to the firm's capital equipment base without expenditure. The final hypothesis says that the top management of the military industrial firm has to seek additional advantage through the use of political influence. This includes direct solicitation of politicians and media advertising aimed at the general public.

The computer simulation mentioned earlier provides an interpretation of how the military industrial firm will evolve over a long period of time with respect to the five hypotheses. Included in each time interval of the simulation is such information as the number of contracts in the modeled firm's backlog, the number of contract attempting to be won, and any technical advances achieved over the competition. Many probabilistic relationships are embedded in the model for such factors as the technological advances, resource allocation, technical competence, and political influence. Several ratios are generated as output to the simulation which measure the firm's efficiency, thereby setting the stage for strategies in subsequent iterations. The book concludes with several detailed recommendations for improving the procurement and acquisition process based on the provisions of the theory, and the results of many iterations of the simulation.

Because of the huge amounts of money which have been spent in recent years for the procurement and acquisition of military hardware, a considerable amount of public debate and scholarly research has been centered around the question of whether or not the United States and the Soviet Union are engaged in an arms race. Ward (1984) has examined this question using a continuous time simulation model based on a combination of ordinary differential equations, and a non-linear least squares minimizing algorithm.

The results of his model indicate that the two superpowers are indeed involved in an arms race. The model suggests that each country bases its own military spending budget on comparisons between stockpiles, rather than comparisons between military budgets. This results in a situation where each nation stimulates the other to spend more, because existing stockpiles of the opponent's weapons are always perceived to be very large.

Several variables have been used in this simulation including the standard economic constraints of budget availability, depreciation, and investment, as well as such factors as perceived hostility. Also included in the simulation are the effects the natural buildups associated with the military actions in both Korea and Vietnam. Estimated and actual plots of stockage and spending levels are presented for the periods from 1950 through 1980. They indicate the model is capable of providing predictions which very closely fit the actual historical data for that same period of time. The author suggests that while the model is probably capable of accurately forecasting the military and strategic climates of the superpowers in the near term, it may also have value in the examination of the effects of internal and external social influences on military spending patterns in the future.

A seldom written about topic involving operations research in the procurement and acquisition of new weapons systems, namely the role of human factors analysis, has been addressed recently by the Staff of the United States General Accounting Office (1982). In a recent study they state that it has been the policy of the Secretary of Defense for some time to insure that certain analysis has been performed concerning various training, manpower, and human factors engineering constraints. This analysis has been required as part of the justification for moving on to subsequent phases in the acquisition cycle. The four phases are

Program Initiation, Demonstration and Validation, Full Scale Engineering Development, and Production and Deployment.

The policy requires each of the services to provide specific information concerning several relevant human factors issues, including peacetime versus wartime manning requirements, and desired skill and training levels required by each system throughout their projected life spans. Inherent in this process is the quantification of man-machine tradeoff criteria, and system imposed operator workload and safety restrictions. The GAO has identified auditing guidelines to address these issues, and has provided its field personnel with an extensive set of checklists and questions with which to audit both sides of the service/contractor team. To conclude this section on the use of operations research in military procurement and acquisition activities, two applications will be presented.

The inherent uncertainties associated with the procurement of weapons systems for the satisfaction of future battlefield applications was addressed by Daniel, McCullagh, and Moffat (1984). They developed a linear programming model to determine how to stockpile the optimum mix of air delivered weapons for multi-role aircraft. The information obtained from this model was fed to decision makers for use during procurement activities. This model was designed as a decision support system for determining the optimum air deliverable ordnance stockpile policy to be used in preparation for a conventional war in Western Europe in light of several important financial, logistical, and tactical constraints.

The modelers were faced with the task of quantifying and balancing the factors of cost and operational flexibility which would allow their decision makers the greatest amount of freedom in both the procurement of the munitions and their associated use in combat. This was done by first understanding the full potential of both the primary and secondary roles of the aircraft and weapons involved and second, by understanding various stockpile strategies so as to fully realize the potential benefits and penalties for all given munitions policies under study.

The objective function has been designed to first, minimize shortfalls in weapons stocks, second to maximize flexibility, and third to organize the mix of weapons among aircraft roles. It provides for a model which not only addresses the three topics required to maximize the flexibility in the stockpile of weapons, but also allows the user to adjust the relative importance of each component. This has been to done to allow for additional analysis into the resulting sensitivity of the optimal mix.

The results of their study indicated some interesting facts, most of which are intuitively correct. First, the number of sorties controls the flexibility of the mix, regardless of how much is spent at the upper limits of the budget. As the budget is reduced the number of weapons held in the stockpile stays relatively constant without a loss in flexibility. This is because, in general, cheaper more versatile weapons are being purchased and used in a greater number of roles rather than fewer expensive, specialized weapons being used in a limited number of roles. At the low end of the budget the stockpile level drops dramatically and flexibility approaches zero.

Nickel and Mangel (1985) developed a model very similar to this in which two special cases of optimizing the utility of the mix were examined. The first case involves a simultaneous attack model where all weapons are used at once. The optimal mix is determined by a two-stage procedure where an association is made between a certain weapon type and certain target type. The second case examines how the optimality of the mix is altered when the weapons are used over a period of sequential attacks where targets appear in a randomly distributed order.

The results of this study were essentially the same as the one previously discussed. General purpose weapons are well suited to situations where there is uncertainty about targets. Additionally, the author found that the value of special purpose weapons are generally overestimated unless large percentages of potential targets are known at the time of the procurement. Finally it was found that if there is an adversity to risk over a number of possible scenarios then the optimal mix of weapons to procure will include a high percentage of general purpose weapons.

Costing

Fox (1974) states that in large development programs the Department of Defense is responsible for evaluating the potential militaristic value of a given system and its projected fielding date against what the estimated future cost of the system will be. To produce adequate cost estimates depends in large part on the personnel and methodology employed. Decision makers must have confidence that the assumptions on which the estimate is based are sound and that the model being used will subsequently yield reliable data. Additionally, it is important for decision makers to understand the bounds of accuracy of the estimate presented for consideration. Cost estimates are required for five types of activities in the military. They are planning, budget preparation, contract pricing, contract change pricing, and program measurement and control.

In addition, the military uses three basic types of estimates for large development and production contracts. Parametric estimates are derived by correlating the actual costs of previous systems to the physical characteristics of the system under study. Engineered estimates are obtained by summing the costs of the detailed components of the system, and learning curve estimates are obtained from the application of a standard algorithm to the actual cost of units previously produced.

Substantial systems analysis is required in the procurement and acquisition cycle. It is used in the Office of the Secretary of Defense to analyze cost estimates and prepare detailed cost-versus-effectiveness ratios for new systems under study in the defense budget. This analysis provides a framework to determine cost effectiveness, describes the activity interactions which affect cost, and allows for the comparison of program alternatives. Once the initial model is established new cost calculations can be formulated as assumptions are modified. The internal systems analysis function is vital to the entire procurement and acquisition process, because it provides the Secretary of Defense with the only scientific analysis not provided by the various branches of the military or their prospective contractors.

