ARMY OPERATIONS RESEARCH—HISTORICAL PERSPECTIVES AND LESSONS LEARNED

SETH BONDER

2900 Fuller Road, Ann Arbor, Michigan 48105, sbonder@mediaone.net

This paper provides some of my historical perspectives on Operations Research (OR) in the U.S. Army. It is based on my 40+ years of personal experience and, thus, focuses on the modeling and analysis (M&A) aspects of OR in the Army. I have attempted to highlight the changing problems and growth of M&A in the Army over the past 40 years. Although I refer to approaches taken by others for some of this growth, more information is provided on those of Vector Research, Incorporated (VRI), since all of my experience has been with VRI since 1969. The paper has four main sections. Since OR in the Army started before 1960 and my activities interacted with many others in the Army, the first section briefly reviews the lineage of some of the Army's main OR organizations. The second and third summarize my M&A activities and perspectives for the periods 1960–1989 (the "Cold War" era) and 1990–2000, respectively. Based on this experience, I offer some "lessons learned" for today's military M&A community in the concluding section.

1.0. U.S. ARMY OR ORGANIZATIONS

I doubt that we can trace the birth of Operations Research to a specific date since the roots of OR are as old as science and the management function. In 1938 the Army formed the Ballistic Research Laboratory (BRL) which performed engineering-level-type OR analyses (e.g., fire controls, firing tables, warhead lethality, etc.) for different weapon systems and has continued to do so for the past 60+ years. However, its name and the first formal OR efforts date back to the military OR activities of World War II. This "heroic age" of OR is well documented by George Kimball and Phil Morse (Kimball and Morse 1951). Following the war, each of the Services formed its own sizeable OR organization.

Early on, the Army created OR organizations to address three levels of issues: Force design and force structure issues were usually addressed at the operational level of war including Army Groups and Theater Armies. System requirements, system mixes, and tactics were usually addressed at the battalion-to-division level units. Both of these levels also addressed operational concepts, doctrine, and tactics development issues. Detailed systems-engineering-level issues were addressed at small unit up to company/battalion level. There is an historical lineage of organizations that have addressed these issues. Force design, force structure types of issues at theater level were initially addressed with the creation in 1948 of the Operations Research Office (ORO) of the Johns Hopkins University, the Army's first FFRDC. The lineage of organizations performing these functions includes the Research Analysis Corporation (RAC) in 1961 and the Strategy and Tactics Analysis Group (STAG) (primarily a theater-level wargaming activity) about the same time RAC was formed. The Concepts Analysis Agency (CAA) replaced STAG in the early 1970s with a much broader theater-level analysis mission. In 1998 CAA was renamed the Center for Army Analysis. The systems and operational concept/doctrine/tactics-level issues early on were addressed with the creation of the Combat Operations Research Group (CORG) in 1951–1952 as an ORO field office at the Continental Army Command. CORG continued its support to the newly formed Combat Developments Command (CDC) from 1962 until its demise in the early 1970s. In the late sixties the Army created the Office of the Assistant Vice Chief of Staff, Army which became a strong user of OR and related analyses. This was particularly true for its Weapon Systems Analysis Directorate (WSAD), headed up by then MG Bill DePuy. The WSAD was a breeding ground for many future Army generals who had an appreciation for the value of OR analyses in defense decision making. The Army's Training and Doctrine Command (TRADOC) was established in 1972 as the organization responsible for future doctrine, force design (up to corps-sized units), combat (systems) developments, and training. General DePuy became the first TRADOC commander and created a substantial OR organization to include the Combined Arms Research Activity, TRADOC Systems Analysis Activity, and OR cells at many of the branch centers. In 1975, Wilbur Payne (the first Army Deputy Undersecretary—OR) integrated all TRADOC analysis organizations into the TRADOC Operations Research Activity. In 1986 this became the TRADOC Analysis Command, which still exists. In the 1950s, BRL expanded its analysis activities to include much more OR flavor in support of the Army Material Command and, in the late 1960s, spun off one of its divisions to form the Army Material Systems Analysis Activity (AMSAA). This organization, which continues today, performs a spectrum of OR analyses for development of weapon systems.

Many OR analyses in the Army have involved the use of various kinds and levels of models. The M&A capability has grown substantially over the past 50 years. I and many

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Contributors

Kenneth J. Arrow ("The Genesis of 'Optimal Inventory Policy'") shared the Nobel Prize for Economics in 1972 with Sir John R. Hicks for the development of theories underlying the assessment of business risk and government economic and welfare policies. He is the Joan Kenney Professor of Economics Emeritus and Professor of Operations Research Emeritus from Stanford. He received a Ph.D. and M.A. from Columbia University. His current research interests lie in negotiation, information and communication in the economy, equilibrium under monopolistic competition, and shifts in income distribution. Other research areas include the economics of information and organization, collective decision-making, and income distribution. Dr. Arrow's interests in OR date back to the 1950s. At Stanford, he played a major role in creating the Department of Operations Research. He served as the tenth president of The Institute of Management Sciences (TIMS) in 1963. In 1986, he was awarded the John von Neumann Prize by ORSA and TIMS.

