

Proceedings of

**Management of Risk
And Uncertainty**

In the Acquisition
Of Major Programs

U. S. AIR FORCE ACADEMY
COLORADO SPRINGS, COLORADO
FEBRUARY 9-11, 1981

CO-SPONSORED BY:

UNIVERSITY OF SOUTHERN CALIFORNIA
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U. S. AIR FORCE BUSINESS RESEARCH MANAGEMENT CENTER*

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Proceedings
MANAGEMENT OF RISK AND UNCERTAINTY
In the Acquisition of Major Programs

U. S. AIR FORCE ACADEMY
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EDITED BY:

COL. M. D. MARTIN
DR. ALAN J. ROWE
DR. HEROLD A. SHERMAN

PREFACE

In every major system acquisition the project manager must review and assess the uncertainty confronting the acquisition. How this uncertainty is perceived, assessed, and approached has not been determined. Risk and uncertainty are integral aspects of the manager's decision making role, whether the decision is micro or macro and it requires an assessment of the scope and magnitude of uncertainty. Yet, research disclosed that decision makers in the Department of Defense and the private sector seldom give the concept much attention.

There is a need to develop an awareness and a better understanding of the state-of-the-art in managing risk and uncertainty. The need exists particularly in DoD for proper attention to the policy established for the identification of risk in DoD Directive 5000.1 and DoD Instruction 5000.2. These require management to provide estimates that identify bands of uncertainty and the risks for technological and production milestones.

It was an awareness of this lack of attention and focus that led to the first Risk and Uncertainty Conference at the University of Southern California in February 1979. This conference was adjudged an outstanding success. One of its outputs was an intensified awareness of the fragmented and ad hoc approach that existed to understanding the subject of risk and uncertainty. Thus, the seeds for the genesis of the second Risk and Uncertainty Conference were planted in Los Angeles. The staff of the Air Force Business Research Management Center and faculty at the University of Southern California sensed the urgency to continue the further defining and bounding the discipline of risk and uncertainty and thus co-sponsor this second conference.

The conference had as a theme or overall objective: "Define the Current State-of-the-Art in Managing Uncertainty in Major Acqui-

sition Activities." A basic approach used for the conference was the selection of outstanding professionals with the expertise to generate and present significant papers and/who would, by their personal contributions as panel members, be able to place initial boundaries around this emerging field of knowledge. The idea of having experts, theoretical and practical, from industry, government and academe helped pace the organization and execution of the conference.

The conference theme and subject of risk and uncertainty was divided into four areas (or sections): applications, taxonomic concepts, methodologies, and assessments. The applications area was covered first to identify and intensify the problems associated with the application of risk and uncertainty concepts. The four areas then served as the basis for conducting the panels. The panels in each of the areas had additional objectives, including the preparation of recommendations. The panels met the workshop objectives, and made a significant contribution to the conference.

The panel format was based on using a small group approach. Outstanding theorists, and practitioners were invited to present papers, to chair panels and to serve in appropriate other roles. Each paper was presented to a panel composed of ten to fifteen individuals. Thus, it took the form of a seminar. The panel chairmen served as moderators and later summarized the panel discussion at a plenary session.

This interaction, in small groups, on a well defined subject for a lengthy period of time (over two hours) led to a much greater depth of discussion, personal involvement, exchange of ideas and cross fertilization than occurs in a typical professional meeting. The response was well beyond our expectations. The people who attended came with enthusiasm and dedication to the task, they interacted and they hammered out the general beginnings of a new discipline which has at its focus

risk and uncertainty.

The initial thrust for the conference was established in a penetrating manner by the keynote speaker, Brig. Gen. William Thurman, Commandant of the Defense Systems Management College. He reviewed the sophisticated weapon systems that will be acquired in the 1980's, and the levels of uncertainty that will surely be associated with them in terms of cost, schedule and performance. He placed the problem of improving management of risk and uncertainty squarely on the shoulders of the conference participants.

While the published papers reflect the experience and research effort of the authors, it is difficult to adequately recognize the dynamic interaction and intellectual stimulation that occurred during the panel discussions and after the presentation of each paper. Those serving as panel chairmen in each area (or section) met, selected a recording secretary and reported on these discussions, suggestions, and the recommendations of each panel. The recorders then presented this information to the final general session. Again, there was lively discussion.

The written reports and notes of the panel chairmen have been synthesized and combined into a summary for each area or section of this proceeding. The range and thrust of the recommendations from these panels are an indication of the momentum that was attained. The seriousness and dedication of participants to continue their study and research is also evident from the recommendations for future activities.

One recommendation receiving almost unanimous recognition was the need for definition. The identification of semantic differences from the mathematical to the practical usage of terms in discussions was most apparent and frequently frustrating. The same terms were used for many very different concepts and methodologies.

This problem leads to the next major recommendation for the need of further definitional categories and developing an appropriate taxonomy as essential to the order and progress of the discipline. Without well defined and understood terminology the semantics required to translate or integrate applications into state-of-the-art via a taxonomy and flush out the skeletal framework will be extremely difficult.

There were a number of specific recommendations made by the panels. They constitute a substantive list of problems and issues for further study and research. These are

shown at the end of each section of papers in the proceedings.

Above all we believe that the conference established a technical and management baseline upon which to build. Thus, in closing our challenge to the participants who will now study the conference results and to those who study these proceedings is that they accept the challenge of the research, and experimental applications needed to meet an ever increasingly complex and turbulent acquisition environment. The resources must be applied to this task and contracting agencies must focus on how best to integrate these concepts into more meaningful contractual expectations.

As a final note, two dedicated individuals, Ed Cochran and Capt. William Glover, who to a large extent were responsible for the concept of this second conference are no longer with us. It is our fond hope that what we accomplished will serve as a fitting memorial to two incredible people.

May 1981

Col. Martin D. Martin
Dr. Alan J. Rowe
Dr. Herold A. Sherman

ACKNOWLEDGEMENTS

Without the dedicated support and effort of many individuals, this conference could not have achieved the results obtained. We would like to thank the many individuals involved. Capt. Mike Tankersley, Major Bob Golden and Linda McLaughlin from the Air Force Business Management Research Center provided invaluable expertise, enthusiasm and energy. Janet M. Shea at the Air Force Academy was instrumental in assuring smooth operations. Charmelle Toyofuku in the Office of Executive Programs provided full support of the effort. Finally, our dedicated secretaries, Tia Davis and Marj Tamaki helped make the whole process work and kept the ship from sinking in meeting tight deadlines.

To the panelists, chairmen and paper presenters, our thanks for their enthusiasm and contributions. Without them there could not have been a conference.

To Ed Cochran, who not only fathered the "s" shaped learning curve, but did the basic work on disruption theory, we owe an extreme debt of gratitude.

Conference Co-Chairmen
Col. Martin D. Martin, Dr. Alan J. Rowe

RISK AND UNCERTAINTY WORKSHOP

Held at

UNITED STATES AIR FORCE ACADEMY, COLORADO SPRINGS, COLORADO

(9 - 11 February 1981)

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BRIGADIER GENERAL WILLIAM E. THURMAN

Brigadier General William E. Thurman is com-
mandant of the Defense Systems Management Col-
lege, Fort Belvoir, Virginia.

He graduated from the U.S. Naval Academy, An-
napolis, Maryland, in 1954 with a bachelor of
science degree and was commissioned as a sec-
ond lieutenant in the U.S. Air Force. He
earned a master of science degree in aeronau-
tical engineering from the Air Force Institute
of Technology, Wright-Patterson Air Force Base,
Ohio, in 1962 and a master of administration
degree in management engineering from the
George Washington University, Washington, D.C.,
in 1971. He completed Squadron Officer School
at Maxwell Air Force Base, Alabama, in 1959;
the Army Command and General Staff College at
Fort Leavenworth, Kansas, in 1965; the Indus-
trial College of the Armed Forces at Fort Les-
ley J. McNair, Washington, D.C., in 1975; and
the Stanford University executive program in
1977. He also attended the University of Ken-
tucky and Ohio State University.

Assignments in research and development have
included tours of two years with the Aero-
space Research Laboratories at Wright-Pat-
terson Air Force Base, one year with Air De-
fense Command at Ent Air Force Base, Colo-
rado, two years in Headquarters U.S. Air Force
at the Pentagon, two years with the National
Aeronautics and Space Council staff in the
Executive Offices of the president, and 6½
years with the Aeronautical Systems Division
at Wright-Patterson Air Force Base.

Assigned to the Aeronautical Systems Division in August 1971, General Thurman became a charter member of the Prototype Program Office as its assistant director. He was named the deputy for prototypes in June 1973, deputy for air combat fighter in May 1974, deputy for F-16 in January 1975 and deputy for engineering in May 1976. He received the Air Force Associations Meritorious Award for Program Management in 1976.

In May 1978 General Thurman was assigned to the Electronic Systems Division at Hanscom Air Force Base, Massachusetts, as deputy for control and communications systems. General Thurman began his current duty in July 1979.

MR. RICHARD D. ABEYTA

Mr. Abeyta has spent the last four years researching, teaching, and applying risk and uncertainty analysis in the Army material acquisition process. He has researched and published several studies applying Operations Research and Decision Analysis to the Army logistics process and has coauthored a handbook on Decision Risk Analysis. He is currently on the graduate night school staff of the Florida Institute of Technology and Chapman College, teaching Operations Research. He is a member of Alpha Pi Mu and Tau Beta Pi honorary societies. Mr. Abeyta is Chief of the Decision Risk Analysis Committee in the Systems and Cost Analysis Department of the U.S. Army Logistics Management Center (ALMC).

DR. DAVID N. BURT

David N. Burt currently is lecturer in marketing and logistics at San Jose State University. Dr. Burt is a frequent guest lecturer and speaker in this country and abroad on topics in the areas of acquisition management, logistics, production, and purchasing. Dr. Burt received his Ph.D. from Stanford University in 1971. Since that time, he has taught at the two graduate schools of the Department of Defense and been a consultant to several DOD and private organizations. He has authored some 20 articles in the areas of acquisition, logistics, and long range planning. His current efforts are directed to a book on the material acquisition process in the private sector.

MAJ RICHARD F. DeMONG (USAF Reserve)

Major DeMong is an Associate Professor of Commerce at the McIntire School of Commerce, University of Virginia. He is a Doctor of Business Administration in Finance and Management Science (University of Colorado). He has published articles in the American Journal of Small Business, Journal of

General Management, National Contract Management Quarterly Journal, and the Defense Management Journal. Also, he is a member of several national financial associations. Major DeMong is a Research Associate (USAF Reserves) at the Air Force Business Research Management Center, Wright-Patterson AFB, Ohio.

DR. WARD EDWARDS

After spending 15 years at the University of Michigan, Dr. Ward Edwards moved to the University of Southern California in 1973. He is now Director of the Social Science Research Institute and Professor of Psychology and of Industrial and Systems Engineering at USC. The Institute that he directs conducts large scale research programs applying scientific tools and methods to problems such as evaluation and improvement of criminal justice systems, techniques for resolving criminal and civil disputes without recourse to the courts, use of geographically coded records for planning and social program evaluation, differential equation models of social phenomena, biological and social determiners of schizophrenia and criminality, physical and social tradeoffs among alternative energy sources, and the like.

Dr. Edwards is a psychologist by training, and his personal research interests are mostly concerned with the methods and applications of decision analysis with behavioral decision theory. He helped introduce Bayesian ideas into psychological research, primarily from the point of view that uses Bayes's Theorem as a model of human inference processes. His current research is concerned with the characteristics of multiattribute utility models, with elicitation methods appropriate to their use, and with their application to social program and evaluations. His research has always attempted to blend abstractions with applications; most of it is set in or relevant to solution of some real-world decision problem.

MR. JOHN S. W. FARGHER, JR.

After his graduation from the Montana College of Mineral Science and Technology in 1969, Mr. Fargher began his Department of Army civilian career as a Production Design Engineer at the Red River Army Depot Intern Training Center. He was graduated from the center in 1971 with a certificate as a Production Design Engineer, and also received a master of engineering degree in industrial engineering from Texas A & M.

His initial assignment was the Systems Engineer for the Small Caliber Ammunition Modernization Program (SCAMP), Frankford Arsenal, where he directed the development of the Ballistic Test System, which is now the Army standard for ammunition proof and acceptance. In 1973, he was Chief of the Production Planning and Control Division, U.S. Naval Ammunition Depot, Hawthorne, Nev., directing the workloading of the Ordnance Department. In 1974, he became Lead Mechanical Engineer with Rodman Laboratory, Rock Island, Ill., and attended PMC 74-2 at the Defense Systems Management College. In 1975, Mr. Fargher was Industrial Engineer with the Iranian Aircraft Project Manager's Field Office, Teheran, Iran, managing the Bell Helicopter International contracts for establishment of a helicopter logistics system for the Government of Iran. After completion of his tour in 1977, Mr. Fargher was Deputy Chief of the Materiel Systems Development Division, Directorate of Combat Developments, U.S. Army Transportation School, Fort Eustis, Va. He joined the staff of the Defense Systems Management College in December 1978. Mr. Fargher also completed a second masters degree, an M.S. in systems management (logistics option) in 1978, started while a student at DSMC in 1974.

Since joining the DSMC faculty, Mr. Fargher has managed the research for A Guide for the Management of Joint Service Programs for the Joint Logistics Commanders, and a NATO RSI Acquisition Guide for the Office of the Secretary of Defense, as well as developing courses and teaching in PMC, SAFMC, and MPMC. He is also the Executive Secretary of the Defense Acquisition Research Element (DARE) for coordinating acquisition research with DOD and FAI.

His current position is Professor of Acquisition/Program Management, Research Division, Department of Research and Information, DSMC.

MR. ALFRED M. FEILER

As President of Log/An, Inc. since its founding in 1965, Mr. Feiler has directed the firm's operations, including development of its proprietary computer-based project risk management tools which have received widespread acceptance in industry and government. Such techniques are now in worldwide use of projects totalling over \$35 billion in value.