A decision-making method which has gained in popularity over the years called cost effectiveness analysis has been addressed by Fritz (1976). He states that estimates of cost effectiveness can be used for project selection, as justification for continuing from one phase to the next in the acquisition of a system, or to highlight potential problems concerning cost weakness in a program.

Several algorithms are used in the various cost effectiveness analysis models presented. They include linear and non-linear programming, branch and bound, stochastic dynamic programming, and game theory. The basic objective of cost effectiveness models are to minimize resource expenditure while satisfying defined specifications. Objective functions are defined in terms of either maximization of effectiveness subject to cost and time constraints or, minimization of cost subject to effectiveness and time constraints. Effectiveness is measured for different states in terms of availability, capability, and dependability.

Seldon (1979) contends that as high as the initial costs for the acquisition of new military systems are, the costs of maintaining existing systems and the personnel and facilities organic to their operation are even higher. The Department of Defense has been a victim in the past of purchasing a new system for a low price only to find out over the course of subsequent years that the operation and support costs associated with the system were grossly underestimated at the time of the procurement.

To help eliminate this problem a methodology called Life Cycle Costing has been developed. This concept requires more money to be spent during research and development in order to more thoroughly quantify the operation and support costs of a system during its useful life. By following this methodology the Department of Defense gains a substantially better total system cost as a data point for source selection decisions.

Several of the primary uses of Life Cycle Costing are: long range planning and budgeting; comparison and selection of competing programs; decisions concerning the replacement of aging equipment; control of an existing program; and comparison of logistical alternatives. The Life Cycle Costing model recognizes the fact that estimating is a probabilistic process, and provides for bias weighting of any estimator's input by statistical adjustment.

The Navy has been quite active in the use of Life Cycle Costing for all CONFORM feasibility designs (Spaulding 1984). CONFORM is the Naval Sea Systems Command's Surface Ship Continuing Concept Formulation program. This program seeks to provide costed design information to the Office of the Chief of Naval Operations of projected mission requirements for periods of up to twenty-five years in the future. Credible cost estimates for these new designs are considered an absolute necessity.

It is the strict intent of the Navy to use life cycle costing as a means of escaping the trap of acquisition cost justification for new programs. By embedding life cycle costing in the mechanics of the CONFORM program it is hoped that more weapon systems acquisition decisions will be based on complete life cycle cost considerations. It is for that reason that the Navy requires all CONFORM final feasibility design reports to include life cycle cost analysis. Even though these estimates are not considered official for the purpose of bid analysis, the information is vital for study purposes within the Navy bureaucracy. Additionally, as more and more cost information is captured for particular technologies and systems, the data is fed to a central automated estimating system, where it becomes available for all other program estimators to use.

STRATEGIC AND TACTICAL COMBAT OPERATIONS

Deitchman (1979) has described in great detail how the operations research community and the military have teamed up over the years to greatly advance the state-of-the-art in analytical war gaming through the use of increasingly sophisticated computer hardware and software. Programs have been written to mathematically describe the operations of the opposing forces, and then calculate the effects of such variables as artillery, armor, ground forces, air forces, logistics, and defensive conditions, on each force.

Dependency of the variables in such complex models are established mainly through the use of historical data of actual battles, and various forms of testing. Using the mathematical relationships established in the models makes it possible to study the effects of a battle, or of successive battles, and relate them back to the players. The first such mathematical description of modern combat operations was presented by Englishman F. W. Lanchester in his famous 1916 book entitled, "Aircraft in Warfare: The Dawn of the Fourth Arm."

Since those crude beginnings, operations researchers have created combat models of such complexity that today's simulations can describe entire theaters of operation such as that of Western Europe. This includes the probabilities associated with target acquisition and target damage, ammunition usage rates, the effects of threat weapons systems, required aircraft sortie densities, and combat effectiveness degradation resulting from casualties.

Multiple interactions in the logistics base have also been evaluated in such areas as troop movements across large geographical areas, closing of resupply routes, degradation of depots by land and air attack, and the organization of forces for offensive or defensive operations. The decisions in the models are rule-based and dependent on serial activities over large spans of time.

The shortcomings which still remain in such models include many factors which are difficult to satisfactorily quantify, but which are all crucially important to the outcome of conflicts of any magnitude (Deitchman 1983). They include such things as the effects of troop training and morale, the experience and attitude of commanders, effectiveness of communications and intelligence gathering, the effects of ideological and political factors, and the economic interactions of opposing forces and affected third parties.

Another shortcoming of analytical war game models is that they are generally very sensitive to their respective input parameters. This means that extremely small changes in some parameters can cause huge differences in outcome of the simulation. An analysts' assumption concerning a seemingly insignificant parameter such the amount of time tanks fight from protected positions versus unprotected positions can effect the outcome of all tank engagements and thus effect the outcome of all battles which include tanks. This in turn will have an effect on the outcome of the simulation.

Deitchman (1979) also says that, " although the models cannot describe the impact of extreme events that have often occurred in warfare--the loss of the will to fight by one side, the poor use of overwhelming force by the other, collapse of a retrograde movement into a rout--they can describe what would happen in a war based on the interplay of resources alone." Even so, analytical war game models provide a great deal of utility. In the case of modern warfare in Western Europe it is generally felt that the casualty rates on both sides will be high, especially in the losses of certain weapons systems, so model outcomes based purely on the interplay of resources continue to give increasingly better information with which to plan for the actual conflict.

Thomas (1961) indicates that military war gaming dates back as far as the Prussian Army of 1824 when von Reisswitz, Jr. introduced the Kriegspiel. During World War I the Germans used war games as substitutes both for actual field experience, as well as to rehearse projected campaigns. Along with the use of war games through the years has come much praise and much criticism. They have been found to be universally accepted as excellent training devices, and universally scorned because of limitations in the abilities of the games to be simultaneously faithful to both realism and ease of play.

Combining classical war gaming with two important products of the middle of the Twentieth Century, mathematical gaming theory and digital computers, have brought the state-of-the-art to its present form. The following section contains some of the latest work being done in this field.

Sherif (1982) states that game theory involves describing the outcome associated with a competitor making one of many possible decisions, while an opponent makes similar decisions but with a diametrically opposed intent. He has classified war games according to the following categories.

- General air defense
- Antiballistic missile
- Antisubmarine
- Attrition
- Blotto
- Bomber interceptor
- Combat (duels)
- Fighter versus bomber
- Hunter versus bomber
- Lanchester
- Missile versus bomber
- Missile penetration
- Point and area targets
- Pursuit and evasion
- Search-Attack-Defense
- Submarine versus submarine

Through the research conducted for this paper it was found that most of the work being done by operations researchers involved in the quantification and mathematical representation of war games is concerned with duels. Duels are games which deal with the timing of individual decisions during a competition. Practically all of the categories listed above deal with duels, therefore the subject will receive considerable attention in this section.