Robert E. Bixby ("Solving Real-World Linear Programs: A Decade and More of Progress") holds a B.S. from the University of California, Berkeley and a Ph.D. from Cornell University. He is President of the Technical Advisory Board for ILOG, Inc., and a Research Professor of Management in Rice University's Jesse H. Jones Graduate School of Management. He is the Noah Harding Professor Emeritus of Computational and Applied Mathematics in Rice University's Department of Computational and Applied Mathematics. Dr. Bixby is chairman of the Mathematical Programming Society and was formerly editor-in-chief of the journal *Mathematical Programming*. In addition, he has published over 50 papers and nearly 20 research reports. He is a member of the National Academy of Engineering, and has received the Mathematical Programming Society Beale-Orchard-Hayes Prize for Computational Mathematical Programming. He cofounded CPLEX Optimization, and he has served on ILOG's board of directors.

Alfred Blumstein ("Crime Modeling") is a University Professor, the J. Erik Jonsson Professor of Urban Systems and Operations Research, and former Dean at the H. John Heinz III School of Public Policy and Management of Carnegie Mellon University. He is also director of the National Consortium on Violence Research (NCOVR). He holds a Ph.D. in operations research from Cornell University and an honorary Doctor of Laws from John Jay College of Criminal Justice of the City University of New York. Dr. Blumstein was President of the Operations Research Society of America (ORSA) in 1977–1978; he was awarded its Kimball Medal for service to the profession and the society in 1985 and its President's Award for service to society in 1993. He was president of The Institute of Management Sciences (TIMS) in 1987–1988 and was President of the Institute for Operations Research and the Management Sciences (INFORMS) in 1996. He is a Fellow of the American Association for the Advancement of Science (AAAS). He served on the President's Commission on Law Enforcement and Administration of Justice in 1966–1967 as Director of its Task Force on Science and Technology. Dr. Blumstein is a Fellow of the American Society of Criminology, was the 1987 recipient of the Society's Sutherland Award for contributions to research, and was the President of the Society in 1991–1992. His research interests include many aspects of criminal justice, including crime measurement, criminal careers, sentencing, deterrence and incapacitation, prison populations, demographic trends, juvenile violence, and drug-enforcement policy.

Seth Bonder ("Army Operations Research—Historical Perspectives and Lessons Learned") has been a leader in applying operations research to planning national defense and a pioneer in applying prospective modeling methods to reengineering health care delivery. He received a B.S. in mechanical engineering from the University of Maryland and a Ph.D. in industrial engineering (operations research) from Ohio State University. He was a Professor in the Industrial Engineering Department at the University of Michigan and Director of the Systems Research Laboratory. He also served as a captain and a pilot in the U.S. Air Force. In 1969, he founded Vector Research, Inc., and served as its Chairman and CEO until recently. As principal investigator on many projects, Dr. Bonder, together with his team, provided scientific guidance in solving force structure, readiness, modernization, and manpower problems, as well as expertise in materiel research and development, production, and procurement. Dr. Bonder helped construct major systems of organizational, doctrinal, and materiel structure at the strategic, operational, and tactical levels of war. In his work with the military, Dr. Bonder used operations research to model telemedicine—a new field that offered better ways to treat members of the Armed Services who are distant from care providers and medical expertise. He extended these contributions to support reengineering healthcare in the civilian sector using prospective analysis to replace trial and error. A respected theoretician, Dr. Bonder, with the late Robert Farrell, developed the Bonder-Farrell Theory. Dr. Bonder is a member of the National Academy of Engineering and a member of the U.S. Army Science Board. He has been a consultant to the Defense Science Board and is a past president of the Military Operations Research Society and the Operations Research Society of America (ORSA). He was the 2001 recipient of the INFORMS President's Award.

of my colleagues have been intimately involved with and have contributed to this M&A growth. The next two sections of this paper provide historical perspectives on this facet of Army OR in the context of some of my M&A experience since 1960, either for or interactive with a number of the Army OR organizations noted above. They highlight some of the growth directions and provide the basis for the lessons learned in the concluding section.

2.0. HISTORICAL PERSPECTIVES 1960–1989

This section of the paper provides historical perspectives on Army modeling and analysis during the Cold War era (1950–1989), particularly after my involvement in 1960. Background information on the global security environment over this period and available models for OR analysis are presented first. This is followed by M&A perspectives during the 1960–1972 period where major focus was on tactical-level (system and battalion-sized units) analyses, and then M&A perspectives in the 1972–1989 period with a growth into combined arms and operational-level (division-, corps-, and theater-level) analyses.

2.1. Background Circa 1960

The Cold War era was born in 1950 and lasted through 1989. It pitted the NATO alliance against the Soviet-led Warsaw Pact. The Warsaw Pact maintained a significant conventional force capability advantage over NATO during the Cold War—an approximately 2:1 strategic advantage in armored systems and a much greater operational-tactical advantage. NATO relied on nuclear means to deter a massive Soviet offensive in Europe.

During the Cold War era, the United States and the Soviet Union were military superpowers who maintained a strong influence over policies and activities within their alliances. The Soviets simultaneously exercised significant control over many third-world country military activities via economic means, technology controls, and subtle military pressure. Although regional conflicts occurred during the Cold War era, it was a relatively stable global security environment.

There was also equivalent stability for defense planning and associated OR analyses during this period. The focus was Europe—the United States and NATO were committed to stop a Soviet-led Warsaw Pact attack. The threat was clear. We knew the size and location of the Soviet-led Warsaw Pact forces. We knew their attack options, equipment, their command and control processes, and many other characteristics. Both defense planners and decision makers recognized that feasible conventional changes in various components of warfighting capability (new systems, force design, force size, etc.) could not alter the conventional force imbalance.