Mr. Feiler's experiences have centered on the systems approach to solution of complex management problems in the fields of research and development, engineering, and construction.

Mr. Feiler recently retired from the academic staff of the University of California (Los Angeles), where, for 16 years, he directed research and development in the management sciences for several government agencies.

Prior to that, Mr. Feiler was Area Vice President of Pneumodynamics (now Pneumo) Corporation, and earlier was Division Manager of Pneumodynamics' Advanced Systems Development Division, El Segundo, California. During this time, he successfully applied the systems approach to development of a line of products for industrial and military uses. Previously, he was Chief of Advanced Systems Research, Aircraft Division, Hughes Tool Company, where he was primarily concerned with systems analysis of logistics and transportation problems.

Mr. Feiler has authored numerous reports and papers on simulation, project risk management, and systems analysis; and has served on several government committees and advisory boards in connection with his specialty fields of interest. He is a registered Professional Engineer in California and New York. Mr. Feiler received his B.S. and M.S. degrees in Civil Engineering from Carnegie Tech in 1941 and 1942, respectively.

DR. PETER C. GARDINER

Dr. Peter C. Gardiner, newly appointed as Associate Chairman of the General Systems faculty, is an Associate Professor at the University of Southern California's Institute of Safety and Systems Management.

Prior to joining the USC faculty, Dr. Gardiner served as Systems Control Officer and Operations Project Officer for the Defense Communication Agency, European Area, while serving in the Navy from 1963-1969.

He is the author of numerous professional publications in such subject areas as systems dynamics modeling and simulation, multi-attribute utility measurement, and managing complex systems.

Dr. Gardiner, who was formerly a teaching Fellow in the Industrial Engineering Department at the University of Michigan, belongs to the Society for Computer Simulation, The World Futures Society, the Society of Logistics Engineers and the Institute of Management Sciences.

Since coming to the University, he has also been continuously active in analytical research problems, principally in

his role as a research associate at USC's Social Science Research Institute.

Dr. Gardiner was awarded his BS in Electrical Engineering, MS in Systems Management and his Ph.D. in Urban Studies, all from the University of Southern California.

DR. GEORGE P. JONES

George P. Jones joined the University of Southern California in 1970 as chairman of the Systems Management Department at the Institute of Safety & Systems Management.

At the Institute, Jones participated in promoting and opening new study centers. He was Principal Investigator on funded research studies such as a "Risk Analysis of Hazardous Materials Transportation" study for DOT's Office of Hazardous Materials (OHM). He also led a research study for the development of a safety plan for the Urban Mass Transportation Administration (UMTA). Jones has functioned as Director of the Institute's Research Center and Acting Executive Director of ISSM's worldwide graduate level program.

In addition to his administrative duties Jones holds a joint appointment as Associate Professor in Systems Management and Industrial and Systems Engineering (ISE). He has consulted for organizations such as R.A.N.D., application of management science techniques, statistics and risk analysis.

Formerly, Jones had a career ranging from research and development engineering

through management of systems analysis projects at North American Rockwell and other industrial organizations. He served as Chief Engineer and Director of Advanced Systems during the inception of the FJ series, RA-5, X-15, OV-10, B-1 Aircraft and other missile and space systems.

Jones earned his Ph.D. degree in Industrial and Systems Engineering, with concentration in the management sciences, from Ohio State University; a M.Sc. degree from the same university in Mechanical Engineering, with specialization in thermodynamics and heat transfer, and a B.M.E. degree from The Cooper Union College of Engineering in New York City, his native town.

DR. CRAIG W. KIRKWOOD

Craig W. Kirkwood is a member of the decision analysis group at Woodward-Clyde Consultants, San Francisco, California

94111. He has extensive experience directing and participating in studies of risk and uncertainties associated with the acquisition of major systems. This experience includes site selection for electric power generation facilities and nuclear waste repositories, analysis of public risks associated with a proposed liquefied natural gas terminal, evaluation of proposals for solar photovoltaic demonstration projects, and a variety of other studies. He has utilized decision analysis on these and other problems, and has published articles on both theoretical and applied aspects of decision analysis. He received S.B., S.M., E.E. and Ph.D. degrees from the Massachusetts Institute of Technology.

MR. GERALD A. KLOPP

Served as a Production Engineer at the Electronics Command, Ft. Monmouth, NJ; an Operations Research Analyst at the Comptroller's Office, Ft. Ritchie, MD; Operations Research Analyst, Systems and Cost Analyst Department, US Army Logistics Management Center, Ft. Lee, Va; and Operations Analyst in the Technical Design and Validation Branch of the Operations Analysis Directorate of the US Army Logistics Center, Ft. Lee, VA. Currently serving as the Statistician at the Army Procurement Research Office, Ft. Lee, VA. Experience in Operations Research include a Hybrid Computer Simulation of a large scale production system; senior instructor and Course Director of the ORSA Military Applications Course I; publication of 7 articles on computer modeling and simulation; and several interactive computer programs for statistical, economic, and Operations Research applications. Education includes a BS in Electrical Engineering from Michigan State University (1972) and ME in Industrial Engineering from Texas A&M University. Production System Analysis, and Systems Analysis for the Florida Institute of Technology at Ft. Lee, VA.

MR. GEORGE T. KRAEMER

Manager of Engineering Control and Risk Analysis at Boeing Vertol Company under the Director of Engineering Operations. Graduated from the University of Pennsylvania with a degree in mathematics (B.S. 1951) and in 1970, received a Master of Business Administration (statistics) from Temple University. Member of the American Helicopter Society. Thirty years ex-

perience in engineering business management, subcontract management, and master planning in aircraft and electronic industries. Also have written several papers.

DR. DAVID V. LAMM

Dr. David V. Lamm is currently an Assistant Professor of Administrative Sciences at the Naval Postgraduate School in Monterey, California where he instructs military officers and civilians in the fields of Acquisition, project management, and contracting.

He holds a BA in History and Political Science from the University of Minnesota, a MBA in Procurement and Contracting from the George Washington University, and a DBA in Procurement and Production, and Science and Technology Management from The George Washington University.

He is currently serving on active duty as a Navy Commander. He has held various tours both afloat and ashore in the Navy. Acquisition and contracting tours include duty at Headquarters, Defense Contract Administration Services (DCAS) and Headquarters, Naval Air Systems Command where he served as Assistant Director, Missile Weapon Systems Purchase Division.

He is a member of the National Contract Management Association (NCMA) and is a Certified Professional Contracts Manager (CPCM). He has participated in the CPCM program since 1975 as the first Chairman of the CPCM Examination Board and currently as an examination grader. He has been a frequent speaker and panelist at various meetings and workshops. He was the First Place Winner of the 1978 Blanche Witte Award and is currently director of the Monterey Peninsula NCMA Chapter.

DR. RICHARD LORETTE

Dr. Richard Lorette is a member and Fellow of NCMA and editor of the National Contract Management Journal; he has held management positions in the Air Force Systems Command (Weapons Acquisition; B-52 SPO and C/KC-135 SPO) and Air Force Institute of Technology prior to his retirement from the Air Force in 1973. Dr. Lorette has taught courses in Procurement, Systems Management, and Program Management and published several articles in the general area of Procurement and Systems Acquisition. Recently, he completed a one-year consulting assignment (from the University of Southern California) to the Federal Acquisition Institute, studying major acquisition issues and problems in the federal civil agencies. He is a 1950 Graduate of West Point has an MBA in Engineering Administration (AFIT), a Doctorate in Business Administration from the Harvard University Graduate School of Business Administration and is

currently Professor of Management Science in the College of Business at Ball State University in Muncie, Indiana.

COLONEL MARTIN D. MARTIN

Colonel Martin currently serves as the Executive Director of the Air Force Business Research Management Center, Headquarters USAF, Wright-Patterson AFB, Ohio.

Colonel Martin holds a Bachelor of Science Degree in Industrial Education from the Louisiana State University and both a Master of Business Administration Degree and a Doctor of Philosophy Degree in Financial Management, Marketing, Systems Management, and Economics from the University of Oklahoma.

He has extensive experience in the acquisition and contracting areas as a manager. In the contract administration area he has served as both the Chief of Management Engineering and the Assistant Chief, Office of Planning and Management, of a major Defense Contract Administration Services Region and as the Chief of a Defense Contract Administration Services Office. At major command level, USAF, duties included the function of a procurement management staff officer in the area of weapon systems acquisition and procurement pricing policy. He also served as a Deputy Program Manager. He has served as a Director of Manufacturing for a major Systems Program Office and the Director of Contracting for Wright-Patterson AFB. His Air Force functional experience has included duty as a procuring contracting officer, administrative contracting officer, and a price and cost analyst in the contracting and acquisition operational area.

In the education, research, and consulting areas, Colonel Martin served for four years as Associate Professor of Logistics Management and Department Chief, Functional Management Department, Graduate Education Division, School of Systems and Logistics, Air Force Institute of Technology. He is at present an Adjunct Associate Professor of Marketing, Wright State University, Dayton, Ohio. He has also taught and delivered lectures at Stanford University, University of Southern California, University of Oklahoma, Wittenberg, Sinclair Community College, and the University of Dayton. He has consulted and conducted seminars for industrial, government, and military management in the United States and the United Kingdom.

Colonel Martin is a member of Phi Kappa Phi, national education honor society; Omicron Delta Kappa, national scholarship honor society; Beta Gamma Sigma, national business administration honor society; and others. His professional and business organizations include the Project Management Institute, the American Finance Association, the National Contract Management Association, and the Society of Logistics Engineers.

LT COL JACK L. McCHESNEY

Lt Col Jack L. McChesney is an Assistant Professor of Logistics Management in the Contracting Management Department, School of Systems and Logistics, Air Force Institute of Technology. He focuses his teaching in the specialized areas of the Graduate Contracting Major.

Lt Col McChesney holds a Bachelor of Business Administration Degree from North Texas State University, A Master of Business Administration Degree from the University of Texas at Austin, and a Doctor of Business Administration Degree from George Washington University. His Air Force experience includes assignments as Base Procurement Officer at England AFB, Louisiana, and Cannon AFB, New Mexico. In that capacity, he made purchases and administered contracts for supplies, services and construction. He served as a staff contract administrator in the HQ Defense Contract Administration Services at Cameron Station, Alexandria, Virginia. While in DCAS, Lt Col McChesney was responsible for developing, implementing and monitoring policies and procedures for contract administration on a DOD-wide basis. His most recent assignment was with the HQ Air Force Systems Command, Andrews AFB, where he worked in the Directorate of Procurement Data Systems, DCS/Procurement and Manufacturing. During that tour of duty, he participated in the development and implementation of a command-wide acquisition management information system. Lt Col McChesney is a member of Beta Gamma Sigma, Phi Kappa Phi, Phi Eta Sigma and Blue Key national honorary societies and a Fellow member of the National Contract Management Association.

DR. GERALD R. McNICHOLS

Dr. McNichols is President and Technical Director of Management Consulting & Research, Inc. (MCR) a firm which specializes in resource analysis studies including Life Cycle Cost, Design-to-Cost, Uncertainty Analysis and Risk Assessment, manpower, operations research, and economic analyses. He is co-author of a textbook, Operations Research in Decision Making (1975), past editor of the Cost-Effectiveness Newsletter, and past-president of the Washington Operations Research Council. For the past 17 years he has been developing and applying resource analysis techniques in government and industry. He was a Vice President of J. Watson Noah Associates, Inc. (cost analysis consultants) and a Vice President and Director, Defense and Technology Programs Division of GENTECH, Inc. (management and information system consultants). During his nine years of government service he worked for the Deputy Assistant Secretary of Defense for Resource Analysis, Deputy Assistant Secretary of Defense for Strategic Programs (both under the Assistant Secretary for Systems Analysis), and in the Office of the Chief, Operations

Analysis, HQ USAF. While in DoD, Dr. McNichols directed efforts to formulate fiscal guidance for the annual service budgets, evaluated forces and systems requirements as proposed by the Military Services using cost-effectiveness tools and models as an advisor to the DSARC, and developed parametric cost relationships and Life Cycle Costs as a member of the Cost Analysis Improvement Group (CAIG). He introduced cost uncertainty analysis to the DSARC Milestone Reviews in 1972. He is also Professor of Engineering at George Washington University.

He holds a Doctor of Science degree in Engineering/Operations Research with a minor in economics and has authored numerous articles/research papers in the fields of resource analysis and operations research.

DR. HERBERT MOSKOWITZ

Herbert Moskowitz, Ph.D. UCLA, is Professor of Management at the Krannert Graduate School of Management, Purdue University. His publications include papers in such journals as Management Science, Operations Research, Omega, Academy of Management, IEEE Transactions on Engineering Management, AIIE Transactions, Decision Sciences, and Organizational Behavior and Human Performance. He is a vice-president and a member of the Executive Board of AIDS and a member of TIMS, and ORSA.

MR. MICHAEL D. RICH

Mr. Rich is currently Director, Resource Management Program at the Rand Corporation in Santa Monica, CA. He is also directing a study of prospective Air Force participation in Multinational coproduction programs. Topics being studied include cost and schedule implications of various types of collaborative arrangements, the problem of third-country sales, and U.S. and European design practices, business methods, etc.

He participated in the 1979 Defense Science Board Summer Study on Reducing the Unit Cost of Equipment and contributed to the 1979 Defense Resource Management Study. He is a member of Phi Beta Kappa, where he studied law at the University of California, Berkeley.

DR. ALAN J. ROWE

Dr. Rowe currently is a Professor of Management and Policy Sciences in the School of Business Administration at U.S.C. He was previously Director of the Decision Systems Program, Associate Dean and Chairman of the Management Department. He was responsible for programs in Denmark, Tehran and Singapore covering Management Decision Making, Management Control Systems, Management Information Systems Project Management, and Acquisition Management.