Sherif (1982) says that in duels the best strategy is to delay decisions as long as possible without being penalized. Duels in which an opponent is informed about the actions of their enemy as they occur are called noisy. If neither opponent is informed of his enemy's shots the duel is called a silent duel.

Duels are fought under various conditions which include the number of shots fired (one versus many), accuracy (equal versus arbitrary), opponents (combinations of one, few, or many), survivability, and target worth. Obviously the greater the complexity, the greater the difficulty to model, and the more restricting the assumptions must be in order to even get started.

One model which attempts to address some of the more complex conditions has been presented by Feigin, Pinkas, and Shinar (1984). In this model an attempt has been made to describe and analyze air combat in which there are multiple opponents on either side. There are major differences between one-on-one air battles and many-on-many air battles. Some of the specific problems generally faced by modelers have included a general inability to mathematically describe a knowledge of the folowing factors; the number of opponents on each side, the performance characteristics of aircraft and weapon systems, accurate information on the positions of opponents and friends, and the probabilities of successful weapon firing.

Much of the complexity arising from such a combination of probabilistic and deterministic factors have been eliminated in this model by reducing the total battle into major events in which very small numbers of planes engage for short periods of time. It has been submitted by the authors that the characteristics of these individual engagements will lead to a doctrine which can be extended to include the case of multiple air-to-air combat engagements.

This model is a departure from other techniques traditionally used to study the many-on-many air combat case. This is because most models disregard the dynamics of simultaneous, multiple, individual duels. This particular model has been developed from a simple case at the micro level of the overall battle and then used as a prototype for far more complete and complex Markov models at the macro level.

Aircraft are described to always be in one of three roles during the battle, either as pursuer or evader, or in a free state not engaged in any duel. Also, four states exist for the combat in progress at any time. In the first state an individual duel is ended by the destruction of the evader by the pursuer, who then becomes free. In the second state, a new duel begins when two free opponents engage. In the third state the evader successfully disengages from the pursuer, and both opponents become free. In the final state a free plane engages a pursuer, who in turn becomes the evader, and the original evader becomes free. The time dynamics of the model are described by a continuous, discrete state Markov process.

In their conclusion the authors felt that after examining several possible modifications to the model, it would be able to serve as a useful analytical tool for decisions concerning development planning for future aircraft and aircraft weapon systems. This would include both cost effectiveness of competing designs and optimal force sizing for multiple engagements.

Another type of war game model under the category of point and area target acquisition has been presented by Schroeter (1984). This article addresses the problem of firing on units which consist of any combination of multiple vehicle types, such as tanks, self-propelled artillery pieces, or trucks. From the attacker's standpoint these units are considered to be multiple-element targets with the vehicles dispersed randomly within a boundary consisting of all individual target elements comprising the unit. Usually an aircraft or artillery salvo is fired at the center of the unit, rather than at a single vehicle, with the intention being to produce detonations sufficiently close to individual elements of the unit to inflict the maximum amount of casualties possible. Most models developed in this area of study seek to describe the probabilities associated with randomly hitting a single point target in a given salvo.

The author contends, however, that the data which is really needed by weapons effect analysts is the probability that a certain number of casualties will occur in a collection of a finite number of point targets. The model presented by the author describes the derivation of the integral expressions of those kinds of probability distributions.

The probabilistic variations associated with three basic error sources are also explored. They are the errors caused by inaccuracies in locating the center of the target, independent movement of the individual target elements within the target area, and ballistic impact point variations of the weapons involved. The model provides two capabilities. First, it describes the relationship between higher salvo coverage in the target area with the likelihood of killing a certain number of point targets within that area. Second, this data can then be used to compute the associated casualty probabilities, thus filling in a major missing link in this type of prediction.

In an analogous article by Hamburger and Slagle (1986) the question addressed concerning target acquisition and destruction was one of how to decide whether to fire at an identified target in the first place. Their model discusses how a fire decision center should proceed in the case of a direct observation of a point target in the open given a choice of many possible engagement weapons.

The purpose of the model is to quantify five basic parameters and base both the decision to fire, and the selection of the weapon on a probabilistically derived destruction expectation. The five parameters are the value of the target, the cost of firing any single round, the probability of hitting the target with any given round, the expectation of target destruction with any number of weapons firing a single round, and the additional or marginal expectation of target destruction realized by firing the last weapon.

The results from this examination indicate that it is possible to compile specific firing rules derived from heuristics, expert systems, and calculated probabilities. These guidelines will then provide information about when not to fire at observed point targets, when to fire only minimal amounts, and when to mass many weapons to absolutely assure destruction.

Once the decision to fire has been reached the problem then becomes how to calculate the position of the target and translate that information into range, elevation, and propellant data which can be used by the gunners. In a recent paper by Sherif et al. (1985) it has been proposed that the firing tables of field artillery pieces can be modeled through the development of a family of functions describing all factors involved in successfully placing a round on the target. They propose that by embedding those functions in a PROM (Programmable Read Only Memory) chip of a microcomputer, it would be possible to eliminate the need for both the conventional manual tables, as well as the current computer stored tables which require large amounts of memory.

The new microcomputer based system being proposed would be much smaller than what currently exists, and would better facilitate transportability, reduced power consumption, and human interpolation. Extensive testing of the derived functions indicate that the variance factors included in the current tables, propellant charge and temperature, projectile-fuze weight combinations, air temperature and density, wind speed and direction, and rotation of the earth, can be successfully modeled within established parameters. Using this new method would eliminate the current problems associated with variations in human performance, and inadequacies inherent in present automated systems.

In recent work sponsored by the U. S. Army Research Office, the theory of the fundamental stochastic duel has been examined by Anker (1984), and subsequently extended. This general type of mathematical problem considers two opponents firing at each other. Each of the opponents begins with unlimited ammunition and time, and an unloaded weapon. Additionally, they are assumed to fire at one and other at either a fixed time interval or at a continuous random time interval. In the fundamental theory, the probability of a hit on each round that is fired is assumed to be constant.

In this particular examination, the theory was extended to describe hit probabilities as a function of time since the duel started. Time varying hit probabilities of this type have several important combat applications, including the increased likelihood of artillery hits as accuracy is introduced through the observation and adjustment of fire in subsequent rounds. The author presents two unique derivations. In the first it is assumed that there is but one marksman firing at a passive target. This was done to secure the characteristic functions used in determining the time involved to secure a target hit. The second derivation examines the probabilities associated with a given side winning under the conditions of a duel when both sides are firing.

In addition to the fundamental one-on-one stochastic duel described above another mathematical model has been developed by Gafarian and Anker (1984) to describe the previously unexplored case where two contestants on one side face a single contestant on the opposing side. It is assumed in this model that each of the two contestants on the first side have the same random interfiring times and the same kill probabilities during their continuous firing. As was previously the case, the engagement continues until one side is completely destroyed with no limitation on the number of rounds fired or the length of time involved.

This model also begins by assuming that each of the three contestants is a separate marksman firing at a passive target. It also looks only at shots that are kills, rather than every firing, in order to simplify the already complex equations presented in the body of the article. To obtain the desired results a technique described as backward recurrence is used to determine the three marksmen's state probability functions. The conclusions reached by the author indicate that the traditional approaches used in the one-on-one models are not valid for the two-on-one case.