In 1960 Army models existed at two levels—small unit tactical-level operations and large operational-level units. The small unit model was CARMONETTE (Adams et al. 1961), a Monte Carlo simulation developed at ORO in the mid-1950s. The original version simulated details of each system in a company-level counterattack against a defending Soviet company. Each system was represented by many parameters describing its individual performance characteristics. During the 1960s, CARMONETTE was extended to represent battalion-level operations—40–50 systems on the defender side with three times that number for the attacking force. CARMONETTE was a *synthetic* model in that it explicitly represented military processes (aiming, firing, moving, etc.) and integrated them over time to estimate combat results.

NATO theater defense against a potential Warsaw Pact attack could involve eight NATO Corps and 20–25 Pact Corps equivalents, where each Corps contained about 25 battalions. Except for war games (e.g., RAC's Theater Quick Game) (Johnson and Zimmerman 1963), there were no large-unit models for use by the Army in 1960. Early in the 1960s, RAC developed the closed ATLAS theater-level model (Kerlin and Cole 1969) and later in the 1960s, the Theater Combat Model. Both were *holistic* models in that they did not explicitly represent large-unit military processes such as maneuver combat, air defense, air warfare, etc., and portrayed a large unit such as a Theater Army or an Army Group as a one-dimensional undifferentiated entity. That entity, the "firepower score" (FPS), was calculated as a weighted sum of all combat systems in the unit (a many-to-one transformation). The ratio of attacker-to-defender FPS was used to compute daily movement of opposing units and attrition of the unit's FPS.

In addition to the detailed Monte Carlo simulation and large-unit FPS models, *analytic* models were available. An important class were the differential structures, historically referred to as the Lanchester equations (Lanchester 1916), in various deterministic and stochastic formulations. At the time, they were of academic interest but of little use as a combat analysis tool because of their holistic nature. Because of later developments to enhance their utility, the original "direct fire" or square law formulation is noted below:

$$\frac{dn(t)}{dt} = \alpha m(t)$$

$$\frac{dm(t)}{dt} = \beta n(t)$$

where m and n are the numbers of surviving weapons on each side, and where α and β are the per-firer attrition rates (also called kill rates).

2.2. Historical Perspectives 1960–1972

Army OR, and particularly M&A during 1960–1972, was heavily focused on systems and tactical-level issues in part because it was close to engineering analyses understood by the military and in part to build a scientific base for looking at tactical-level operations. This was the particular focus of my own efforts in the sixties, which facilitated my interactions with many of the ongoing M&A activities and research in OR.

I joined the Systems Research Group (SRG) at the Ohio State University (OSU) in 1960 and began work with planners at the Armor Combat Developments Division at Fort Knox. Their principal objective was to develop a set of system characteristics to be used as performance requirements for developers to design the next-generation armored weapon system (e.g., tank, infantry fighting vehicle, etc.). Characteristics of the system included vehicle speed, driving range, target detection probabilities, hit probabilities, firing times, survivability, and numerous others. Sounded easy but it was not! Information was needed to address two interrelated questions: First, "Is it *technically feasible* to achieve the specified performances?", recognizing that the characteristics are technically interdependent. For example, adding more armor to increase survivability would require a larger engine to maintain the vehicle's mobility, which in turn would require more fuel to maintain its driving range, and the additional fuel would reduce its survivability. Secondly, "What characteristics *should* be specified to have an effective system against a projected threat force?" Planners would need to make performance capability trade-offs within technical feasibility constraints. In 1961 I received a contract to provide planners with a methodology and methods to address both problems. The program put me into the mainstream of the scientific era of Army OR with a focus on experimentation and process modeling.

Army OR in the 1950s, 1960s, and 1970s was replete with experiments on systems performance and operating tactics. In the mid-1950s the STALK experiments (BRL 1960) investigated the impact of different fire control systems, crews, tank rounds, attack paths, targets, and other control variables on visual detection, firing times, and firing accuracy. Experimental data was used to understand performance levels, learn how to improve performance capabilities, learn how to model and predict them for future systems, and learn how to represent them in combat models. In the early 1960s, BRL ran extensive experiments to understand round lethality effects on tank functionality (physical effects and wound ballistics) to build kill probability models. In 1962–1965 at OSU we ran experiments and built models of visual detection capabilities against stationary and moving targets and models of tank mobility. My research team (primarily graduate students with one or two military officers attending graduate school) annually drove tanks and fired their armament to understand each of the performance processes. We collected crew firing data and built firing time models. Project Pinpoint experiments (Young et al. 1958) were conducted in 1957 to understand and build models to estimate detection probabilities and location errors from firing stimuli. The Army Combat Developments Experimentation Center (Army CDEC) created in 1956 was the site of many experiments in the 1956–1981 period. TETAM experiments (Army CDEC 1972, 1973) were conducted in 1970–1973 to understand the effects of terrain line-of-sight (LOS) on detection and firing opportunities in Europe. These data provided the basis for developing a new generation of long-range weapon systems. The Basic Attack Helicopter Team experiments (Army CDEC 1971) were conducted in 1970–1975 to learn about and develop effective attack helicopter tactics, tactics later used in building combined arms combat models. Many more experiments were conducted during this era, an era in which OR in the Army was scientifically based. Experiments were run, the data were used to understand performance and combat processes, and this knowledge used to build models for analysis of Army decision issues.