Prior to joining the U.S.C. Faculty in 1965, Dr. Rowe was the Director of Industrial

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His academic Career has included teaching at UCLA, Syracuse, Columbia and NYU in addition to USC. He is active in professional societies and is listed in American Men of Science and Who's Who in the World.

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Dr. Herold A. Sherman, Associate Professor of Systems Management, served as Executive Director of the University of Southern California Institute of Safety and Systems Management from 1968 to 1980.

During those 12 years the Institute grew from a small division of USC's University College to a major element of USC with over 60 centers in the United States, the Pacific, the Far East, and West Germany.

As Executive Director Dr. Sherman administered three USC degree Programs. The Institute baccalaureate and master's degree programs in Safety were among the first developed at major universities. The innovative master's degree program in Systems Management, with a current international enrollment of over 2000, has become a model for off-campus degree programs in the United States.

Dr. Sherman was also responsible for the overall administration of major research contracts (funded at over \$5,000,000) conducted by the Institute for several federal agencies. The Institute activities managed by Dr. Sherman further included an extensive program of non-degree extension courses in Safety.

Dr. Sherman formerly served as President of the Flight Safety Foundation, an international non-profit organization. During his term as President he reorganized and revitalized the Foundation's programs, bringing it into a sound fiscal position. The Flight Safety Foundation's membership now includes most of the major air carriers of the world and the majority of aerospace manufacturers.

Dr. Sherman, who has been published in the field of aviation product liability, maintains a broad spectrum of professional activities. He is a member of numerous professional societies, has testified before Congress concerning aviation, and has been an invited speaker at both foreign and domestic universities and corporations. He is a former winner of the Air Force Association's Outstanding Educator Award and the Strategic Air Command's Award for Outstanding Achievement in Aerospace Education. Dr. Sherman is a

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Dr. Charles W. N. Thompson is presently a Professor of Industrial Engineering and Management Sciences, The Technological Institute, Northwestern University. He received his BS from Kutztown State College, an LL.B, Harvard Law School, an MBA, Ohio State University and a Ph.D. Northwestern University.

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He was Chief, Electronic Reconnaissance Section, Aerial Reconnaissance Laboratory at WPAFB, responsible for design and management,

including the first two major systems designed and procured as complete airborne reconnaissance systems with ground support components. Developed a systems procurement of a major computer based data handling system.

At Admiral Corporation, he was Director of Engineering Services, which included systems and advanced engineering. Responsible for and participated in design and management of major en route air traffic control bright display system, and in systems design over a variety of battlefield sensor and communication equipments.

Various information and decision system designs and resins, including two political caucus decision processes, and a quasi-judicial university hearing and appeals system.

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Dr. Varley has been Director of the Operations Research Program, Office of Naval Research, Arlington, Virginia, since 1970. He is a Doctor of Business and Economic Statistics from George Washington University, Washington, D.C. As a member of the Operations Research Society of America he has held many positions, including chairman in 1976 and 1977. Dr. Varley has also functioned as chairman for the Institute of Management Sciences College on Logistics (1975-1980) and the DoD Ninth Annual Acquisition Symposium (1979). He is currently a member of the Board of Editors for the Naval Logistics Research Quarterly.

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Mr. Wilder is Manager of the Econometrics Section in the Operations Analysis Department of Grumman Aerospace Corp. This section engages in the parametric costing of advanced aerospace systems, and other economic analyses. He has been involved in the development of various methodologies, particularly project evaluation and cost risk. He earned his undergraduate degree in Mechanical Engineering from Cornell, and he holds master's degrees in Management Engineering from Long Island University, and in Applied Mathematics from SUNY, Stony Brook.

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Dr. John R. Adams holds the Ph.D. in Business Administration from Syracuse University, and is currently an Associate Professor of Organization and Management at Western Carolina University, North Carolina. He is also the Director for Educational Services of the Project Management Institute. Dr. Adams has published a number of articles on various aspects of project management, risk and uncertainty analyses, weapon systems acquisition, and logistics management in nationally distributed journals, and is a frequent speaker at national professional and at Department of Defense symposia. His experience include management of major weapon systems acquisition programs and supervision of a major Air Force research laboratory.

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MANAGING RISKS AND UNCERTAINTY:
LOOKING TO THE FUTURE
General William Thurman, Commandant
DSMC Fort Belvoir, VA 22060

I appreciate the opportunity to address this august, multidisciplinary group. And I look forward with great anticipation to the end products of this conference as they may affect and assist us in our complicated world of project management. (See page 13)

Highly developed, modern, and technologically based societies look to the future. Likewise, change, progress, and planning are integral parts of our defense structure, and are crucial to our management processes. We in government often emphasize a future that will be characterized by complex weapons systems. These systems will create management problems and opportunities that far surpass our current contemporary management theory and practice. (See page 13)

Formal recognition and emphasis on risk and uncertainty analysis in DOD resulted from a 31 Jul 69 memorandum from David Packard, DEP SEC DEF to the MIL DEPs identifying problem areas in the weapon system acquisition process. In this memo, Secretary Packard cited inadequate identification and consideration of risks in major programs as a problem area requiring action and that risk analysis be applied by program managers in their daily activities. This growing recognition of the need for risk and uncertainty analysis over the past decade has been attended by the need for philosophical foundations. This need has been manifest in many ways. Numerous R&D organizations have reorganized in attempts to produce more efficient systems of greater complexity. Many universities have revised their programs to provide multidisciplinary educational opportunities for personnel with training in engineering and science, as well as from the more traditional academic backgrounds. The past decade has also witnessed an explosion of books and technical papers on risk and uncertainty analysis. The PM has recognized the benefits of this analysis and the required resultant management of these risks. It is well known that the PM's task is the management of the project's risk and uncertainties. It is evident that this decade will require the DOD to come to terms with an imposing array of problems: affordability of complex weapons systems, sufficient manpower to operate and maintain this equipment, and the ever increasing threat posed by the Warsaw Pact as it affects the world balance of power. Tremendous risks and attendant uncertainties must be taken if we are to progress. Technology must be challenged in many areas if we are to overcome the numerical superiority of the Warsaw Pact.

The common element to many complex programs is uncertain technology. Whether we talk about new construction methods, electronic devices, aircraft, or tanks, there are numerous uncertainties that derive from inadequate knowledge of the basic technology or its specific implementation. These problems have no clear cut solutions. Largely because of the number of organizations involved, as well as the uncertainties and risks, the problems and processes involved can be typified as lacking of boundary conditions; solutions must be derived on the spot, not simply from scientific and engineering principles; and implementation is going to involve collaborative and integrated activities that criss-cross organizational and national boundaries. As has been evident in the private sector, it would appear that an increasing number of defense ventures, because of their size, capital requirements, and technological uncertainty, will require collaborative "federations" as well. When the countries within NATO recently sought to exploit new technologies for early warning of an attack by Warsaw Pact forces, the sovereign countries joined forces to coproduce 18 NATO Airborne Early Warning Systems. (See page 13)

Traditionally, ours is an optimistic society. American technological pragmatism is unchallenged. Confidence in the expertness with which we can move from research through development to production, even when the uncertainties and risks are staggering, has resulted in a growing demand for engineering-management "know how" being applied to solve any problem. The transferability of technology and our omnipotence to solve any problem need to be tempered. There is an impressive and growing list of failures in large-scale advanced-technology programs. Many of these failures involve military programs, but there have also been numerous failures in non-military projects. We know less than we think we do about the management process by which new technology is converted into operating systems. (See page 14)

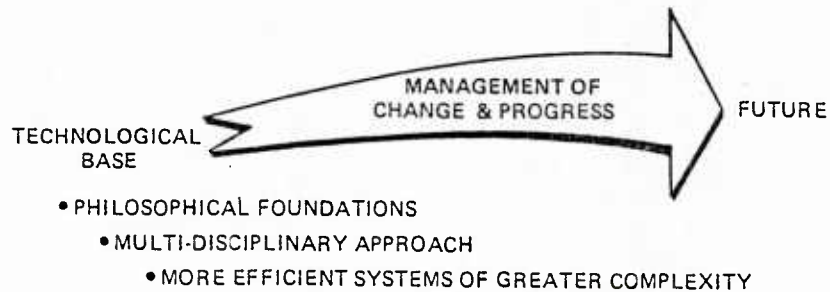
A major paradox within defense is that effectiveness in development programs has been shown to require a high order of responsible autonomy and the opportunity to innovate and even change plans. These complex projects with very demanding performance requirements and cost and schedule constraints also require precise integration and coordination. While parts of a total system (i.e. engine, airframe, armaments and their sub-assemblies) are designed and fabricated at distant places by separate industrial firms, they must interface perfectly not only in form, fit and function but within schedule & budgetary constraints. (See page 14)

Even planning is a rather different function in developmental systems where risk and un-

MANAGING RISKS AND UNCERTAINTY LOOKING TO THE FUTURE



PLANNING UNDER RISK & UNCERTAINTY



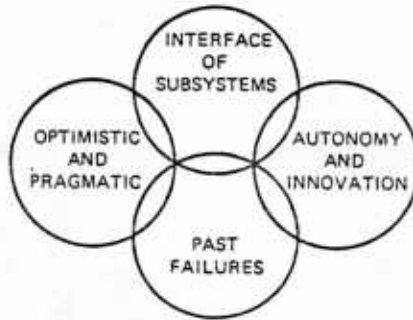
ISSUES

PM's TASK IS TO MANAGE RISK AND UNCERTAINTY:

- AFFORDABILITY
- MANPOWER
- THREAT
- TECHNOLOGY
- MULTI-NATIONAL



TECHNOLOGICAL CHALLENGES

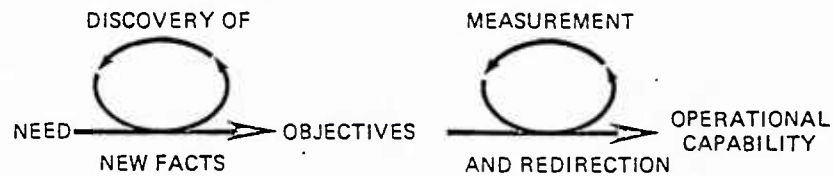


PLANNING

TRADITIONAL MANAGEMENT



MANAGEMENT UNDER RISK AND UNCERTAINTY (ITERATIVE)



certainty predominate. Traditionally, managers are taught to identify their ultimate need, to set objectives that will help them obtain the required operational capability, and then develop their acquisition strategy and plans. Unfortunately, this logical sequence is inverted in the real world.

Planning for uncertainty and risk assessment turns out to be a dynamic, iterative process.

In traditional management theory, managers are expected to collect and weigh facts and probabilities, make an optimal decision and see that it is carried out. In developmental projects, a clear sequence is not possible because of the extended duration, the many technical unknowns, the continual discovery of new "facts" and the changing constraints and pressures. The process must be designed that allows recommitment, reassessment and redirection without allowing never-ending improvement and excuses for missing budgets and schedules.

In the area of contracting, traditional contract monitoring is perceived as a legal and accounting problem. The whole concept of responsibility changes, however, when the designs keep evolving, risks are undefined and substantial uncertainty is involved. There becomes no clear-cut division between the planners, the doers and the monitors. The customer, DOD, must be able to speak and understand the language of the contractor's experts, to know as much about the problems and risk as the contractors, to check and supplement the work of the government laboratories and contractors, and to step in when required with the necessary specialists to help solve the problem.

Modern development programs have life histories filled with unanticipated crises, unpredicted barriers, and impediments. What appears to be a reasonable design, given prior knowledge and experience, turns out to have a neglected small, crucial factor, and some subpart--say a new valve, fails to work properly. This in turn means that the subsystem may have to be redesigned to "work around" the problem, which in turn affects other subsystems and ultimately the system. A small technical problem thus pyramids within an interdependent, integrated system.

Obsolescence is a continuing threat. The mission requirements accepted when the concept was chosen may be obsolete by the time the program is nearing the production decision. Newer technologies or new data may make the chosen alternative wasteful, or unable to meet the new threat.

Recognizing this obsolescence factor, participants in a project may develop changes to in-

corporate the most up-to-date technology. There is a tendency for schedule slippages to be compounded as professionals in the program seek to improve the design--this further delays the project, increasing costs, & complicating development process.

By definition, complex programs are mission-oriented and require an interdisciplinary effort. Most professionals, however, have been trained and are experienced in the context of specialization, and they expect to pursue careers in that specialty. The welding and interweaving of professionals, and the professional knowledge required for risk assessment and planning for uncertainty, challenges the professional and manager alike. They must find ways to redirect the areas of interest into risk and uncertainty fields, while providing for maintenance of the ties to the professional's field of expertise.