In order to diminish the effects of increasingly lethal and numerous missile attack systems, a model has been developed by Gould (1984) which attempts to minimize the allocation of two vital defensive resources, available shots to destroy the inbound threat, and the available rate of fire. This model shows analytically how to decrease the use of these two resources while still maintaining the required probability of threat kill.

Most current battle doctrine advocates firing several shot at a given target, thereby substantially lowering its probability of surviving. The author contends however, that by dividing the number of defensive shots fired into several sequential discharges, or salvos, the same kill probabilities are obtainable with fewer total shots, and at a reduced rate of fire. This in turn raises the threshold at which defensive forces are overwhelmed by sheer numbers. In order for this type of policy to be implemented however, requires increased surveillance and weapon systems ranges as well as an adequate kill assessment capability.

The analysis offered by the author shows that if the single shot kill probability against any target is nondecreasing from shot to shot, then the same is true for the salvo policy. This means that the expected number of total shots required to kill a target decreases as the number of salvos increases. The example presented shows that if the kill probability of any single shot is constant at .6, then a policy of a single, simultaneous, six shot salvo would produce a joint probability of kill of only .6. However, if the policy was six, successive, single shot salvos with the same kill probability of .6, then the resulting joint probability of kill would be in excess of .99 and the expected number shots used to kill the target would be reduced from 6 rounds to 1.66 rounds.

A subject which has received a great deal of attention in recent years has been the many facets of ballistic missiles used for both attack and defensive roles. As excellent model on this subject has been proposed by Hoyt (1985). It allows decision makers to see how a simple model, which utilizes only essential information, can be useful in providing a straightforward introduction to the complexities of the ballistic missile problem. The model is designed to evaluate the capabilities of any given layered defensive scheme. Prior to actually presenting his model, the author first provides some very useful information which will serve as an excellent introduction to the subject of ballistic missiles.

From the offensive standpoint, missile trajectories pass trough three basic phases, namely boost, midcourse, and terminal. The boost phase lasts only a few minutes and, from a defensive standpoint, constitutes the most fruitful time for destruction. This is due to the fact that there is a nearly universal capability among weapons producers of packaging several warheads on a single rocket, therefore, destroying one rocket destroys several warheads.

The midcourse phase begins as the payload is deployed into its many separate reentry vehicles and decoys, each on their own trajectory, in the upper atmosphere. This generally takes about thirty minutes and culminates upon reentry. The ensuing terminal phase, which lasts less than a minute, delivers the warheads to their individual targets.

Engaging the hostile missile for defensive purposes can occur during any phase, with each phase requiring its own technology. Defense in the terminal phase means having to fire many, very fast, very accurate interceptors. During the midcourse phase there is more time, but there are also many more things to attack. The general consensus has been to provide defense in layers, which increases survival prospects by increasing combined effectiveness. The offensive strategy, on the other hand, has been to shoot so many real missiles and decoys that the defender will simply run out of interceptors. This means that the attacker's remaining missiles will then be able to proceed with attack unhindered, and literally destroy targets at will.

In describing his model, Hoyt points out that it is important not to waste defensive interceptors if at all possible. As incoming targets are destroyed they must deleted, somehow, from the remaining list of possible remaining targets. This must be done to insure active defensive weapons are always seeking to destroy active offensive weapons. The author calls this type of system shoot-look-shoot, and bases his model on this principle.

A successful defense in this scenario depends on two basic commodities, the amount of time it takes to detect, launch, and intercept a hostile missile, and the number of defensive weapons available in the arsenal to attack the missiles during the three phases described above. For that reason, the model's algorithms deal mainly with keeping track of time and the total number of defensive missiles available during the simulation. Parameters of both the offensive and defensive systems are input at the beginning of each simulation.

It was acknowledged by the author that this is a somewhat unorthodox approach to use in simulating ballistic missile engagements. However, it has been found that because the model is so easy to use, and so readily shows the relationships of the variables involved, it is easily adaptable as both a training system, and as a benchmark systems for testing other ballistic missile models.

The possibility of fielding long range strategic missiles on large underground track systems has necessitated analysis concerning evasive movements to avoid possible destruction by hostile missiles (Turner and Holmes 1984). The purpose of this model is to develop a strategy for a vehicle continuously moving along a track at a constant speed, reversing directions at random. In addition, it is also concerned with the attacker's objective of observing the target and predicting its position in the future so that a missile can be accurately sent to destroy it.

In the way of simplification, it has been assumed therefore, that the underground vehicle will travel along a fixed path and change directions according to an exponential distribution. In actuality the direction of travel and the time between direction changes will have arbitrary probability distributions. Semi-Markov processes have been used to determine the state of the vehicle and its direction of travel. The product of this work yields a model which provides for an adequately secure movement plan and includes "sufficiently complex" random attributes to confuse enemy prediction attempts.

Another model that has been developed to address the problem of incoming missiles is described by Burr, Falk, and Karr (1985) in which attacking missiles are intercepted and destroyed. The roots of this study date back to the late 1950s when the Secretary of Defense wanted to describe the process of defending separated point targets from an attack by sequentially arriving ballistic missiles. This has come to be known as the Prim-Read doctrine for its original developers. The model presented by the authors looks at minimizing the total interceptor missile force needed to successfully defend a know number of separate point targets when the number of attacking missiles is unknown to the defender.

The assumptions made for this model provide a very realistic view of how the conduct of a battle is likely to occur. First, the assumption is made that the defender must set his strategy before the attacker, and that the kill probability of any interceptor is fixed and known. Second, defending interceptors can only be used to defend a single point target because the individual targets are separated by such a distance to make dual assignment impossible.

Third, the incoming missiles arrive sequentially such that the fate of each can be determined independently from all others. Fourth, neither side can change strategies once the attack has begun, and once an attacking missile has penetrated the defense it will score a kill against the target with a probability of one. Finally, it is assumed that since the defender must set his strategy first, the attacker has complete knowledge of not only where the interceptors are stationed and how many there are, but also the firing schedule of each.

The model has been used to solve the problem of defending the cities of the United States against an attack of intercontinental ballistic missiles using 1980 Census data. The defender's strategy states that no single incoming missile will be able to kill more than 200,000 people and that the probability of an interceptor kill is .50. In this case the model indicates that 414 interceptors will be needed for an adequate defensive outcome.

Limitations of the model include the fact that damage functions are constant for all cities, the assumption that an unlimited number of independently fired interceptors can be used against any incoming missile, and that the damage functions assigned each attacking missile are linear rather than concave or convex.

The subject of deceptive basing has also received detailed examined by Bracken and Brooks (1985). Their model is an attempt to describe interceptor defenses and attacker target allocation for Intercontinental Ballistic Missile (ICBM) bases. In this model it is assumed that the ICBMs are based in a number of identical areas across a nation, each of which contain an identical number of missiles and identically configured shelters. The purpose of the model is to examine deceptive basing from the standpoint of both the defender and the attacker.