As part of the OSU project, we built an integrated set of models to estimate feasible performance capabilities of future armored systems. The methodology we were building then needed a combat model which would take system performance characteristics as input and which could be used to estimate the combat effectiveness of making trade-offs among the system performance capabilities. The CARMONETTE Monte Carlo simulation was the only small-unit combat model in 1963. But it presented some problems for trade-off analyses in the methodology I was developing for the armor planners. It required 30–60 minutes of computer time per replication and 15–30 replications to obtain reasonable estimates of the mean results, and thus made it difficult to conduct extensive parametric analyses on many performance characteristics. The many individual system details tracked in the simulation made it difficult to interpret results and diagnose cause-effect relationships. And so in 1963 I set in motion a research program to develop the underlying methods for a more analytic combat model that was still synthetic in nature but easier to use for analysis purposes (SRG 1964).

Although the differential equations first proposed by Lanchester had many problems, their simplicity was appealing. Based on a study for MG Pickett, I recognized that many characteristics of weapon systems would have to be considered if one wished to predict the attrition rates. Since the characteristics were range-dependent, the attrition rate would also vary with target range when mobile systems were employed. In the vernacular of the mathematician, the attrition rate was viewed as a nonstationary stochastic process. During this period a theory for predicting the attrition rate in the differential equations was developed, and I explored the theoretical impacts of attrition rates which varied with time. The logic and details of this early research are presented in a paper (Bonder and Thompson 2001) being prepared for the *Military Operations Research* journal. Extensive research in the 1964–1972 period (at OSU and my Systems Research Laboratory (SRL) at the University of Michigan) was devoted to developing process models to predict the attrition rate for different weapon systems, firing doctrines, types of engagements, and their variations with dynamic changes in location, posture, movement, etc. throughout a battle.

When the attrition rate varies with range, attack speed can have a significant impact on combat dynamics. The constant coefficient differential equations proposed by Lanchester became nonlinear and explicitly included the attacker's speed and acceleration capabilities. The military for many years has recognized the nonlinear importance of a force size advantage (i.e., force concentration or mass). The results of some theoretical battles imply a new dynamic obtained by solving the nonlinear differential equations as shown in Exhibit 1.

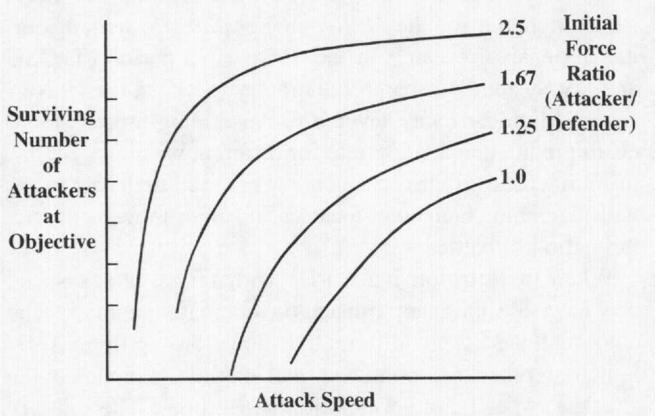
The results suggest that increasing attack speed provides a means of conserving the attacker's force and of saturating the defender's retaliatory capability but with decreasing marginal benefits. Together speed and mass (force concentration) are synergistic means to rapidly saturate an enemy's retaliatory capability.

My research on the differential structures of combat continued in 1965–1972 at the University of Michigan. The objective was to create methods that could be used in the development of deterministic, highly differentiated, synthetic models of heterogeneous force-on-force combat operations. In addition to developing attrition-rate models for many different weapon systems, research was performed on modeling environmental effects, on allocation of fires, force mixes, and tactics using data and knowledge from the many experiments performed in the decade and in collaborative efforts with analysts from BRL, CDC, and other Army OR research organizations (Bonder and Farrell 1970).

In late 1969 General DePuy (then the Assistant Vice Chief of Staff in charge of WSAD) asked me to apply our "model" to help him address some questions raised by the Deputy Secretary of Defense (then David Packard of Hewlett-Packard fame) regarding development of the MBT-70 main battle tank. Two problems existed: We had lots of equations but no model, and the University had a moratorium on classified research. DePuy suggested I start a company and a week later VRI was born. In two months, Bob Farrell (Deputy Director of the SRL) and I developed the battalion-level "Bonder-IUA" model (Bonder and Honig 1971), tested it against results of the new Individual Unit Action (IUA) Monte Carlo simulation model (AMSAA 1969), and provided General DePuy with answers to the Deputy Sec Def's questions.

The structures and equations developed in the SRL and used in the Bonder-IUA model became known as the Bonder-Farrell methodology. Because the models involve

Exhibit 1. Impact of attack speed.



differential equations, and because F. W. Lanchester pioneered differential equation models of attrition, some people call these Lanchester models. To the extent that this is intended as a well-deserved tribute to a pioneering analyst, this is fine terminology. However, the methods of Bonder-Farrell are synthetic in nature and are quite different from Lanchester's, which are holistic models.

In contrast to the CARMONETTE and IUA Monte Carlo simulation models which simulated all activities in a battalion-level engagement, the Bonder-IUA was the first "hybrid analytic/simulation" model. It analytically described all the attrition processes and simulated terrain line-of-sight via a deterministic map, movement of system groups via attack routes, and command control via tactical decision rules. This facilitated rapid running times, eliminated the need for replications, and made it relatively easy to interpret results of engagements. Another approach to achieve similar objectives was pursued by Gordon Clark in the late 1960s with the Combat Analysis Model (COMAN). The model had an analytic structure with some free parameters which were fitted using results from a Monte Carlo simulation model (Clark 1969).