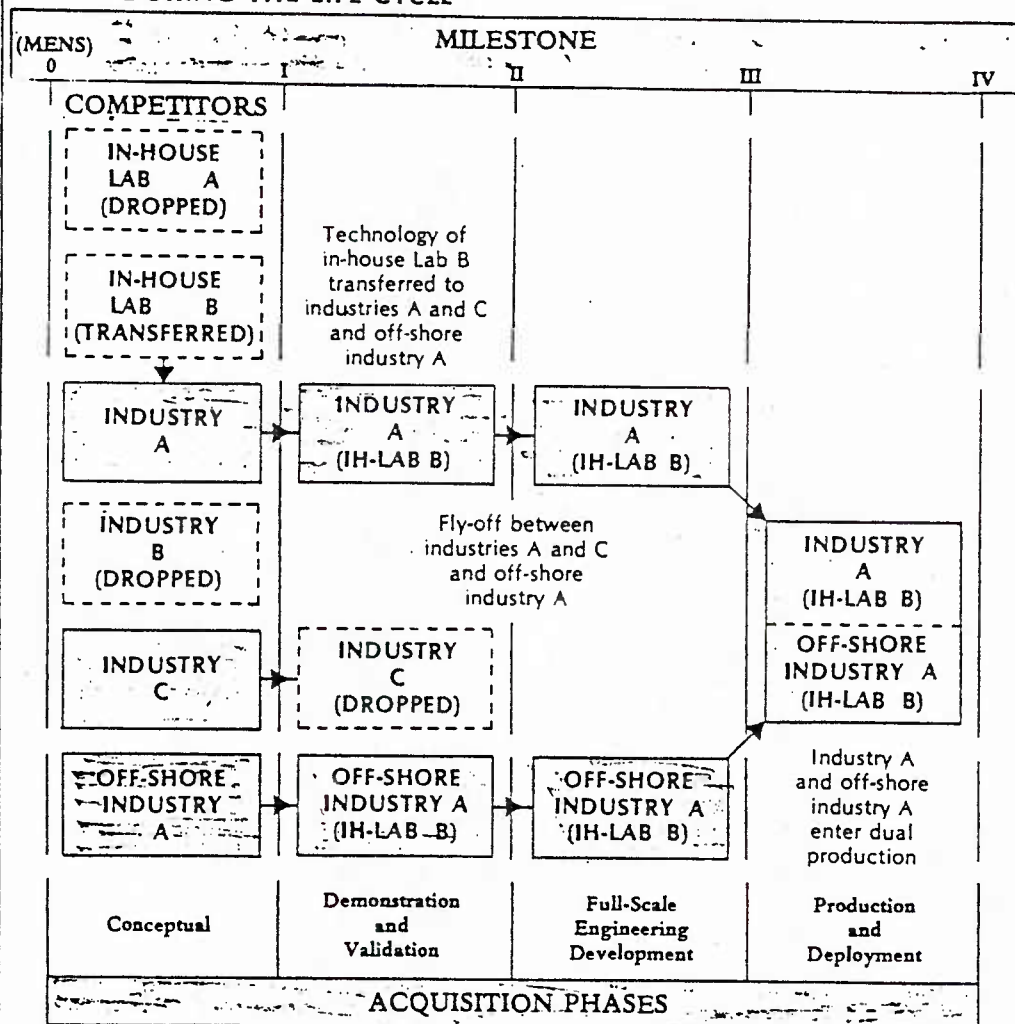
The DOD Acquisition Process is in actuality a phased project planning system. During the early stages, simultaneous parallel efforts are encouraged. This technique is adopted to reduce the risk from uncertain technology development and to determine objectives and their feasibility, as well as the potential cost, scheduling, performance & management dimensions of the program. If these exploratory studies are not made, a contractor may be engaged to start costly development work on a project where the risks remain unknowns. Expenses mount up rapidly in such cases. For these reasons, the management system adopted provides for a series of go-no go decision points. Management can halt the program at three points during the process even after approving the MENS. In reality, there are no automatic route markers, each program actually uses a "tailored" approach. (See page 16)

Developing parallel efforts, as described in OMB Circular A-109, stems from the need to explore competing concepts and approaches to optimize life-cycle cost, schedule & performance, taking into account known risks and the possibilities for uncertainties. Competition is induced to take advantage of the technical and cost motivation to the contractors created in this environment, and to prevent an advocacy for a technology which may yet be proven. Followed literally, these parallel efforts would be developed at each phase of the acquisition cycle, to the extent that substantial risks and uncertainty exist, and that it is economically feasible.

Now let us turn to the specific areas of risk and uncertainty analysis. DSMC has developed a taxonomy for the area of operations research /systems analysis. Under decision analysis, we find the area of risk analysis which also includes uncertainty analysis. Our definition for decision analysis, decision risk

* Insert V 7, V 8 here

Figure 2 METHODS TO MAINTAIN COMPETITION DURING THE LIFE CYCLE



analysis, sensitivity analysis, and uncertainty analysis are devined as shown here. These analyses techniques are employed to discriminate between parameters or a range of parameters which would cause an alternate strategy to be selected. The purpose for the use of these techniques is to improve the decision-maker's decision by providing a structure for the analysis and quantifying the differences between parameters, to provide insight and understanding into the decision, and hopefully to involve the decisionmaker in the analysis, even if only on a "what if" basis.

(see page 18)

Risk has two sides, the probability of failure and the consequence of failure. Uncertainty also has similar considerations in determining the probabilities associated with potential outcomes and also the consequence of these outcomes. The point I want to make is that although not all management understands the various risk and uncertainty techniques, the consequences stated in terms of performance degradation, cost increases and schedule slip-pages are well understood. A method utilized at DSMC to evaluate risk, uncertainty and their consequences is a powerful technique using utility theory. Decision trees are used to map out all possible relevant decisions and events to define program alternatives.

(See page 19)

In any analyses, as the risks and uncertainties are identified, alternate approaches must be developed and the cost, schedule and performance impacts considered. Contingencies must then be built into the acquisition strategy to cover the anticipated cost escalation, correct possible performance shortcomings, and provide adequate time in the schedule to recover. (See page 19)

The Reagan transition team has emphasized the shortcoming of the weapons research and development cycle. The Reagan initiatives can be expected to have a tremendous impact on risk and uncertainty analyses. The results are likely to be:

- Less time and raw data available with which to analyze risk and uncertainty.
- Greater use of concurrency and acceptance of increased risks and uncertainty at the DSARC decision points.
- Shortened formal testing periods and reduced test data.
- Greater emphasis on off-the-shelf technology and commercial products adapted for military use as well as Pre-Planned Product Improvements (P³I) after fielding systems.
- Increased use of "tailored" acquisition approaches to include a maturation phase as opposed to a Full-Scale Engineering Development (FSED) phase.
- Greater dependence on the PMO's ability to perform data analysis and their own inde-

pendent risk and uncertainty analysis as well as increased responsibility and authority to deal with the anticipated problems.

The above impacts will require a greater emphasis in the program office to identify schedule risks and uncertainty earlier in the R&D cycle in order to institute specific actions to deal with the time-sensitive factors. Early data analysis will, of necessity, be investigative and actively incisive with the emphasis on the discovery of the unexpected.

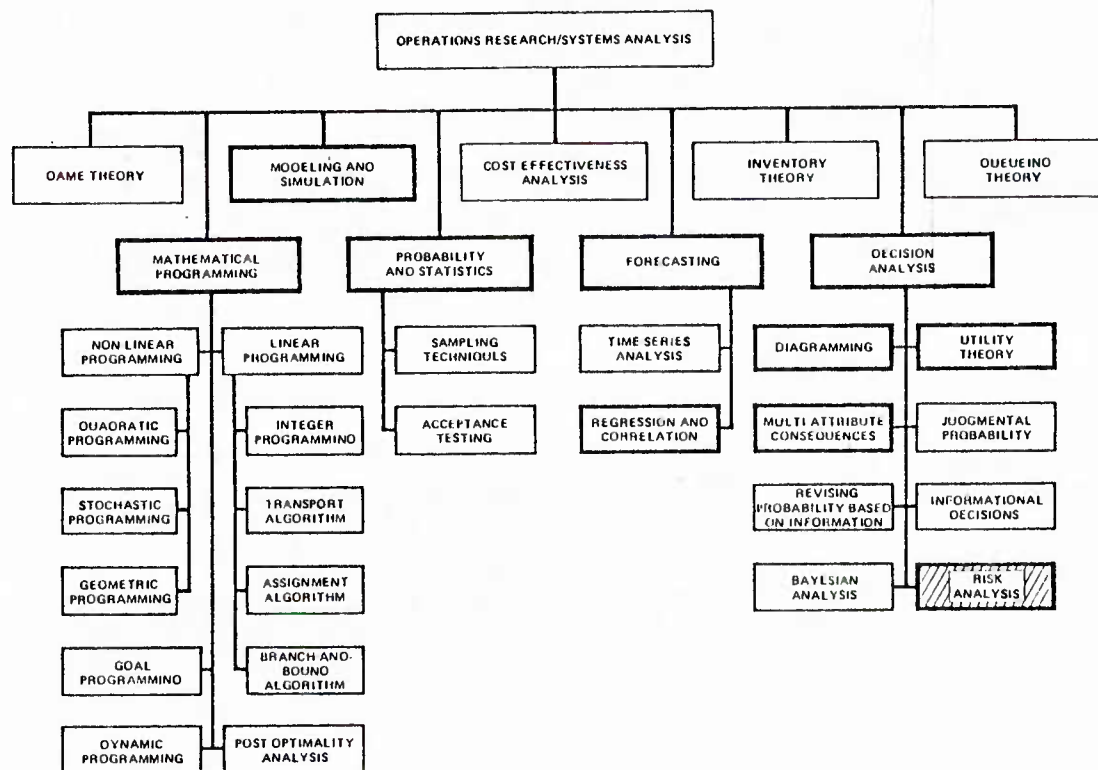
Looking at the Acquisition Life Cycle, the program initiation decision or approval of the MENS validates that a need exists and approval is given to identify and explore alternate solutions to the mission need. During the ensuing conceptual phase, the PM is responsible for developing his acquisition strategy to provide the basis for selection of one or more systems for further development to satisfy the mission need. This acquisition strategy integrates technical, business, and management program elements. The major risk and uncertainty analyses areas include the following PM responsibilities:

- Continuing analysis of assigned mission responsibilities in mission areas.
 - Managing exploration, identifying and developing of alternative system concepts, to meet mission element tasks.
 - assessing program risk areas and conducting trade-offs in performance, cost and schedule, to achieve best balance for alternatives.
 - Considering alternative maintenance concepts to identify impact on system design and resources.
 - Preparing Technology Assessment Annex (TAA) to identify areas of technology risk remaining in the program.
 - Including productibility considerations in the evaluation of alternative design concepts to determine production risks, and the actions necessary to eliminate those risks.
 - Developing program management constraints for selected program factors of each alternative.
 - Developing resource projections, in terms of program objectives and constraints.
- (See page 20)

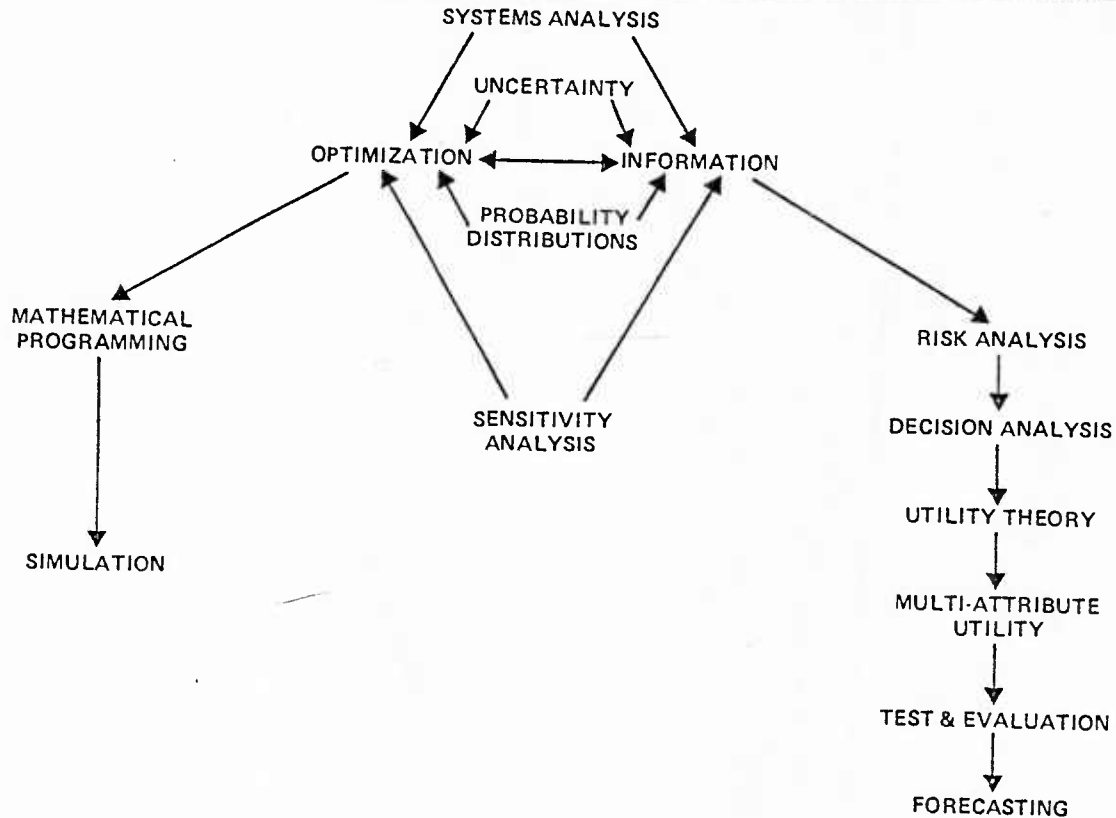
Because of the lack of hard data and uncertainty in the technical approaches, this phase is the most unstructured, from a risk & uncertainty analysis standpoint. Very few models have been developed that handle these analyses well. Risk and uncertainty analyses at this point, however, are also the most important because 80% of the Life Cycle Costs are sunk in concrete in this phase. After developing and testing "breadboard," or experimental prototypes to prove out the technology to reduce the