In this model both defender and attacker have prior knowledge of the number of warheads the attacker has, and the number of missiles, shelters, and interceptors the defender has. The attacker is then able to allocate missiles as desired, and the defender is able to allocate interceptors according to two strategies. The first strategy stipulates that the defender distribute a fixed number of interceptors uniformly within all areas, and the second allows the defender to assign interceptors preferentially within areas while observing an attack, in order to maximize the overall survival rate.

Additionally, two preferential schemes have been examined. In the first, 70% of all interceptors are allocated to half the areas, and 30% allocated to the other half. In the second, 90% of all interceptors are allocated to half the areas, and only 10% allocated to the other half.

It has been found, interestingly enough, that when comparing defensive strategies using the model there is no benefit to nonuniform interceptor allocations when the defender can observe the attack and use the preferential defensive scheme. It is thus more sensible, at least from a treaty verification standpoint, to allocate interceptors uniformly across all areas.

One kind of model not previously discussed is that of knowledge engineered artificial intelligence systems. One such system, described by Freck and Bonasso (1985), is a United States Army system called Analyst. This system is designed to collect, analyze, and display huge amounts of tactical combat intelligence data so that battlefield commanders can quickly grasp ongoing developments and react to them accordingly. This program, still in its research and development stages, will continue to evolve as the computing power, and artificial intelligence data bases required for such an application become available. This evolutionary process is being accomplished through continued iterative field testing and development efforts in the lab.

Another interesting problem relating to the difficulties involved in fielding a force and fighting a conventional war in Western Europe has been presented in an article by Lorentzen (1986). This work, performed at the SHAPE Technical Centre in the Netherlands, concerns comparing the strengths of opposing NATO and Warsaw Pact forces.

The model presented is concerned with a static analysis of the time based availability of weapons systems deployed by the opposing forces. Military balance has traditionally been measured by a force ratio, which is derived by weighting the weapons systems available on each side, and then calculating a final score for both opponents. The ratio of the two scores is the force ratio. The weakness of such a system is the fact that it discounts the actual arrival times of the forces for useful deployment. That means that a tank asset in a National Guard unit in the United States which has been identified for deployment in times of conflict is scored the same as a tank already deployed just five minutes from the East German border.

The author has used Lanchester integral equations as a starting point for the time based arrival of forces. After completing the derivation of the equations an illustrative example has shown that significantly more realistic force ratio estimates are possible under the provisions of this model. The final force ratio is "discounted" by adjusting both the Warsaw Pact and the NATO force arrival functions by the standard net present value algorithm.

This has been done to adjust the forces available for, and able to engage in, actual combat. The contention here is that as forces arrive in Western Europe they can only engage the enemy in combat after certain necessary logistical functions are performed. This includes off-loading incoming battle assets at railhead locations, and their subsequent movement to forward battle areas. In this scenario the force ratio increases over time as more and more of the arriving units are deployed to battlefield positions. The increase in the total force is analogous to the increase in a savings account as compound interest is calculated and applied to the account over time. The adjusted force ratio obtained through the application of the standard net present worth algorithm is called, logically enough, the discounted force ratio. When the discounted force ratio is applied to the force arrival functions, a better picture of the force ratio over time is clearly apparent, and gives a much more accurate representation of the real world condition.

The question of the mobility of ground forces has also been addressed in an article by Turnage (1985). In a less theoretically based approach the author has pointed out that the Army is indeed interested in the ground mobility of its forces. In order to provide field commanders exact information concerning the time required to move vehicles between different points in the battle area, a computer based model called CAMMS has been developed.

The Condensed Army Mobility Model uses digital simulation to describe vehicle performance in every type of on-road, or off-road condition. It includes factors for driver/vehicle interaction, terrain, weather, battlefield conditions, and convoy vehicle mix. The author states that the model has had repeated success in predicting vehicle speeds within a margin of plus or minus ten percent of the actual results obtained from direct testing.

The input to this model is quantitative in nature and includes four factors: vehicle type; driver; terrain; and operational scenario, which includes such things as weather and vehicle mix. The output is a plotter-generated, color-coded map which indicates predicted speeds along the specified route. It is envisioned that this tactical decision aid will soon become a valuable and easy-to-use tool for all field commanders.

A major area of study conducted by the Navy has been in the area of detection theory. Detection is the quantification of the presence and position of an enemy or presumed enemy (Operations Analysis Study Group 1977). The models being developed are probabilistic in nature and address the physical characteristics, path, and location of both the observer and the target. They also address the direction and deployment required for friendly forces to effectively meet and engage detected threat forces.

Two facts are true of all types of detection. First, there are certain physical requirements necessary for all types of detection, whether they are visual, or from some imaging source such as sonar or radar. Second, even when the correct conditions for detection exist, there is only some positive probability that detection will actually occur. This is true largely because of the significant role of the human in the detection process. Therefore, the conclusions made by detection models are expressed in terms of probabilities.

One of the main reasons the Navy has become so concerned about detection theory and detection technology is the fact that it is faced with an environment that is much more multithreat than at any point in the past (Mensch 1984). In an effort to respond to this new environment the Navy has deployed several new detector sensors and complimentary weapon systems for the fleet. One problem that has stemmed from the increase in information available to commanders has been the fact that there have not been systems designed to integrate and organize the data.

To help solve this problem a new network model and analysis system called Ship's Combat System Simulation has been developed (Mensch 1984). In this model each ship's combat systems are treated as a network in which information flows through the components of the system. At each component the information is studied in terms of what information is actually being received, processed, and used. Link-node network diagrams are used to represent each system modeled. This computer-based system is modular in nature and the documentation exists on-line with the model's program code to facilitate easy update.

Combat Support Services

A logical complement of the detection theory studies described above has been presented by Heil (1985). It is the simulation of continuous airborne surveillance, which provides not only detection and tracking of hostile forces but also has alternate uses such as command and control, search and rescue, and the use of military assets against the illegal flow of drugs. The simulation model presented by the author describes a complete mission cycle to demonstrate its continuous airborne surveillance capability.

The cycle begins with an aircraft being selected from an operational pool of assets and readied for its mission. The aircraft is then deployed on station for a specific period of time before being returned to base. Once back at the base, the plane is inspected in preparation for routine and nonroutine maintenance. The maintenance cycle in the model provides for organizational, base, and depot repairs to be completed before the operationally readied aircraft is returned to the pool of assets used in the initial step above. The simulation also provides for three types of surveillance aircraft, as well as both in flight fueling, and the use of defensive escorts.

The parameters for the model have been established by conducting three phases of analysis; requirements analysis, capabilities analysis, and feasibility analysis. This has been done done so that a mathematically logical representation of the system can be defined for the computer solution, written in the FORTRAN language. This program is event-oriented, simulating the progression of time according to discrete events rather than by some fixed interval method.