2.3. Historical Perspectives 1972–1989

Although this period was part of the Cold War era, there was significant expansion in the activities performed by the Army OR community following the end of the Vietnam war. General DePuy, creator of TRADOC in 1972 and its first commander, became the architect of the post-Vietnam Army—new systems, new operational concepts/doctrine, and associated new force designs. He also became a champion for M&A analyses, as did in later years many of the officers he had mentored (notably General Max Thurman, Commander of the Panama invasion and the "Music Man" who captured Noriega in 1989).

The requirement for OR support on systems planning issues continued in the 1970s and 1980s with the development of many new systems (M1 tank, Bradley fighting vehicle, Apache and Blackhawk helicopters, Patriot air defense system, etc.) and incorporation of new technologies (e.g., fiber-optic, laser-designated, self-designated precision munitions). The battalion-level models were enhanced to facilitate analyses of these new issues. CARMONETTE went through a number of enhancements until its replacement CASTFOREM (Army, TRADOC Analysis Center 2001) arrived in the late '80s. The COMAN model "fitted parameter" approach was extended, leading to the Low Resolution Small-Unit Model (Clark 1982) and then the COMANEW model (Boehner and Bailey 1982). Championed by General DePuy and Wilbur Payne, the Bonder-IUA hybrid analytic/simulation model was used by the government and VRI as the basis to develop a large family of hybrid analytic/simulation models of battalion-level engagements during 1970–1990. The different versions were developed in a "prototyping process" of enhancements by addition of new relevant systems, technologies, and tactics. A VRI branch of developments led to the Battalion-Level Differential Model (BLDM) (VRI 1975) which was used at least through 1990. Each used the deterministic LOS formulations and was "closed" in that there was no intervention during a model run. The Bonder-Farrell methodology was also adapted for use in the JANUS gaming version (Buzzell and Smith 1980) which continues to be used today.

In addition to continuing OR work on tactical-level issues, in the 1972–1989 time period there was a renewed interest by the Army in operational-level issues (corps and echelons above corps)—new operational concepts/doctrine, new force design/force structures, and new operational-level systems. This renewed interest expanded the application of OR M&A activities in the Army and required the development of more credible operational-level models involving more combined arms and joint forces.

Three operational-level model lineages were initiated in the early 1970s. The Institute for Defense Analyses (IDA) began with the IDAGAM model (Anderson et al. 1974) and through a series of enhancements evolved into the TACWAR model (IDA 1977) which employed the "anti-potential potential" eigenvalue methodology to assess attrition in large-unit battles. The Theater Combat Model was substantially enhanced in the late 1960s and renamed the Concepts Evaluation Model (CEM) (RAC 1972). The first version of CEM which used FPS to assess attrition and movement of major units was picked up by the CAA in the early 1970s. An alternative approach to including results of small-unit engagements in large campaign models was through the use of a model *hierarchy* as part of the Army Model Improvement Program (AMIP) in the early '80s (Robinson and Fallin 1982). Through a prototyping process, today's version of CEM uses the hierarchy ATCAL methodology to assess attrition in large units (Army Concepts Analysis Agency 1995).

Finally, in 1972 General Glenn Kent asked me to develop a theater-level model with a much more synthetic structure for the direct-fire battles than IDAGAM or CEM using the hybrid analytic/simulation approach of the Bonder-IUA model. Through extensive analysis of the line-of-sight data generated in the TETAM experiments, we developed the mathematics for an extended version of the Bonder-Farrell methodology which analytically represented the LOS as a stochastic process rather than as a deterministic LOS map (VRI 1973). This change made it feasible to embed or "nest" the Bonder-Farrell differential models of battalion-sized engagements in a larger-scale model representing corps- to theater-level campaigns.

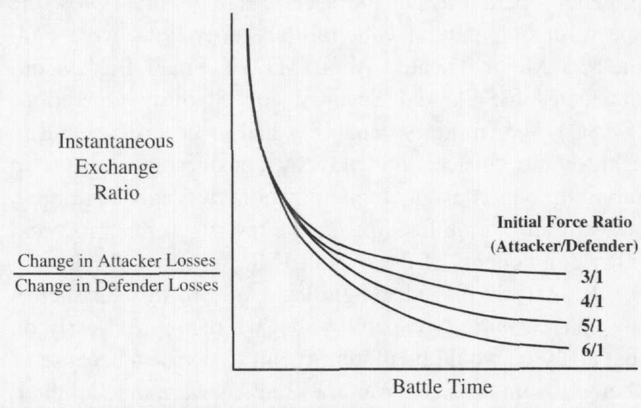
The first prototype version in the nested approach (VECTOR-0) was developed in 10 months and used to examine some issues for General Kent. Based on this experience an enhanced VECTOR-1 version was developed in 1974 (VRI 1974). Through this prototyping process, a lineage of VECTOR campaign models was developed from 1972 to 1990, including VECTOR-1 Nuclear, VECTOR-2, VECTOR-2 SWASIA, VECTOR-3, VECTOR-3 IEW (to address "information war" issues), and others as needed to address relevant military decisions. VECTOR-2 was successfully tested against the 1973 Golan Heights campaign in a blind study before performing mideast balance analyses for the same sponsor (Bonder 1982). The stochastic LOS version of the Bonder-Farrell attrition methodology has been used by other modelers in campaign models such as VIC, Eagle, STAR, and most recently the JWARS model.