DSMC TAXONOMY OF DEFENSE SYSTEM ACQUISITION MANAGEMENT



RELATIONSHIPS

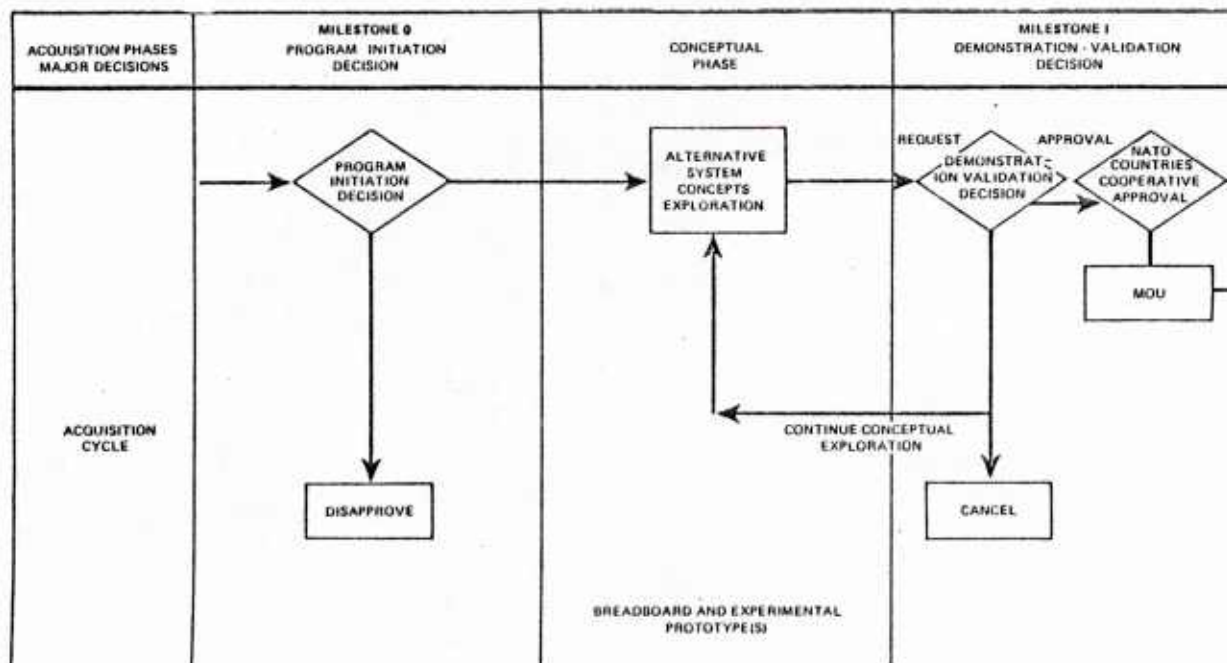


RISK AND UNCERTAINTY ANALYSIS

- DECISION ANALYSIS:** ELICITS DM'S PREFERENCES (USING UTILITY THEORY) AND INCORPORATES THESE PREFERENCES IN THE SELECTION OF AN ALTERNATIVE.
- DECISION RISK ANALYSIS:** A DISCIPLINE OF SYSTEMS ANALYSIS, WHICH IN A STRUCTURED MANNER, PROVIDES A MEANINGFUL MEASURE OF THE RISKS ASSOCIATED WITH VARIOUS ALTERNATIVES.
- RISK ANALYSIS:** AN ATTEMPT TO QUANTIFY UNCERTAINTY.
- SENSITIVITY ANALYSIS:** AN ANALYSIS CONDUCTED TO DETERMINE THE EFFECT ON THE OUTPUT OF A CHANGE OF ONE UNIT INPUT.
- UNCERTAINTY ANALYSIS:** AN ANALYSIS CONDUCTED TO DETERMINE THE LIKELY RANGE OF VALUES OF A PARAMETER.



LIFE CYCLE OF MAJOR SYSTEM ACQUISITIONS INCLUDING RISK CONSIDERATIONS



risk of proceeding, a DSARC I is normally held on major systems where alternate system design concepts are approved for development. The purpose of the next phase, Dem-Val, is to develop the alternative systems designs and establish relationships between need, urgency, and risk and to make practical trade-offs in system capability, cost and schedule. Advanced development prototypes are normally the vehicle for conducting demonstrations of viable alternative systems and critical subsystems in a realistic environment. The acquisition strategy is expanded and refined by the PM. The major risk and uncertainty analyses areas in the Dem-Val phase include the following PM responsibilities:

- Developing DTC and LCC goals.
 - Completing the Demonstration/Validation Testing and Evaluations, as specified in DCP.
 - Continuing mission analyses.
 - Conducting System Requirements Review (SRR) and System Design Reviews (SDR).
 - Preparing TAA identifying areas of technology risk remaining in the program.
- (See page 22)

After developing and testing the AD prototypes, a DSARC II is held to approve the system or systems for FSED, including procurement of long-lead production items and limited production of systems for test and evaluation. The risks of procuring long-lead are evaluated at DSARC II, or a DSARC II is held to weigh the risk factors. The purpose of the last development phase, FSED, is to develop, test, and evaluate the total system of all items necessary for support, to include training. Production prototypes are used for operational test and evaluation. The acquisition strategy is further expanded and refined for production of the weapons system, logistics support and deployment. The major risk and uncertainty analyses areas include the following PM responsibilities:

- Conducting Production Readiness Review.
- Continuing mission analyses.
- Developing funding requirements to support production schedules.
- Determining optimal production schedules and rates.

A DSARC III is held at the end of the FSED phase for a production-deployment decision to ascertain that the mission element task is still valid, determine that the engineering is complete, commit resources to product and deploy the system, and evaluate readiness to produce the system. Various production alternatives to include co-production, leader-follower, & second-sourcing must be evaluated for the DSARC III.

Lessons learned in the acquisition process are that the concept phase is the critical phase for risk and uncertainty analysis; and that an

innovative, tailored approach is required for every program. Although important at every phase and decision point, the analyses at the concept phase establishes the basis for the rest of the program by developing system specifications and technology base. Cost models and estimates, threat models and analyses, new technology and system application, and concept and trade-off studies with configuration definitions are initiated during this phase to be built upon in subsequent phases.

It is important to mention here the four methods that the PM uses to reduce risk and uncertainty, to be used separately or in combination:

- Test and Evaluation.
 - Prototypes and Demonstrations.
 - Studies and analyses.
 - Developing new ideas and concepts.
- (See page 23)

The PM's choice is governed by the stage of the acquisition program, nature of the risk or uncertainty, and the time and money available.

In speaking to your first conference on Managing Uncertainty in Major Acquisition Activities, my predecessor at DSMC, Admiral Freeman, offered some challenges to the participants. There were:

- To set solid baselines and goals for the program, or the product will not meet the program objectives.
 - To estimate financial needs as accurately as possible.
 - To anticipate the environmental catastrophe, and be prepared to deal with it.
- (See page 23)

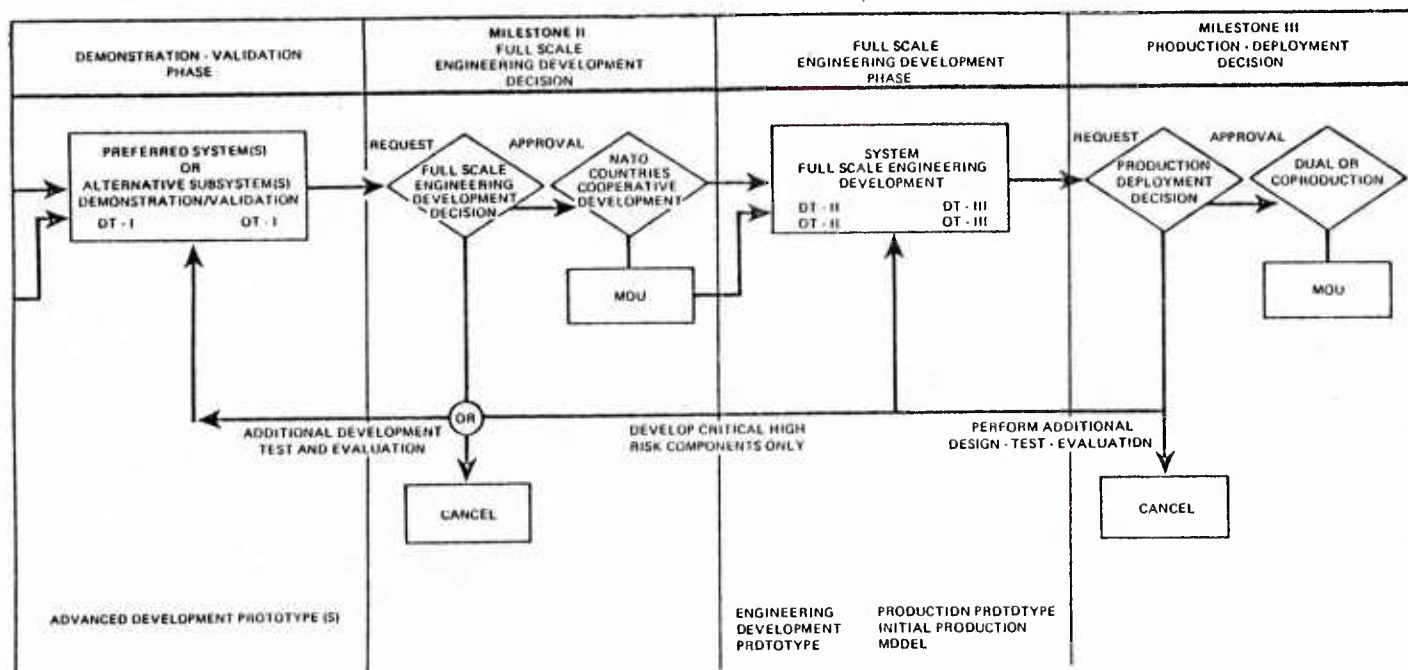
Hope for the best and expect the worst. To these challenges I would like to add some of my own. First, specific techniques are needed to address the front end of the acquisition where data is lacking and suspect. More needs to be done on managing uncertainty based on the data developed for similar systems. In analyzing the critical elements in the acquisition process, DSMC has constructed a matrix that is the combination of the experts' thoughts on which factors are cost drivers. Of significance is the high preponderance of high-cost drivers. These factors in acquisition are then matched against the data bases available to measure them early in the acquisition process. The result is that the high-cost drivers have poor data bases as shown in orange. These high-cost drivers require specific tailored approaches for risk and uncertainty analysis because of the poor and sometimes suspect data base. (See page 23)

In dealing with change, the heart of the matter in both intervention and decision-making is quickness of response, the focusing collective energies toward the solution of a critical problem. The second challenge is not only to look at models and their interaction with the data



LIFE CYCLE OF MAJOR SYSTEM ACQUISITIONS INCLUDING RISK CONSIDERATIONS

(CONTINUED)





METHODS TO REDUCE RISK & UNCERTAINTY

- TEST AND EVALUATION
- PROTOTYPES AND DEMONSTRATIONS
- STUDIES AND ANALYSES
- DEVELOPING NEW IDEAS AND CONCEPTS



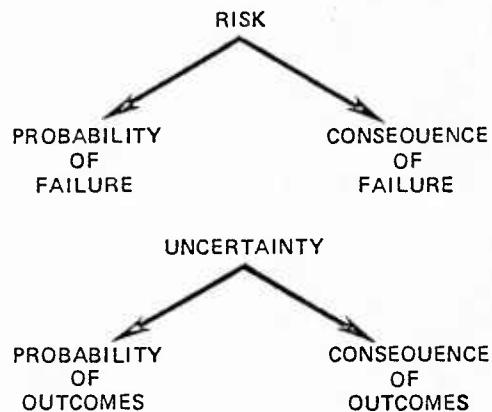
POSSIBLE REAGAN INITIATIVES TO SHORTEN THE R&D CYCLE

RESULTS

- LESS TIME AND DATA
- CONCURRENCY
- ACCEPTANCE OF RISKS & UNCERTAINTY
- TESTING
- OFF-THE-SHELF, ADAPTED COMMERCIAL PRODUCTS AND P³I
- "TAILORED" ACQUISITION APPROACHES
- CREATE PM RESPONSIBILITY AND AUTHORITY
- INVESTIGATIVE DATA ANALYSIS



RISK AND UNCERTAINTY



- WHAT ARE THE OBJECTIVE AND MINIMUM ACCEPTABLE STANDARDS TO BE MEASURED AGAINST? (SCHEDULE, COST, AND PERFORMANCE)

for "out of tolerance" conditions, but to look at trends in the data to anticipate "out of tolerance" conditions in the future. Well-publicized computerized schedule control techniques, such as PERT networks, are often well behind the action. Anticipating trouble requires very close contact. Another penalty for waiting is that in a good many situations corrective action is possible only during a brief "window." CS² only shows cost imbalances after they happen. New applications of existing techniques or new techniques are required to show trends in risk and probabilities of uncertain outcomes. The second challenge is to develop models that track trends in the basic given parameters of the program, including major objectives, basic resources, and some of the basic restraints so that "surprises" based upon changes in the requirements and rules or "discoveries" of changed parameters are identified by the trend lines. These change require program changes all the way down the line including replanning, renegotiation, and reanalysis of many program decision, and the acquisition strategy. (See page 25)

The analysts employed within any program to accomplish the risk and uncertainty assessments are normally also required to accomplish at least some of the meticulous planning and laying out of schedules, costs and performance criteria. There is sometimes a mistaken belief that a program is nothing more than the sum total of a number of these relatively routine, production-like functions. Program managers may soothe their own doubts, or those of their sponsors, by giving the impression that the knowns far outweigh the unknowns. If the true scope of the problems, and the attendant costs were known, as Hirschman argues, the endeavor might never be started.

There is a sharp contrast between the precision of specifications and accounting in today's and tomorrow's high-technology programs and the risk management process associated with their effective pursuit. This risk management is characterized by a highly fluid, iterative and imprecise series of activities that require a high degree of personal interaction between the analyst and the technical experts, engineers and scientists, consultants, service staff, contractor personnel, and other professionals.

My third and last challenge is to improve communications to both the professional and the analyst's program manager. To do this, the analyst must use the language everyone in his program understands: performance, cost & schedule. Analysts, like other professionals caught up in the stringent demands of advanced technology, must not only be willing and able to communicate with other professionals, but they must learn related parts of other fields. Analysts must know a good deal of engineering, contract management, quality assurance, pro-

duction control, logistics, basis for testing, elements of program management, etc. Risk and uncertainty analysis is a complicated process of continuous interaction to keep the program within its constraints of time, money, and performance. It requires skills in differentiation, the evolution of change, and the exploration of various alternatives. It also requires integration, and collaboration among the specialist-designed subsystems. Both integration and differentiation must take place at the same time and take the other into account. Changes in subsystem components must be made in light of the interaction between subsystems.