For the three types of aircraft used in the computer simulation an individual set of characteristics has been developed for such factors as fuel consumption (determined by changing aircraft weight during mission), maintenance (Mean Time To Repair--Normal Distribution), reliability (Mean Time Between Failures--Poisson Distribution), and refueling capabilities. The output of the simulation is formatted as a chronological log of system and event elements, and each Monte Carlo replication provides extensive summary information.

The problem of maximizing the utilization of aircraft in a cargo role has been addressed by Cochard and Yost (1985). They describe a system developed for the Air Force called the Deployable Mobility Execution System (DMES), with which the field manifesting of cargo aircraft is being accomplished.

The objective of DMES is to provide an automated cargo load planning system which will optimize the aircraft constraints of center of balance, height, allowable total load, allowable linear load, and incompatible hazardous cargo elements. The program, which has been written in Pascal for use with a portable microcomputer, consists of both mathematical and heuristically based decision rules. Files in the computer contain specific information on the standard containers used in the Air Force, and the flight and cargo parameters of various types of aircraft. The program requires the load planner to input information concerning the total amount of cargo to be loaded, and the type and number of aircraft available for the lift. The output of the program is shown on a screen display, and graphically provides the optimum location of all individual cargo elements.

The system has been tested extensively under simulated wartime conditions in field exercises and has, with some minor modifications, decreased the man-hours required for cargo planning by over 90%. It has also decreased the total number of aircraft needed for lifts by over 10%. The authors state that a 10% increase in the utilization of cargo aircraft worldwide represents a potential savings of over twenty million dollars a year.

The topic of mission availability and effectiveness has also been addressed by Lie et al. (1984). In their paper, an analytical model has been developed which calculates mission effectiveness for any given military system. It differs from previous models in that it assumes that the system under study is required to carry out several different mission types, rather than just one single mission type as was previously the case. The objective of the model is to study the effects that unfavorable environmental conditions and poor operator performance have on overall mission accomplishment.

The authors state that in order for a mission to be successful the system under study must do three basic things. It must first be available at the beginning of the mission. The system must then accomplish the mission within a specified maximum allowable time frame, and finally it must not fail at any time during that period. Poor operator performance and adverse environmental conditions will have a negative impact on nominal mission duration. As the time of the mission increases the statistical probability of hardware failure also increases.

This model also provides for an increased operator error rate over time as a component part of system hardware failures. Other factors which affect mission performance have also been quantified, including several operator and hardware peculiar variables. The authors say that extensive sensitivity analysis is possible once the required inputs have been made for the fist iteration involving a particular military man-machine system.

A combination of integer programming and network analysis has been used by Mathur et al. (1985) to provide a methodology for assigning radio frequencies in large, complex communications networks. This analysis has been done to insure fast, accurate, interference free military communications networks. There are three aspects to the total solution addressed by this model, frequency assignment, network evaluation, and intermodulation free frequency set generation. This work was conducted as part of ongoing research for the Office of Naval Research and the Naval Ocean Systems Center.

Frequency assignment requires a decision maker to assign each individual net within a given ship's total network a frequency which will not create interferences greater than an acceptable level. Additionally, there must exist some minimum separation between all assigned frequencies. This type of assignment problem is generally solved using a branching decision tree. At each level of the tree a frequency for an individual net is assigned and then tested as partial solution for separation and intermodulation interference. If the test fails, the node representing the partial assignment is redone and retested until the two constraints are satisfied.

Network evaluation is the process of evaluating the same constraints of frequency separation and intermodulation interference across all networks operating within a given area, such as ships in a convoy. The solution to this part of the problem necessitates a computer evaluation of all operating networks. The computer model allows for adjustments to be made to individual frequency assignments interactively until an acceptable set is found.

Intermodulation interference is caused when secondary frequencies are created as a result of interactions with other active frequencies in a communications network. Intermodulation free frequency set generation is a topic of great interest in light of the needs described above. Another integer program has been developed to define, within a given list of all frequencies, the largest intermodulation free subset of unassigned frequencies available. These can then be used by the frequency planner to eliminate identified interferences. Two computer based branch and search algorithms have been written to find this subset of frequencies.

The study of military operations research in combat support services applications also extends into the area of training technology. The task of instructing military personnel has been characterized by Ellis (1986) more as training than as education. Training, at one end of the continuum called instruction, involves a three-step process of: first, identifying the specific tasks which are needed for a given job; second, identifying the skills needed for these tasks; and third, identifying the level of competence to be acquired in light of the restrictions of the job environment. Education, which lies at the other end of the continuum, is not keyed to specific jobs, and can be viewed as preparing people for general life experiences, including job training.

Ellis states in the article that, "research and development in instruction is an attempt to apply science and technology to the problem of instruction, and nowhere are the applications more immediate and pressing than in military training communities." Thus the application of operations research techniques by the military to the problems of instructional technology represent considerable effort and contribution. What follows is a summary of some of the most recent and important work accomplished in the field of instructional technology at the military laboratories.

Instructional Systems Development (ISD), as described by Montague and Wulfeck (1986), has been designed to structure the military training process so that the training given to its personnel is sufficiently job relevant and cost efficient. ISD has been born out of the realization that military curriculum design efforts and the conduct of training have continually been hampered by a shortage of training experts. The ISD approach has been adapted from a standard operations research problem solving methodology used for the development of weapon systems.

ISD user procedures have been developed to simplify the difficult process of designing adequate programs of instruction. This has been done utilizing a four step systems approach which begins with the formation of a team of experts from all involved disciplines. The next step in the process is for the experts to generate subtasks which reduce the overall complexity of the problem under study. Step three involves the development of unique and systematic solutions to the subtasks. The final step is the conduct of operational testing so that information for fine tuning of the solution is possible.

The ISD model has been designed to guide nonexperts through a process which results in job-relevant, cost-efficient training for their personnel. It has evolved as not only a way to teach a certain subject, but also as a way to determine the content of the material being presented to ensure adequate understanding and retention. ISD allows for any medium of instruction, such as traditional classroom, computer aided, or self-paced, but suggests the latter because on its proven superiority.

It was originally hoped by the developers of the ISD methodology that their instructional expertise could be transmitted to nonexperts through manuals, and that in turn the nonexperts would be then be able to successfully carry out training development. However, two basic problems exist in the manuals, and it is felt by the authors that these problems are keeping ISD from realizing its intended potential.

Instructional engineering problems result from the fact that while the procedures in the manuals explain in detail what is to be done to develop an instructional system, they fail fundamentally in explaining how it is to be done. This results in low quality instructional systems because of the relative inexperience of the users in the areas of instruction and communication.

Management problems result from the false sense of security that the users of the manuals feel when they assume that by following the procedural steps of the ISD model, the resulting instructional material will be adequate. ISD does not provide a method for insuring the quality of the material produced, and since managers do not know what constitutes a quality instructional product to begin with, the final instructional material is often lacking in quality.

The authors suggest three ways the ISD methodology can be improved. First, they recommend continued research and development aimed at making the techniques presented in the manuals more complete and usable. Second, they recommend filling the obvious gaps which exist in ISD, such as quality control and test development methodologies. Finally, they say that ISD must take advantage of available computer technology to improve both the implementation and management of the system.