Using many of the above-noted tactical and operational models, the OR community assisted the Army in developing new operational concepts/doctrine and new organizational designs (e.g., Division 86, the Light Division, Army 86, and Army of Excellence) during the period 1972–1990. Analysis was instrumental in developing and understanding combat dynamics underlying the Active Defense Concept, Central Battle, and Air Land Battle doctrine in the 1980s. Exhibit 2 is an example of the types of insights generated to support doctrinal development.

During the Cold War, it was estimated that the Warsaw Pact could attack NATO along the Inter German Border with tactical armored force ratios ranging from 3:1 to 6:1. Based on an analysis of many simulated engagements in Europe, the exhibit shows the instantaneous *loss exchange ratio* (LER)—the ratio of the rates of attacker and defender losses—as a function of battle time for different initial force ratios. The instantaneous LER is very high and relatively independent of the force ratio (and particularly threat size) early in the battle because of concealment and first shot advantages accrued to the defender. The LER advantage moves to the attacker as the forces become decisively engaged, because more attackers find and engage targets and the concentration and saturation phenomena come into play for the attacker. This suggested that an in-depth use of a large number of small-unit engagements, in which defenders get off a number of shots (operate at the high end of the LER) and fall back to subsequent prepared defensive positions to repeat the process, would be an effective tactic for Europe. This dynamic was at the core of the Active Defense concept created by General DePuy.

Finally, a brief observation on Army experimentation in support of OR analyses during the period 1972–1989: The

Exhibit 2. Instantaneous exchange ratio as a function of battle time.



extensive experimentation observed in the 1950s and 1960s continued in the 1970s, much of it at the CDEC. In 1981–1982 there appeared to be a shift to more operational testing of systems at CDEC and less real experimentation. This trend continued through 1994, when CDEC was closed.

3.0. HISTORICAL PERSPECTIVES 1989–2000

The global security environment of the Cold War era was characterized by relative stability and little uncertainty. In a brief span of four years from 1989 to 1993, the global and national security environment changed dramatically. The Conventional Forces Europe talks and treaty eliminated the major force imbalance in Europe that had existed since 1950. The breakup of the Warsaw Pact alliance, reunification of Germany, collapse of Soviet Communism, and dissolution of the Soviet Union further reduced the massive threat to NATO and led to unilateral reductions by non-U.S. NATO allies. U.S. defense budgets were cut substantially to achieve a "peace dividend," leading to major reductions in military forces (approximately 30%–35% lower). Operation Desert Storm provided a window into future potential conflicts—ad hoc coalition conflicts, power projection rather than forward stationing, contingency operations, and the importance of advanced technology on the battlefield. Modern technology was now available to all nations, including weapons of mass destruction. The world was becoming more politically and militarily unstable with a resurfacing of ethnic and civil disagreements. In a few short years, the Cold War era transformed into a new multipolar world that was more disorderly, more unstable, and more uncertain with increased likelihood of multiple third-world conflicts.

The United States was the sole remaining superpower in this very chaotic and uncertain global security environment. We developed a new National Military Strategy (NMS) which emphasized regional conflicts and crisis response in contrast to the Cold War emphasis on defense against massed Soviet/Pact forces. The NMS success criterion was to apply "decisive force" to win swiftly and minimize casualties. The strategy focused on forward presence instead of forward positioning. It involved a drawdown of overseas forces and an emphasis on power projection for contingency operations. In the second half of the 1990s, the spectrum of potential U.S. military operations were codified as Major Theater Wars (MTW), Small Scale Contingencies (SSC), and Security and Stability Operations (SASO). U.S. military capability had to be restructured to achieve the "peace dividend" by considering changes in force structure/design, modernization, forward stationing, strategic lift, mobilization, active/reserve force mix, and other components of the overall U.S. military capability.

OR analysis played a significant role in this restructuring of U.S. military capability, but we recognized early on that analyses would be more difficult to perform because of changes from the Cold War era. Budgets were much tighter. Analyses needed to consider the requirement for CONUS-based power projection to many areas of the world, requiring explicit consideration of mobilization, deployment, and employment (force capability in theater) processes and their interactions and trade-offs. The new NMS criterion of "decisive force" with minimum casualties coupled with tight budget constraints made the search for acceptable solutions difficult. It was a volatile environment for decision making—with rapidly changing funding, service roles, acceptable scenarios, new administration policies, etc. Analyses had to be conducted with extreme uncertainty regarding potential missions (MTW, SSC, SASO), potential aggressors (where, who, size, equipment, etc.), and potential coalition partners (where, who, degree of modernization, etc.).

These issues changed the nature of OR analyses to support the Army and posed some challenges for analysts in performing them. In the Cold War era, studies could last as long as 1–2 years and involve 15–20 analysts. In the post–Cold War era, most of the OR projects were "quick response analyses" with an average duration of 2–3 months, sometimes weeks or days, and involved 4–5 analysts to respond to a much shortened decision process. Analyses had to explicitly consider the impact of new information technologies and related command-control, communications, and information war processes. There was more OR emphasis on high-level policy-type analyses such as force levels to meet the NMS, feasible and effective forward stationing policies, and others. Because of the severe budget cuts, there were more OR studies which considered trade-offs between major components of warfighting capability (e.g., force structure versus modernization, prepositioning versus rapid deployment). Much of the analyses involved consideration of joint and coalition assets, were conducted at theater level, and considered multiple theaters of operation. To address the increased uncertainty of the security environment, analyses at VRI typically involved 1,000–3,000 different simulated campaigns in contrast to 10–15 in the Cold War era.