A lot of work remains in the areas of management of risk assessment and uncertainty forecasting. The tools and techniques, however, cannot take the place of the analyst and manager who is emotionally capable of managing uncertainty in an uncertain environment; who thinks logically and in terms of alternatives, identification of problems and back-up strategies; and lastly, who has the capability risk making decisions with only limited or, sometimes, suspect data.

Thank you.

(See Page 25)

FREEMAN'S CHALLENGES

- SOLID BASELINES AND GOALS
- FINANCIAL NEEDS ACCURATELY ESTIMATED
- ANTICIPATE THE ENVIRONMENT



CRITICAL ELEMENTS IN THE ACQUISITION PROCESS COMPARISON MATRIX

		ACQUISITION ELEMENTS					
COST DRIVERS		HARDWARE	SOFTWARE	TECHNOLOGY (R&D)	MANPOWER	SYSTEM SUPPORT	TESTING
	ECONOMIC LIFE						
	QUANTITY						H/G
	SCHEDULE						
	MAN/MACHINE	H/P	M/H	H/P	H/P	H/G	H/G
	INTERFACE		P				
	MAINTAINABILITY	H/P	H/P	M/H			H/G
				P			
	RELIABILITY	H/P	H/P	H/P		H/G	H/G
	PERFORMANCE	M/H	H/P	H/P	H/P	H/G	H/G
		G					
	SIZE & WEIGHT		H/P	M/H			
				P			
	COMPLEXITY		H/P	H/P	H/P	H/G	H/G

OF 29 HIGH COST DRIVERS, 18 OR 62%
HAVE POOR DATA SOURCES

FIRST CHALLENGE: DEVELOP SPECIFIC TECHNIQUES FOR FEA

SECOND CHALLENGE

DEVELOP MODELS WHICH TRACK CHANGES IN BASIC PROGRAM
PARAMETERS

- "OUT OF TOLERANCE" VS TRENDS
- QUICKNESS OF RESPONSE

FINAL CHALLENGE

COMMUNICATIONS

- COST, SCHEDULE & PERFORMANCE
- LEARN OTHER FIELDS
- CONTINUOUS INTERACTION

METHODS TO EVALUATE, MEASURE & PREDICT COST OVERRUNS

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Hughes Aircraft Co.

INTRODUCTION

Numerous instances have been documented of major acquisitions - both military and civilian - where cost far exceeded the original estimates. With increasing levels of system complexities, limited resources, concurrent development and production, constant changes in scope, continuous advance in technology and urgency in achieving operational status, the probability of cost growth is becoming a critical aspect of the acquisition process. Even where technology is considered current state-of-the-art, programs are not immune to cost growth.

Considerable effort has been expended in attempting to find an answer to why most acquisitions have cost overruns and how to control their occurrence. The research reported here builds on prior work in the field and provides an approach for dealing with the uncertainty involved in the acquisition process. The contributions made by E.B. Cochran to the study of disruption have provided the foundation for much of the material covered in this report.

ACQUISITION UNCERTAINTY

What is now recognized is that variability or uncertainty is an inherent aspect of the acquisition of major programs. The choice is not whether to incorporate uncertainty as an integral part of the acquisition process, but, rather to recognize that "as contracted costs," which are in effect single point estimates can no longer be used as the basis for controlling cost growth.

The objective of this research has been to develop an approach for predicting cost uncertainty, which recognizes that variability cannot be eliminated but rather that there are trade-offs that are available to decision makers. The tradeoffs are predicated on formulating cause and effect models which provide insight needed to improve the acquisition decision process. Thus, inherent in the approach presented here is system dynamics, interdependencies, variability, and uncertainty in the acquisition process. In addition, the processes used to achieve desired objectives are also described. For example, concurrency, learning, change, technological advance, program management, etc., all are part of the acquisition process and contribute to the effects observed.

THE ACQUISITION PROCESS

Any description of the acquisition process is, at best, only a static representation of an ex-

tremely complex set of interdependent activities. For our purpose, we will use two basic diagrams to aid in understanding the process. The first, shown in Figure 1 describes the kinds of uncertainty associated with acquisitions. (see next page)

The matrix shown in figure 1 attempts to develop a basis for understanding causality. Thus, internal control assumes all things are known and controllable with estimates based on past data, procedures, designs, suppliers, etc. The other three categories, however, represent the reality in major acquisition, even though management does not have complete control or ability to predict outcomes. It is this realm of uncertainty that has significant impact on cost and is the principal emphasis of this report. The categories shown in Figure 1 correspond to ones developed by the USAF Academy Risk Analysis Study Team (129). These are shown on the next page.

The description of the USAF categories is as follows:

Internal Program Uncertainty: Deals with the way in which the program is organized, planned and managed. Uncertainty of the initial estimate and its impact on program management. Uncertainty in the acquisition strategy and outcome. Uncertainty in resources needed, flexibility, or lack of contingency plans. Competing demands, including conflict between reliability, vulnerability and maintainability with performance and operating costs.

Technical Uncertainty: Covers the feasibility of developing the system at all, including the degree of technical difficulty. Generally starts with an optimistic estimate of the state-of-the-art and often leads to a slippery technical baseline.

Process Uncertainty: Deals with the sensitivity to changes in the external environment such as changes in priorities or policies, the President's budget, congressional political considerations, etc. Unavailability of funding/resources when needed. Uncertainty in criteria used for changes, control, surveillance, DSARC decisions, etc. Effects of inflation and government regulation.

Target Uncertainty: Covers the uncertainty in meeting performance, cost or schedule goals and determination of needs. Uncertainty in translating abstract needs into concrete specifications. Problems of early estimates which are seldom revised. (shown on page 29)

A comparison of the categories shows that there is considerable similarity between the two.

The second approach to understanding problems

LEVEL OF UNCERTAINTY INVOLVED IN ACQUISITION	UNPREDICTABLE	<u>TECHNOLOGICAL UNCERTAINTY</u> ADVANCED TECHNOLOGY, INADEQUATE TASK DEFINITION, CONCURRENCY OF DESIGN AND PRODUCTION, DESIGN CHANGES	<u>ENVIRONMENTAL UNCERTAINTY</u> UNPREDICTABLE EVENTS, FAILURES, DISRUPTIONS, FORCE MAJEURE, REGULATIONS
	PREDICTABLE	<u>INTERNAL CONTROL</u> PROJECT CONTROLS, RESOURCE ALLOCATION, ESTIMATING, BUDGETING	<u>CUSTOMER UNCERTAINTY</u> CONTRACTURAL REQUIREMENTS, SCOPE CHANGES, TIME COMPRESSION, STRETCH-OUT, CONSTRAINTS, INADEQUATE FUNDING
		CONTROLLABLE	UNCONTROLLABLE

DECISION-MAKER'S
ABILITY TO CONTROL ACTIVITIES

FIGURE 1 ACQUISITION UNCERTAINTY

Uncertainty Categories
in Figure 1

USAF Academy
Risk Analysis Study

- | | |
|------------------------------|--------------------------------|
| 1. Internal Control | - Internal Program Uncertainty |
| 2. Technological Uncertainty | - Technical Uncertainty |
| 3. Customer Uncertainty | - Process Uncertainty |
| 4. Environmental Uncertainty | - Target Uncertainty |

The description of the USAF categories is as follows:

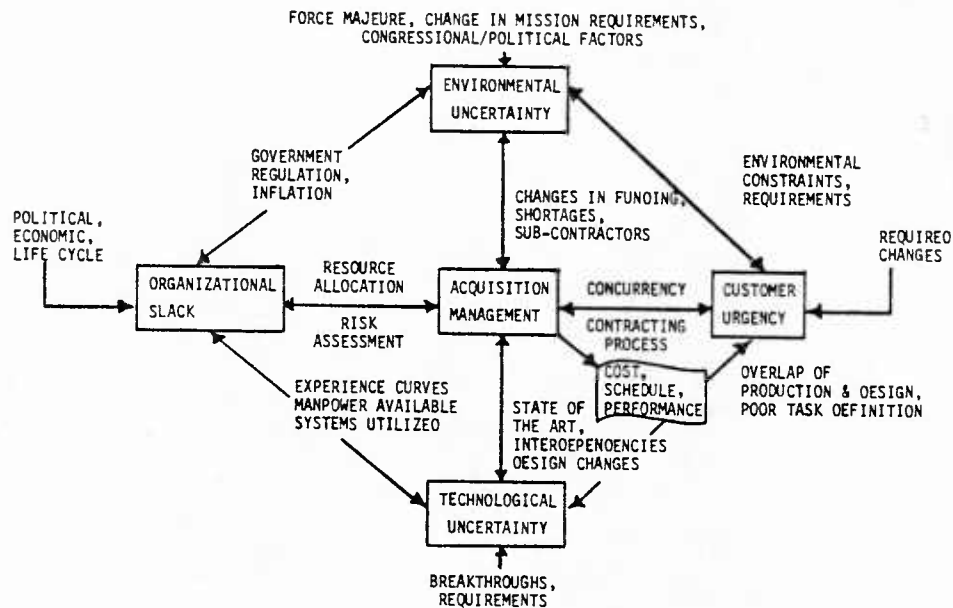


FIGURE 2 - FACTORS AFFECTING ACQUISITION MANAGEMENT

in the acquisition process and the inherent cost overruns is represented by the diagram shown in Figure 2. Illustrated are the factors, the interdependencies, and the processes involved in acquisition management. As described in the USAF report, the acquisition process is a tremendously complex, turbulent network of activities for which a static model is unsatisfactory.

Although Figure 2 does not reflect the dynamics and interactions that occur in an on-going organization, it illustrates a number of key concepts that will be developed in the report. The linkages between the four basic uncertainty variables and acquisition management help to define the processes, activities or variables that contribute to the uncertainty of acquisition management. The four basic uncertainty variables considered are:

1. Organizational Slack: A measure of the organization's ability to perform the task requirements.
2. Customer Urgency: The time compression, concurrency, or degree of overlap between phase of development, and change in scope.
3. Technological Uncertainty: A measure of the state-of-the-art and the degree of interdependency among system components.
4. Environmental Uncertainty: The factors that cause disruption, delays, shortages, failures, etc. that are not under the control of management in the acquisition process.

The exterior linkages identify secondary effects, and relate the four uncertainty variables to one another. Considering the whole diagram, one can see that the variables and linkages define a network of interdependencies which ultimately contribute to the uncertainty and the consequent problems in the acquisition process.

DEFINING THE PROBLEM OF COST OVERRUNS

In its report to congress, the Government Accounting Office (GAO) (73) claims that major weapons' cost growth since World War II far exceeds the rate of inflation and that various efforts to restrain costs seem unlikely to achieve really substantial cost reductions. This statement by the GAO goes counter to the general belief that has been held which contends that closer scrutiny of the acquisition process, such as tighter control and stricter acquisition policies on the part of the government, will significantly reduce the levels of cost growth. However, control alone will not solve the problem since the cost of additional controls can be considered part of a cost growth - adding to the problem rather than the solution. Figure 3a illustrates the effects of various degrees of control on total cost. Also shown is the net benefit of control (value

less cost) as a function of degree of control. This curve leads to an optimal value from which a change in control (increase or decrease) decreases the net benefit. (See page 29)

Figure 3b illustrates a similar approach using degree of planning as a function of cost of planning and cost of errors (lack of complete planning. In the case of figure 3b, the total cost curve (cost of planning plus the cost of errors) will have some optimal value from which a change in degree of planning will increase the total cost.

An alternative to the use of control as the sole means for reducing cost is an approach based on predicting the likelihood of disruptions occurring during performance of a contract and thereby permit cost reductions. Thus, based on a relationship between cost growth and likelihood of disruption, the control of cost can be improved. Knowing when and where disruptions might occur (with a defined degree of probability), the acquisition manager can develop a basis to reduce the likelihood of disruption and thereby lower the level of cost growth. In addition, other approaches can be applied in advance of a probably disruption which will also lower the impact on cost growth due to the effects of disruptions.

"Disrupt" means to cause disorder or turmoil. In our context, the term disruption refers to the disorder and turmoil created in a program plan and in related production procedures, which normally are used to minimize costs. Hence, "disruption cost" is the difference between the actual cost for a program on the one hand, and the cost "reasonably required" to perform the task in the configuration finally delivered, on the other. The "should-cost-as-built" estimate includes the estimated cost of all changes incorporated in the final deliverable product. It does not include penalties caused by the late incorporation of changes (retrofit, rework, lost learning, etc.). See Figure 4. (Shown on Page 29)

The existence of a sizable overrun always raises the question as to the adequacy of the estimate used as the basis to determine the overrun. The overrun may reflect a poor assessment or errors in the estimating process, both leading to a low estimate; such a discrepancy itself could well be disruptive. We shall use an "objective" definition of disruption, with the should-cost to be based on a realistic estimate for each organization. This suggests using estimating methods, which deal with fundamental characteristics of the product such as parametric estimating.