In order for instructional designers to be successful in training development Tarr (1986) points out that they must have sufficiently detailed information about the behaviors involved in completing specific tasks. This process begins with job analysis, which identifies the unique tasks which make up a job, and continues with the breakout of each task into individually taught subtasks. Critical subtasks can also be broken down into step requiring particular skills. Critical tasks can range from the procedurally simple to the nonprocedurally complex.

About 75% of the job performance behavior required of the junior enlisted personnel in the Army have been found to be procedurally related. Of the remaining 25% about half have increased importance in job performance because they involve the aspects leadership and personnel management. These are called transfer skills. The remaining portion are more generic in nature are called complete skills.

Procedural tasks are characterized by the fact that there is usually only one best way to perform them. The best way to analyze the performance of procedural tasks is through the use of a subject matter expert. By directly observing the expert, a checklist type set of instructions can be developed such that an inexperienced person can learn the task by reading and executing each item on the list. There are three basic approaches to this kind of task analysis: flow charting, hierarchial analysis, and paradigming.

Transfer tasks are characterized by the fact that there is potentially a large number of correct ways to successfully accomplish them. Analyzing transfer tasks involves having an expert describe the task at a very general level and then specifying the rules and principles required to successfully accomplish the task. Further, the only way to teach these skills is through the use of examples provided by an expert. The example used by the authors to explain this concept has a soldier finding himself exposed to direct small arms fire. What any one person would do in that situation depends on many factors. The three characteristics of transfer tasks are situational variance, performer variance, and outcome variance.

The analysis of complex skills is by far the most difficult and involves the understanding and quantification of complex, high order, cognitive activities. Complex skills include such things as problem solving, interpersonal communications, evaluation abilities, and leadership. Analyzing these skills requires careful study and documentation of the entire behavior in such a manner that the evaluation format can be used by training developers in parallel with existing formats for procedural tasks.

Decision support in the area of training is also receiving considerable attention due to the high cost of deriving the specific training objectives used to develop course work. This is especially true in the major schools and centers which have a high volume of students. Ruck and Lange (1986) describe how the Navy discovered that the task analysis phase of the Instructional System Design (ISD) model discussed earlier lacked an appropriate methodology for this type of analysis. Because of this the Navy has decided to supplement the ISD model with its own decision support system called the Training Importance Survey (TIS).

As the name implies, the TIS is a survey approach to occupation specific data collection. Its focus is to define the job requirements of a single person, and is administered to the first supervisor in the individual's chain of command. Training priorities are identified from closely related job subgroups which are common to groups as well as those unique to each subgroup. The TIS inventory looks at an individual who is already on the job and documents all task, skill, and knowledge behaviors which are used. Supervisors analyze which of the survey items an individual new on the job should be trained in prior to arriving in a unit, and rate the relative importance and required level of competence for each. These requirements then form the decision support system for instructional designers to use while developing specific training objectives and performance levels.

In looking to the future of the state-of-the-art in training decision support systems, Blaiwes and Regan (1986) propose a computer assisted, data base approach with four subsystems. The four subsystems proposed are the Task Characteristics Subsystem, the Field Utilization Subsystem, the Resource-Cost Subsystem, and an integration system for these three called the Integrated Training Decisions System. The authors submit that this significant advance in instructional design systems will greatly facilitate the entire range of training decisions from determining optimal training sites, to optimizing utilization of trained personnel, and cost comparison of training methods.

In addition to the progress the military is making in developing instructional programs, substantial gains are also being made in the development of training devices as well. These systems simulate, in varying degrees of complexity, the job environments found in actual field assignments. One example of this is the MILES system developed by the Army.

In the last several years the Army has adopted a tactical training system to simulate infantry and armor engagements called MILES. The Multiple Integrated Laser Engagement System, described by Jacobs (1982) simulates the effects of direct fire from individual and crew served weapons. It does so with eye safe gallium arsenide laser beams mounted directly on the barrels of the weapons, and multiple discrete silicon detectors mounted on the targets.

Pulse modulated firing codes are associated with each weapon in order to discriminate between shots fired from various sources. This is so that, for example, an infantry soldier is not able to knock out a tank with his rifle. To facilitate battlefield realism, the laser is fired only when a blank round from the subject's weapon is fired. Additionally, the system is capable of informing the potential victim of near misses as well as direct killing hits. This provides a cue to the target to take evasive action, if possible, before another round scores a kill. Excellent training results have been realized by the Army with this system which is currently in use at over twenty locations in the United States, Germany, and Korea.

Increased emphasis is being given to this area of operations research in the military for several reasons. To begin with, the sophistication of simulation technology has advanced significantly in recent years in areas such as visual and motion fidelity. From a cost standpoint, the simulator is generally significantly better than other methods when it is supplemented with actual job equipment and classroom instruction. Additionally, simulators generally provide greater flexibility than actual systems in terms of mechanical reliability, scheduling freedom, and weather constraints. Finally, and of considerable importance, simulators provide far greater safety in most cases than their production counterparts.

Simulator designs are generally classified in three categories. Generalized designs train people for all systems within a family of systems. General purpose designs are adaptable to any desired system, and system specific designs, like the name implies, are dedicated to emulating a single system. Within these categories, devices are designed to teach operator tasks, maintenance tasks, and procedural, perceptual-motor, and cognitive operations.

One problem which has plagued the training device community over the years has been the fact that instructional designers have been reluctant to accept simulator technology. In part this has stemmed from the fact that rather than praising simulators for what they can duplicate, people have criticized them for what they are incapable of duplicating realistically. This has been especially true in the flight simulator arena. However, as the state-of-the-art has continued to provide more realistic simulations of visual and proprioceptive stimuli (feel) the popularity of these devices has dramatically increased.

The contributions of computer technology across the entire broad spectrum of training devices has been fundamental in the success of simulators. With this increase in capability has come the realization that there are some very definite design trade-offs between training realism and training value. Intensive studies are being conducted to justify additions to current simulators and for the construction of new simulators in terms of what incremental addition to training value is made for each addition to increased realism. This trend toward a systems analysis approach has led to the reduction of overengineering, and a subsequent marked reduction in overall cost.

The military is also recognizing that in order to enlist the creativity of the training device community, that functional specifications and performance specifications are more effective than traditional design specifications. Functional specifications define broad characteristics of systems, while design specifications define precise device features. Performance specifications, which allow the greatest amount of latitude, allow for any design that will satisfy a particular training objective. Combinations of all three are currently in use in the acquisition of new simulation systems.

Future trends in the application of operations research to training simulation systems will follow from current research and development in the area of behavioral training technology discussed earlier. They include the synthesis of learning and cognitive analysis, instructional functions, and expert systems.

Force Structure and Sizing

The problems associated with assigning armed forces personnel to units such that the needs of both the service and of the individual are served in a fair and equitable manner is extremely complex (Clark and Lawson 1984). In critical specialties the problems are especially acute because of the ultimate effect those personnel have on the readiness of the total force.