In order to meet these challenges in the 1989–1995 time period, we and other OR analysis organizations in the United States enhanced and created new operational-level campaign models. We enhanced the scope of the models to consider additional processes such as mobilization and deployment, nonlinear operational concepts, and information campaigns. And we developed and learned to use more aggregated operational-level campaign models such as MACRO (Farrell 1986) to conduct the large amounts of necessary sensitivity analyses.

During the period 1989–1995, the Army OR community performed a large number of studies to address the many issues confronting the Army in the new security environment, not the least of which were the substantial force downsizing, reduced budgets, and a shift from a forward-based force to a deployment one. These studies not only provided valuable specific information to Army senior leaders for decision making, but also generated a large number of observations and insights regarding the dynamics of our military capability after collapse of the Soviet Union. A few are noted below to highlight what can be learned from simulation-based analyses; a more detailed description of these and others is given in Bonder (1993).

- Given the substantial reduction of U.S. and potential aggressor forces, the U.S./coalition conventional warfighting capability is now very sensitive to many factors which had little impact in the Cold War period. The basic warfighting physics changed when the major force imbalance was removed.
- A "decisive overmatch" in capability is needed to win quickly and minimize casualties.
- Modernization provides major leverage in achieving a decisive warfighting capability—the smaller the force the more modern it must be!
- Early arriving forces nonlinearly reduce the risk of failure and overall casualties in a contingency operation.

With the extensive knowledge of the Soviet threat during the Cold War era, Army planners designed the military force to maximize its "effectiveness" against that threat, subject to cost constraints. Analyses were conducted in one or two typical operational situations, usually a Soviet attack in the Fulda Gap area of Germany. In the early 1990s, with the demise of the Soviet Union and belief that U.S. forces would be involved in a much broader set of missions worldwide, there was widespread belief that force planning should be "capability based," not threat based, and that we needed to redesign Army forces from a clean slate to make them more strategically deployable and relevant to the spectrum of missions expected in the 21st century.

I attempted to meet these objectives in some of our force design studies in the 1990s. Specifically, I suggested use of a new force design criterion, that of designing a military force to maximize its "versatility" across many potential future operational situations, subject to attainment of acceptable effectiveness in each and at affordable costs. The first study in 1991 was performed for General John Galvin, the Supreme Allied Commander, Europe, who needed assistance in designing the structure of a new multinational Rapid Reaction Force (RRF) for NATO (VRI 1991). As input guidance he stated that, "The RRF must be politically feasible"—acceptable in peacetime, and " ... The RRF must be flexible"—useable for crisis containment and capable for initial defense in conflict " ... and not just the Fulda Gap." We created the concept of "parametric scenarios" to represent 27 different potential realizations of conflicts (e.g., attacks by aggressors such as Russia, Yugoslavia, Iran, Syria, Iraq, or Bulgaria against NATO forces in countries such as Norway, Greece, Italy, or Turkey). The parametric scenario concept was used in a "zero-based" force design process. For each scenario, this process involved the use of VRI campaign models and heuristic mathematical programming techniques to add force packages incrementally to improve force effectiveness in that operational situation. The overall design process produced an RRF within political constraints that had acceptable effectiveness in most of the 27 operational situations and could be rapidly augmented with TacAir wings to respond to the more stressful remaining situations.

The versatility planning concept was again used in 1994 to help General David Maddox, the Commander in Chief, U.S. Army Europe, determine an appropriate Army force structure in Europe after the drawdown from 300,000 Army personnel to approximately 65,000 (Miller and Johnson 1994). Through an interactive force-structuring process with the CINC, we designed a versatile force of 67,000+ personnel that could *simultaneously* accomplish one of four types of warfighting missions, *and* a peacekeeping mission, *and* one of three noncombatant evacuation operations, *and* a disaster relief mission. The study was a major driver in determining the proper force structure to maintain in Europe.

It is my impression that, relative to the 1960–1995 time period, in the last five years the Army has reduced the use of model-based analyses to address their system, force design/structure, and operational concept/doctrine issues. It appears to be relying more on large field exercises and subject matter experts in a gaming context. As we move into the 21st century, the Army is in the process of transforming itself from a Cold War force to an objective one with the requirement to be lighter and significantly more deployable, agile, and versatile to accomplish the full spectrum of MTW, SSC, and SASO missions expected in the future. It remains to be seen if OR and model-based analyses will play any role in designing the versatile force.

4.0. SOME LESSONS LEARNED

One of the exciting aspects of practicing OR and M&A for the military establishment is the degree of learning that occurs. It is exciting to discover how military processes operate and exciting (and at times frustrating) to learn how to practice our profession better. In this section I will share with you some insights, principles, and lessons I learned over the past 40 years regarding modeling and analysis for the Army. The reader should recognize that these are my personal beliefs, which may differ significantly from those of other graybeards.