The Department of Defense (DoD) and defense contractors have been under increasing pressures to reduce the levels of cost growth in the weapon systems acquisition process. According to The Armed Forces Journal (March, 1978) estimates

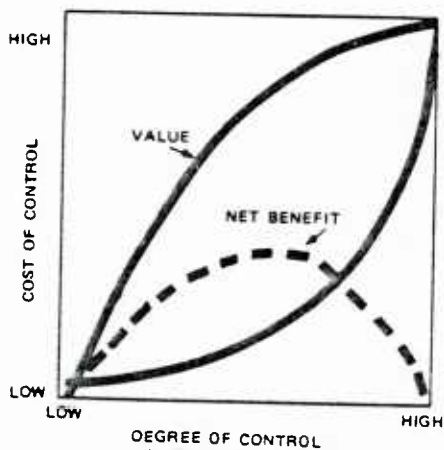
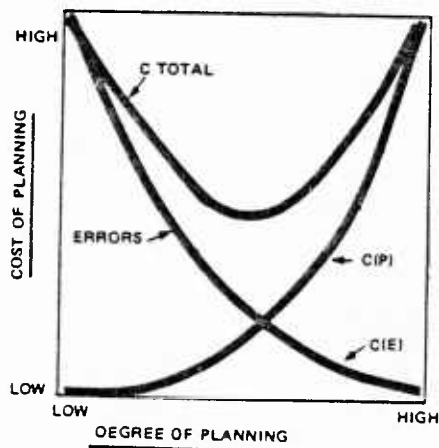


FIGURE 3
EFFECTS OF LEVELS OF CONTROL ON
NET BENEFIT AND TOTAL COST

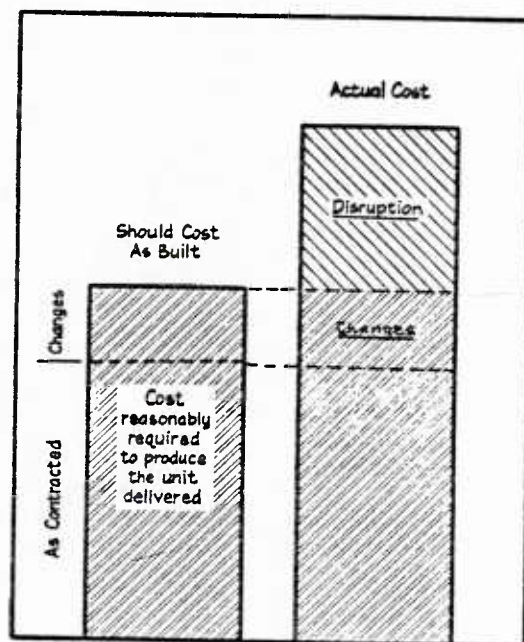


FIGURE 4 COST DUE TO DISRUPTION

Weapon System	Original Estimate	Latest Estimate
1. Dragon Antitank Missile	\$ 1,600	\$ 7,400
2. Condor Antiship Missile	132,000	736,000
3. SRAM Air-to-Ground Missile	338,000	771,000
4. Minuteman III Missile	6,140,000	9,130,000
5. Main Battle Tank	341,000	745,000
6. Heavy Tank (in design)	904,000	1,023,000
7. Troop Helicopter	2,050,000	2,400,000
8. F-14 Fighter	12,600,000	17,900,000
9. F-15 Fighter	9,800,000	12,300,000
10. F-111 Bomber	4,000,000	14,900,000
11. B-1 Bomber	45,600,000	61,500,000
12. Nuclear Attack Submarine	179,000,000	194,000,000
13. Nuclear Carrier	679,000,000	782,000,000
14. Helicopter Carrier	153,000,000	229,000,000
15. Destroyer	86,000,000	103,000,000

TABLE 2 WEAPON SYSTEMS COST ESTIMATE COMPARISONS

based on 1977 Government Accounting Office GAO data indicate the DoD's weapon cost growth averages less than half of other major federal acquisitions. In its Report to Congress, on Financial Status of Major Federal Acquisitions, January 1979 (72), the GAO indicates that major federal acquisitions of all agencies are estimated to cost \$531.2 billion at completion. This amount represents an increase of \$207.4 billion or 64% over initial estimates or baseline estimates when initial estimates were not available.

Cost growth is not limited to the acquisition of weapon systems exclusively. Literature is replete with examples of cost growth on various projects. Several examples are shown below (94):

<u>Project</u>	<u>Cost Growth</u>
Roman Aqueduct	100%
Suez Canal	200%
Panama Canal	70%
Indian Head Atomic Power Plant	250%
Great Eastern Ship	138%
Convair B-58	300%
Lockheed C-5A	86%
Rolls-Royce RB.211 Engine	175%

TABLE 1 EXAMPLES OF COST GROWTH

When programs such as the Apollo Space Program with a 200% overrun, and the Space Shuttle Program are added to this list, the types and levels of technologies spanned becomes diverse. It is apparent from the examples cited above that both military and non-military projects suffer from cost growth. Furthermore, that cost growth is not limited to programs that have advanced state-of-the-art technology.

U.S. News and World Report its quotes a GAO report disclosing the cost of 55 major weapons at 26.3 billion dollar above the pentagon estimates and still rising. Of \$7 billion increase in the last half of 1973, it was estimated that inflation accounted for \$2.5 billion, engineering changes for \$1.7 billion, schedule changes for \$1.4 billion and other causes such as research, development and production difficulties accounted for the remaining \$1.4 billion. Table 2 below illustrates the per unit overruns in a large variety of weapon systems as reported in U.S. News and World Report (June 1974): (See previous page)

Major General Dewey Lowe, at the 1979 Conference on Managing Uncertainty in the Acquisition of Major Programs reviewed an Air Force Study of seven major aircraft systems, including the B1, F15, F16, A10, E3A, E4 and EF111A. The study revealed an improvement in the ability to control program cost growth. In the 1950's major system cost growth exceeded 200%, while systems suffered from high risk, poor definition and low visibility. In the 60's, risk was

moderate, definition was better, total package procurement and concurrency was used, and cost growth was between 100 and 200%. The 70's have witnessed growth of less than 100% with the application of prototypes, change controls and Defense System Acquisition Review Council. When adjusted for inflation, the approximately 90% growth rate was a 30% rate in base-year dollars. General Lowe estimates that as much as 70-80% of the cost overrun is caused by inflation.

One of the classic cases of cost overrun, the F111, is described in the paper by Roesch and Sage (151). They report that unprecedented cost growth of \$3 million per unit in 1966 to almost \$15 million per unit in 1970 was caused by ineffective program management on the government's part, poor DoD/contractor relationships, over-centralization of acquisition management in O.S.D. and poorly defined operational requirements. Here is an illustration of the kinds of problems that can cause growth in costs.

As a counter-example to purely military projects, Cochran examined a number of non-military overruns as shown in Table 3. Based on an analysis of the annual cost growth, which ranged from 4 - 18%, inflation accounted for the major portion of the overrun in 6 out of 14 programs. Overall cost overruns ranged from 124.3% to 387%. The GAO, in its January 1979 report (72), indicated that inflation accounts for approximately 50% of the cost growth in military projects. Thus, both military and non-military programs suffer from the effects of inflation. This is becoming especially acute in the era of double digit inflation.(next page) (See page 31)

Notes to TABLE 3

- (1) Except for the Alaska Pipeline, data is derived from Table 2 of report Alaska Natural Gas Transportation System, U.S. Dept. of Interior, July 1, 1977.
- (2) Includes changes in scope, effects of design & completion delays on time-related costs of force majeure events.
- (3) Original estimate of \$900 million was clearly just a crude guess. The 1972 estimate of \$2.9 billion was based on more careful study, and is compared with a 1977 Alyeska estimate of \$4.6 billion uninflated cost to obtain the scope and inflation breakdown.

Another example of cost overruns as related to energy processing plants is shown in Figure 5 (41). The overruns range from less than 200% to almost 700% for the actual cost compared with the initial estimates.(See page 32)

FACTORS CAUSING COST OVERRUNS

There have been many studies attempting to identify the causal factors involved in cost overrun. In this section, we will summarize findings from a number of sources and use these

	Date of	Last Estimate		Annual Growth(%) (2)			
	1st Estimate	\$millions	ratio	years	Total	Basic	Inflation
<u>Metro. Transit Systems :</u>							
BART	1962	1,640	1,647	14	3.63	0.26	3.37
Washington	1968	5,020	2,008	8	9.11	1.77	7.34
Atlanta	1971	2,100	1,591	5	9.73	2.07	7.66
						1.37	
<u>Municipal Programs :</u>							
Rayburn Office Building	1956	178.0	3.870	8	18.43	15.73	2.70
Dulles Airport	1959	108.3	1.641	3	17.95	14.10	3.85
New Orleans Superdome	1967	98.0	1.531	10	4.35	2.99	1.36
						10.94	
<u>Other Public Projects :</u>							
Arkansas Frypan	1962	54.3	1.932	10.5	6.45	2.15	4.30
Chesapeake Bay Bridge	1968	120.1	1.243	5	4.45	2.00	2.45
						2.08	
<u>Nuclear Power :</u>							
Cooper - Nebraska Rancho	1966	395.3	2.148	8	10.03	7.23	2.80
Seco-Calif. TVA-Clinch River	1967	347.0	2.435	7	13.56	3.11	10.45
Allied Chem-Soc. Car.	1970	195.0	2.790	6	18.65	15.58	3.07
Davis-Besse, Toledo, Oh.	1971	250.0	2.551	5	20.60	11.99	8.61
	1971	466.0	1.524	4	11.11	8.80	2.31
						9.34	
Alaska Oil Pipeline ⁽³⁾	1972	7,700	2.265	5	17.76	9.67	8.09
Total					11.843	6.960	4.883

TABLE 3 - COMPARISON OF RECENT NON-MILITARY OVERRUNS ⁽¹⁾

results, and the cost trade-off curves in the next section as the basis for development of a model to predict likelihood of disruption and the concomitant cost growth.

The GAO and the RAND Corporation have done by far the most extensive and continuing analysis of cost growth. In its report to Congress on Impediments to Reducing the Cost of Weapon Systems, the GAO identifies the military's desire for maximum performance, high technology weapon systems along with instability of congressional funding and constraints as the major contributors to cost growth (73). They also identify low rates of production, absence of price competition, lack of motivation for contractors to reduce cost, impact of government controls, reduced R&D expenditures and lowered productivity as additional elements contributing to cost growth. Their conclusions on how to reduce cost was to provide program stability that helps recover investments, put more emphasis on invested capital than production costs and provide greater flexibility in meeting changing priorities and needs.

In its June 1980 report to the Congress (76), the GAO identified the issues that have had a direct impact on weapon system's mission effectiveness. The majority of the issues were concerned with operational or performance limitations, survivability or vulnerability, availability, meeting requirements and reliability. As concerns program acquisition the major issues dealt with system affordability, requirements of data reporting, concurrency of production and development, inadequate testing, cost-effectiveness assumptions, lack of qualified personnel, indecision on system urgency and technical risks. A summary chart of their findings is shown in Figure 6. (See page 32)

Since the late 1950's, the RAND Corporation has conducted studies to describe the inherent uncertainty of the product development process. From early 1960 to date it has issued a number of increasingly specific reports to show that design and production concurrency accompanies large overruns, which were avoided when development work substantially preceded production. Quantitative measures of state-of-the-art demonstrated impressive correlation between degree and the proportion of cost overrun for cases of design and production concurrency. As a result, RAND researchers recommend reducing uncertainty in advanced technology programs by return to "incremental" product development - a procedure which has long been used by manufacturers of commercial products with stable design (162).

The RAND studies also show that cost and schedule problems are larger as the degree of state-of-the-art advance increases. Sophisticated management planning and control programs and incentive contracting have small effect, and improvement through better cost estimating and

monitoring of cost growth does not seem substantial. Furthermore, concurrency may not even reduce development time significantly. In short, the main problem lies with the uncertainty that affects development and production costs in the presence of urgent time schedules.

The importance of uncertainty as a cause of overruns has been documented by the RAND studies, which after over twenty years of studying complex development programs in the U.S. and abroad concluded that (146):

"High system cost growth appears to arise primarily from efforts to subdue difficult technology on highly compressed schedules..(and the) acceptance of optimistic assumptions about the long-term predictability of technology and the cost of coping with it."

In describing system acquisition experience, Perry, et.al (53)., point out initial estimates tend to be overly optimistic and do not consider or understate technological difficulties actually encountered in program development. As a consequence, these difficulties which lead to increases in total program costs are seldom accounted for early in a program. They found that, in nearly all cases, renegotiated contracts were much closer to actual performance requirements and that this was reflected in adjusted costs. Thus, the earlier a prediction of cost is made, the greater the expected uncertainty of actual cost. In general, in the early conceptualization stage, the required technological advances and eventual system configuration are poorly known. Their conclusions concerning cost growth and performance faults were that they were principally due to changes in program scope and they were outside of the contractor's control. The factors outside of the contractor's control generally accounted for the difference between predicted cost of the original program and the final cost of the program as actually delivered.

In its attempt to control cost, the DoD instituted the Design to Cost Concept (DTC) for major weapon system acquisition. Although this approach is an attempt to keep cost within limits that can be achieved by a specified design, it is recognized that frequent changes can undermine confidence in the process. Thus, flexibility is needed because of the difficulty in estimating major system costs with precision. This implies that performance parameters must be variable if cost remains relatively fixed.

The RAND report by Large (29) on bias in cost estimates illustrates another dimension of the problem of cost overruns. In an analysis of the comparison of initial bid with final cost, he found that where the technological advance required is not fully understood the final cost can be off by a factor of two. He cites statements made by contractors which clearly in-

dicade that initial estimates are designed to win the competition. This approach to winning the contract is also called "buying-in."