Unfortunately, from the standpoint of the assignment problem, these critical specialties usually have several undesirable characteristics associated with them. They are usually concentrated in junior enlisted ranks having the lowest pay, and which generally are in short supply throughout the force. This requires units deployed overseas to be filled before those in the United States, which means that an individual in a critical specialty can expect far greater overseas time than a contemporary in a non-critical skill.

Force readiness is subsequently affected as the result of low retention and the replacement of experienced personnel with newer, less experienced ones. A model to address this problem has been developed in the Air Force to provide a long-term mechanization for the management of such specialties in order to increase retention and thus improve force readiness.

The authors state that traditional static Markov models are inadequate in describing the current assignment system as previously outlined. This prompted them, therefore, to use a dynamic approach in the derivation of their model. Central to the model is the extensive use of information feedback as a continuous aid to decision support for the policy makers involved. It provides for a dynamic representation of the system as a whole, which in turn allows decision makers a better understanding of the affects of changes due to alternate assignment policy formulation.

This methodology is called the system dynamics approach, and most accurately represents the continuous flow and feedback structures present in various military personnel systems. As a result of this analysis, several lasting changes have been made in the assignment of critically skilled Air Force personnel. This has included increasing stateside tours for effected personnel, and has also meant filling certain critical overseas shortages with civilian personnel.

Maurer (1985) has made a similar analysis of the Navy's personnel rotation system, where a problem exists in determining how to periodically allow sailors shore duty in order to promote morale and prevent attrition. The goal of this model, developed at the Center for

Naval Analysis, is to examine the feasibility of proposed rotation policies, and to develop long term distribution goals for sea and shore based enlisted personnel.

The Navy divides its enlisted force into two experience categories, first term personnel and career personnel, all of whom are rotated between sea and shore duties at the termination of any given assignment. The model is assumed to be steady state meaning that each year's losses in enlisted personnel are equal to its accessions. Three basic parameters are used by the authors in the analysis presented: continuation, rotation, and personnel distribution. Continuation is the proportion of career personnel retained each year. Rotation is the number of periods career personnel are assigned to sea duty versus shore duty. And personnel distribution describes the percentages of the total enlisted force based both at sea and on shore during a given year.

The authors have based their analysis on the various interrelationships between these three parameters within the foundation of the steady state system, and found them to be quite complex. Most of the difficulty the Navy faces in developing a rotation policy is the fact that it is primarily a sea-going force. This dictates that the majority of its assignments will be sea based. However, it has been found that the continuation rate among career enlisted personnel is very sensitive to changes in rotation policy. This is because rotation patterns which are consistent with an acceptable distribution of personnel serving in sea and shore assignments hinder morale and adversely affect retention rates.

Under the constraint of the steady state system it has been found that for the Navy to attain the desired three year rotation patterns among enlisted personnel, double the present number of shore assignments would be required. Obviously this is not feasible from an economic standpoint, and as such forces the Navy to assign its enlisted force to longer than optimal sea tours, particularly in low density, high skill groups. The output from the model allows for appropriate adjustments to made in incentive programs in order for desired force requirements to be met. The model is currently in use as a tool for Navy planners to determine the effects ongoing management decisions have on retention.

Miller (1984b) proposed a similar system for the Army comprised of two interrelated models. The first, a flow model, describes how personnel pass through the Army manning system. The second, an optimization model, sets the rate of the flow. The system is called the Army Personnel Planning System (APPS), and has been developed with several planning concepts in mind. The author has assumed that the exact structure of future personnel inventories cannot be directly controlled. As a result, structure must be realized by managing personnel transitions. Transitions include the accession of new recruits into the Army, the migration of active duty members among the various Army specialties, and the separation of active duty personnel over time.

The goal of the system is to develop time phased transition rates which can be used as targets for near term personnel planning activities. The flow model, which is a based on a vector Markov process, predicts future inventories based on a given set of transition rates. The optimization model, which consists of several linear programming models, determines what transition rates should be maintained in order to be insured of a desired future manning level. These two models combine to form an interactive planning system for all ranks, which will provide the basis for decisions concerning medium and long range policy formulation questions.

CONCLUSION

It is evident from the material which has been presented that an enormous amount of work is being conducted for the military using operations research techniques. It is interesting to note that during the research for this paper it has been found that most of the funded research being conducted to extend the state-of-the-art in operations research is in the area of strategic and tactical combat operations. This is evident in the relatively vast amounts of recently published material found on the subject. In way of contrast, there is little evidence that any funded study is being conducted for the military in the areas of procurement and acquisition, which includes such subtopics as project management, and testing and evaluation.

Additionally, only a limited amount of material has been found covering the topic of productivity. A healthy sign that there is interest in this area was presented by Sink (1984). He states that at a conference attended by numerous key experts representing the Department of Defense, government, and industry in 1984, recommendations were developed on how to improve the productivity within the defense industry during the upcoming decade. He points out that a full report was presented to the White House Conference on Productivity later that year which cited a number of key issues for improvement. Among the issues raised were employee incentive programs, implementation of new technology, establishment of a national industrial policy, improvement of the government as a reliable customer, and establishment of training and education initiatives to name a few.

Several other trends have become apparent during the research for this paper. One has been alluded to already. That is the fact, that as long as the defense budget continues to grow as a percentage of gross national product the military will continue to spend heavily on research and development. It is unlikely however, that until some major pressure is placed on the military and its contractors to reduce the costs associated with the fielding of new systems, that much money will be spent to develop such techniques as a usable PERT-Cost system. For such a system to be developed means resources, including people, money, and time, need to be dedicated to solving the problem.

The tremendous growth of the computer as a primary tool of the operations research professional is also quite evident. Several applications discussed in the paper were possible only because computers could be made to do the work at very low levels in various organizations. Others would not have been possible unless there were machines available which could process tremendous amounts of data. Microcomputers will continue to be programmed and taken to the field and used by low ranking enlisted personnel. Huge mainframe computers, on the other hand, are now capable of modeling such things as the dynamics of the movement of aircraft carrier decks so that airplanes and helicopters can land more safely. As more and more computing power becomes available in smaller, more durable, less expensive packages, the military will be there to exploit them.

Finally, and probably most importantly, because of the increased importance of operations research in the eyes of the military, and the availability of both educated people and powerful computers, applications that for years seemed to be unquantifiable are now being modeled more and more frequently, and across a wider range of applications. The research conducted for this paper has shown that while sheer human ingenuity has played a major role in so many of the elegantly simple, and procedurally complex models examined, few would have been possible without various forms of automation.

The services understand the importance of both automation and of having their professional personnel, including those involved in such nontraditional use fields as personnel management, finance administration, and maintenance, literate in the uses of various operations research techniques. The techniques which are proving to be the most useful include linear programming, network analysis, and structured systems analysis and design. Creativity combined with computing power has always been important to successful research, but never has it been more so vitally important to the continued growth of a technology as it has become to operations research.

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