4.1. Modeling Lessons Learned

Before listing lessons in this category, I think it is important to recognize that building a model of a process, a system, or an enterprise is an art. The art is in deciding what elements and activities to include in a model; which dimensions to make variables, constants, stochastic, constraints; what to assume when creating relationships among the variables (linear vs. nonlinear, deterministic vs. stochastic, etc.); and how in a step-by-step process to remove the unrealistic assumptions we necessarily make in building the initial version. And it is an art that can be learned. Some principles and lessons for today's campaign modelers:

- Rely heavily on experiments, tests, and analysis of data to develop a thorough understanding of processes being modeled. Experiments are designed for learning and are useful in all aspects of the modeling process. Unfortunately, the Army today does demonstrations, not experiments as they did in the 1950s, 1960s, and 1970s.
- Develop synthetic models that include physical details of relevant military operational processes. Remember, analytic structures can be used to represent physical details, and although Monte Carlo simulations are stochastic, all stochastic models need not be Monte Carlo simulations.
- Avoid hypothetical constructs such as firepower scores as a modeling basis.
- Given the synthetic requirement, develop hybrid analytic/simulation models with as much analytic structure as possible to facilitate interpretation of results.
- Do not build statistical models if they are to be used to design/reengineer future systems or enterprises—build process models of relevant phenomena that will facilitate prospective analysis (i.e., planning and prediction). Statistical models use data that is intrinsically tied to the current system and thus are best used for retrospective analyses (i.e., evaluation and inference).
- Development of models should be a continual process of research, development, analyses, enhancement, analyses, etc. .... a prototyping or spiral development process, not an event! Build an initial prototype (with unrealistic assumptions, if needed) in a short time period and enhance it continually by removing unrealistic assumptions, adding processes, adding systems, etc.
- Use of a multi-year "waterfall" development process without model application is a recipe for disaster. A deliberate sequential process of developing detailed model requirements specifications, architecture specifications, detailed design specifications, coding, testing, and documentation of a production version takes an order of magnitude too much time before user feedback. My impression is that hundreds of millions, if not billions of dollars, have been spent on the development of JSIMS, WARSIM, and JWARS over a number of years without, unfortunately, any appreciable use.
- Do not develop a single "approved" campaign model for all analyses—although we have made substantial progress over the past 50 years, this is not *yet* physics. We need to perform model validation studies with real or field-exercise operational data to identify the promising models.
- Modelers should have extensive analysis experience. They should have a strong working capability with mathematics/stochastic processes—the language of science. If they do not, all models will be simulations/emulations with significantly less utility.
- Learn from mentors who have built campaign models and used them for analyses, and not just those who theorize about them.
- Do not let computer scientists build the models alone—they are generally more interested in efficient architectures and code than in substance. Make sure they implement the content as designed by analyst modelers.
- Good graphics are useful, but they do not provide or improve content. I have seen many instances where graphics imply underlying content that does not exist.

4.2. Model-Based Analyses Lessons Learned

Before listing lessons in this category, it is important to recognize that models of military operational phenomena are tools which, when used by trained and experienced analysts, provide useful information and insights to assist decision makers in areas where direct experimentation is expensive and, many times, impossible. They are not accurate predictors of the future. There is also much art associated with conducting analysis—art in converting a decision problem into an analysis one, in creating appropriate hypotheses to test, in designing model runs, in determining how to appropriately "trick" a model to represent phenomena not explicitly in it, in designing meaningful measures of effectiveness (MOE), and in developing meaningful and useful observations and recommendations. Some principles and lessons for today's analysts:

- Look for "Hemibel" effects and insights. This is a metaphor from World War II OR to suggest that analysts look for *significant* effects that indicate that a different engagement or campaign has occurred with input changes. My experience suggests that at least 50% change in small-unit engagement-level MOE (e.g., LER) is needed to be significant, while a much smaller change (15%–20%) in campaign-level MOE (e.g., Force Exchange Ratio) is significant.
- Analyze to understand "why" a change is significant, do not just compare MOE among the alternatives—look for model cause and effects. Rationalize the results. Involve the full team—analysts, functional experts, data developers, programmers, etc.—for a full understanding of cause and effects.
- Do not rely on intuition to determine reasonableness of model results—models and analyses help enhance intuition. Intuition is built on experience with the existing system, not the future one being analyzed.
- Do not just examine point alternatives—conduct parametric analyses to look for "knees in the curve." Look for alternative system designs where small changes lead to large engagement/campaign changes and substantial return on investment.
- Conduct extensive parametric analyses on uncertain operational situation variables to understand the impacts of uncertain environmental or threat processes not under your control.
- Beware of and learn about "structural variance" (Hawkins 1982). This is a closed model phenomenon in which an increase in the capability of your system illogically reduces the overall engagement or campaign results. It is caused by interactions between the increase in capability and internal decision logic thresholds.

• Remember a ratio measure has a numerator and a denominator—the ratio measure varies differently for each and can lead to significantly different insights. The ratio measure changes linearly with the numerator and hyperbolically with the denominator.

• Try to conduct continuous analyses in an analysis area, not just for a single decision. It will provide the opportunity to develop knowledge about the dynamics of military operations and build your intuition. It will provide you with the capability to respond quickly to decision makers with previous analysis results and your enhanced intuition.

• If possible, use multiple models to address major resource decisions.

• Involve the client in all aspects of the analysis—it provides immediate buy-in and an advocate for the results. If the analysis is conducted in isolation, it is likely that you will provide a good answer to the wrong question or not have addressed the most innovative alternatives. Both you and the client will learn during the analysis.

• Given the large uncertainty in future activities for our armed forces, design the force to maximize its "versatility" across many future operational situations, rather than maximizing cost-effectiveness in one or two situations.

• Mentoring is critical. It takes 10–15 years to develop a journeyman analyst capable of independent analyses—analyses that produce useful results on time, provide meaningful insights, and provide results that can hold up under detailed, technical peer review.

• Finally, remember it is the analyst not the model that produces meaningful and useful results. Improve the former before the latter! Too many resources have been devoted to "model improvement programs" and too little to improving military OR analysts.

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