Martin, et al, (135) in their paper on the relationship between cost and cost estimation indicate that a cost estimate is at best a reasoned guess about a future outcome. The estimate requires judgment and therefore is subjective in nature. Furthermore, because cost estimates are probabilistic in nature and are valid only as long as the assumptions on which they were based remain the same, there is need to revise estimates in consideration of the uncertainty which exists. They point out that the level of uncertainty is very high in the early phases of an acquisition, in part due to the vagueness of system specifications. The uncertainty is reduced as information is obtained from testing and evaluation. The conclusion that is drawn is that mistakes are made using the wrong approach for the given phase of the acquisition cycle. The appropriate cost estimating basis for each phase is shown in Figure 7 below. (See next page, Fig. 7 & Table 5)

The conclusions drawn by Martin, et al, are supported by studies which show that initial estimates seldom reflect the final cost. Davis (12) supports this finding in his analysis of uncertainty associated with cost estimating. He contends that lack of information contributes to the uncertainty of cost estimates. He also maintains that diffusion of authority and responsibility for cost estimating throughout the acquisition cycle complicates the process. Furthermore, short-fuse requirements impose severe time constraints and also contribute to estimating errors. He concludes that there is a need for greater flexibility in the acquisition of major systems in order to cope with program uncertainties. Single point estimates do not recognize the basic uncertainty involved in cost and cost range would provide greater flexibility. Basically, he argues that cost overruns will be a way of life unless consideration is given to the impact of program uncertainty on estimating. To overcome this problem the Army has applied a cost estimating program called TRACE (Total Risk Assessing of Cost Estimates). Although there is no provision for inflation, TRACE does consider the impact of technical design changes, rescheduling, additional testing and additional hardware requirements (91). This approach specifically recognizes that uncertainty is an inherent part of the acquisition process and that unless the causal aspects of estimating uncertainty are taken into account cost overruns will continue unabated.

The problem of cost estimating is poignantly described in the paper on a theory of cost growth (81). It describes cost as a "dependent" variable that reflects action taken in response to contractual requirements. Thus, if cost becomes uncoupled from requirements, then

the numbers are meaningless. Furthermore, point estimates speed up the uncoupling. A number of reasons why costs become uncoupled from reality include:

1. Budgets do not anticipate technical requirements, but instead react in a lagged manner to changes in requirements.
2. There is a serious gap between those who are knowledgeable about costs and those having technical knowledge.
3. Annual budgetary considerations tend to dominate the incremented acquisition process.
4. The sheer magnitude of numbers of people involved in government functional areas proliferates the problem and reduces flexibility.
5. Differential effects of inflation on given program components.
6. Competition causes cost estimates to decline in the pre-contract award period.
7. Monopsony, which is a market condition where the customer controls demand and tries to minimize cost.

The recommendation, then, is to change these practices so that the acquisition process more nearly follows normal competitive practice which would avoid cost growth based on unrealistic initial bids and unreasonable budgeting and estimating practices during the acquisition cycle.

In a study conducted at USC, six major programs were analyzed to determine the primary causes for cost growth, schedule slippage and performance degradation. Twenty-six factors were identified as specifically contributing to cost overruns. These were placed into the four basic categories described in the beginning of the paper. The relevance of each factor to the six programs is shown in Table 5. The result was that every one of the programs had cost overruns (see Table 4) and all encountered schedule slippage with BART and the F111 having performance degradation. Furthermore, customer urgency had the most pervasive impact on all programs with technological uncertainty second, organizational slack third, and environmental uncertainty having the smallest impact. The specific events or factors contributing to the effects shown in Table 4 and 5 are summarized in Table 6. In retrospect, it is little wonder that these projects, which span civilian and military, high and moderate technology, all experienced varying degrees of difficulty in meeting cost estimates and contractual commitments.

A. ORGANIZATIONAL SLACK

1. Lack of incremental (i.e. milestone) development
2. Lack of control of the entire project
3. Overlapping development of interdependent projects

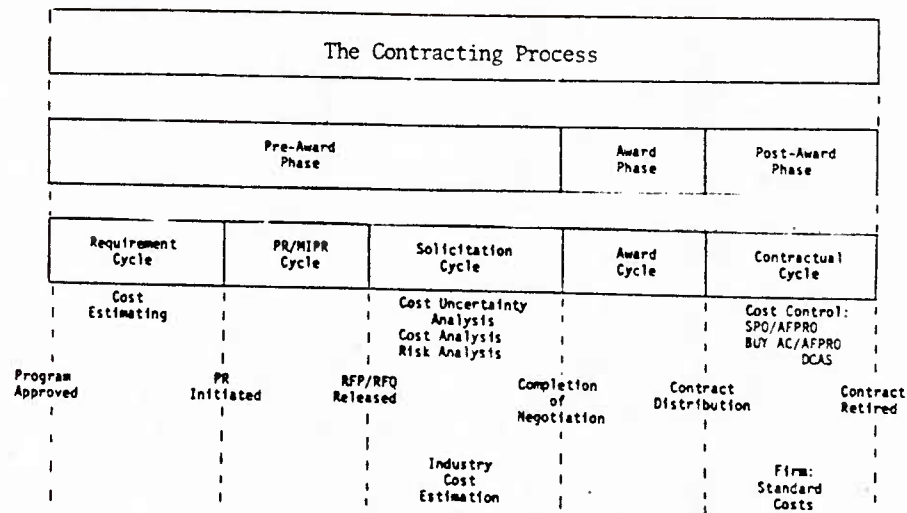


FIGURE 7 THE CONTRACTING PROCESS

Cause/Program	RB 211	LHA	BART	F-111	SRAM	C-5A
A. ORGANIZATION SLACK	Engine	Craft	Train	Aircraft	Missile	Cargo
1.	x		x			
2.	x	x	x		x	x
3.	x		x	x	x	
4.		x	x		x	
5.	x	x	x	x	x	x
6.				x		
7.		x			x	
8.	x	x			x	
9.	x	x	x			
B. CUSTOMER URGENCY						
10.	x	x	x	x	x	x
11.	x	x	x	x	x	x
12.	x	x	x	x	x	x
13.	x			x		
14.	x	x	x	x	x	x
C. ENVIRONMENTAL UNCERTAINTY						
15.	x					
16.	x					
17.	x					
18.		x				
19.	x	x	x	x	x	x
20.				x		
D. TECHNOLOGICAL UNCERTAINTY						
21.	x		x	x		x
22.	x		x	x	x	x
23.	x	x	x	x		x
24.	x			x		
25.	x	x	x		x	
26.	x	x	x	x	x	x

TABLE 5 MAJOR CAUSAL FACTORS FOR SIX PROGRAMS

4. Split and dispersed organizational control of key elements in a high risk project (i.e. fragmentation of responsibilities)
5. Inadequate consideration given to trouble areas (i.e. subsystem dependencies) which could delay the program.
6. Incomplete preplanning
7. Lack of organizational cohesiveness and continuity
8. Lack of adequate manpower to deal with design changes
9. Incongruent personnel career objectives.

B. CUSTOMER URGENCY

10. Inadequacy (or incompleteness) of task definition at the time of contract
11. Contracting simultaneously for cost, time, and technical performance
12. Contract provisions (e.g. elimination of contingency provisions), (e.g. total package concept), and negotiation techniques
13. Mutual acceptance of unrealistic prospective cost estimates of product and delivery schedules (i.e. cost optimism syndrome, schedule, and risk optimism)
14. Over lap of development and production phases

C. ENVIRONMENTAL UNCERTAINTY

15. Lack of financial strength for large, long-term risky projects
16. Low bidding, while lacking the resources to finish the job
17. Political/economic pressure to win the competition at any cost
18. Economic pressures for a general reduction of expenditures
19. Inflation, regulation, and poor cost estimates
20. Optimistic promises concerning schedule, cost, and technical performance

D. TECHNOLOGICAL UNCERTAINTY

21. Underestimation of the degree of technological breakthrough required in a state-of-the-art of product development, while under a fixed and tight time and performance constraints
22. Pushing technology too fast
23. Lack of prototype development
24. Performance requirements beyond state-of-the-art
25. Inadequate test program
26. Major design or scope changes

TABLE 4 CAUSE OF COST OVERRUNS

(See Page 34)
Examination of the data from the many studies conducted reveals that there are no simple answers to reducing cost growth when dealing with the uncertainty inherent in the acquisition

tion of programs such as those described in Table 6. It would be unreasonable to prevent advances in state-of-the-art and changes in design to meet requirements that are determined during system test and evaluation. Furthermore, there will inevitably be some degree of concurrency during development, as well as overlap of authority because of multiple organization involved in the process. There is little doubt that over-optimism in new designs lead to design changes and ultimately to cost overruns. Inflation, changing political and customer influences and environmental castastrophies will continue to plague the acquisition process. Low bidding, poor or inappropriate estimates, improper budgeting and cost control--all contribute to the problem. When these factors are compounded with interrelatedness, delays, disruption, concurrency and extreme variability, it is little wonder that no definitive answer has emerged to solve the cost overrun problem. What is needed is a positive approach to the "management" of risk and uncertainty so that the polemics of acquisition disruption, as described by Cochran in Table 7 are avoided. (Shown next page)

DEVELOPMENT OF AN APPROACH TO THE MANAGEMENT OF ACQUISITION UNCERTAINTY

In the sections that follow, we will attempt to define terminology used in the management of risk and uncertainty in the acquisition of major programs. Patterns of disruption will be examined in terms of predictive causality models. Finally, these will be combined with a proposed simulation model that incorporates the causal models and that treats the factors explicitly contributing to cost overruns so that alternative policies and approaches can be examined in terms of minimizing expected disruption.

Risk and uncertainty are defined based on classical probability theory as well as how they apply to the acquisition process. Lev (33) defines risk as the condition where each outcome of the decision maker leads to one of a set of possible specific outcomes, each occurring with a known probability. Uncertainty is defined as the situation where the probabilities of the various outcomes are completely unknown. Although risk and uncertainty are often used interchangeably, they are not the same state of knowledge in a given situation.

Peck and Scherer's (145) comprehensive analysis of the weapon systems acquisition process defined risk as the level of consequences of a wrong prediction. They operationally defined uncertainty as the relative unpredictability of an outcome of a contemplated action. They categorize uncertainty as either internal or external where internal uncertainty related to the possible incidence of unforeseen technical

Table 6
Causal Factors Contributing to Cost Overruns

Project	Organizational Slack	Technological Uncertainty	Customer Urgency	Environmental Uncertainty
RB 211- Rolls Royce Engine	Engine thrust beyond prior experience, accepted unrealistic deadline, lacked financial strength	20% fewer rotating parts, first 3 spool shaft, 25 hyfil blades, fan failure due to new titanium alloy, higher engine weight due to severe loading, high temperatures prevented early testing.	late redesign to reduce weight, major design changes, urgency in delivery deadline	bankruptcy due to unrealistic estimates
LHA - Landing Helicopter Assault ship	Management and engineers 2000 mi. from ship yard, high management turnover, over 8 year period had 7 program managers, 7 yard managers, 5 chief engineers	Extremely large boilers rear loading ramp, 2 conventional ships and remainder modularized	large number of change orders, shipyard completed 2 years after contract award, DD ship and LHA used same yard	Social and community conflict, difficulty to transfer management to the yard
BART - Rapid Transit System	new organization to manage construction and then operate the system	new self propelled railcar, new sophisticated automatic train control	new government organization involving the Association of Several Bay Area entities. Rohr and Westinghouse both had significant concurrency	system required both subway and elevated facilities in complex environment
F111 - Swing wing fighter aircraft	Two different companies designed and produced the airframe, separate engine development, Secretary of Defense took personal charge of the project	Major advance in the state of the art, swing wing, fully modulated fan jet, self contained crew compartment, terrain following capability, 1226 changes in specifications, poor product definition	Overlapping development of wing and engine development, integration of phoenix and SRAM, concurrency of production and development	Delays in bidding changes in quantity ordered
SRAM Short range attack missile	Coordination between SRAM office, F111 development and SPO	New alloys and new design concept, ambitious SOA solid rocket propellant motors, chamber pressure and burn rate 8 times that of the Minute-man ICBM, low radar cross section	Use of the Total Package Procurement, concurrent development with F8111 aircraft, lack of commonality in launch platforms	Delays in coordinating tests, Switch from TPP concept
CSA cargo air -craft	Significant problems of coordination with the SPO	6200 square feet of additional wing span, integration of subsystems, by far the largest engines ever built, kneeling landing gear, 28 tires, automatic weight balance	Major program changes, quantity changes, overlap of development and production could not test engine because of overlap with wing design	Viet Nam War causing 50% of overrun due to inflation

TABLE 7 THE POLEMICS OF ACQUISITION DISRUPTION

Basic Event	The Contractor's Position	The Customer's Position
DESIGN DELAYS	Customer indecision Customer changes Regulatory body approval cycle	Insufficient Contractor resources assigned Other design work given priority Poor engineering work required Customer correction Poor Contractor communication with Customer Contractor didn't follow instructions
DESIGN CHANGES	Customer changed project's objectives or scope to meet new competition Customer misrepresented the task Required to correct commercial infeasibility	Contractor knew such changes would occur and made provision in his price and planning Changes made to help Contractor meet schedule Poor Contractor design work had to be corrected Contractor failed to follow Customer specs. Most design work actually done by Customer
POOR PERFORMANCE	Meets Customer design specs. Degradation due to customer design changes Not enough time allowed by customer for testing Customer didn't train its field personnel	Poor design work by Contractor Fails to meet Customer performance specs. Poor Contractor quality control Contractor failed to determine design change impact Contractor manuals inadequate
LATE DELIVERY	Customer-caused design delays/changes affected vendors, design or production Force majeure (no one's fault)	See reasons for design delays/changes Poor Contractor planning Poor selection of or coordination with vendors Production inefficiency Poor quality control Force majeure (Contractor responsibility)
COST OVERRUN	Design delays Design changes Customer changed delivery schedule Interactive disruption Escalation due to Customer delays Force majeure	Gross Contractor under-estimating Contractor "bought" the contract Operating inefficiencies; weak management control Escalation due to Contractor delays Poor planning General mismanagement Misstatement of costs by Contractor
DELIVERY ACCELERATION	Customer convenience	Contractor should have expected this
DELIVERY STRETCHOUT (OR CANCELLATION)	Customer convenience; misjudged market; shortage of funds	Schedule was adapted to Contractor capabilities Contractor delays/quality caused lower sales
DISRUPTION OF OTHER PRODUCTS	Reflects problems caused by customer on this product (See above)	Contractor attempt to cover own errors

difficulties in the development of a specific weapons system. Examples of internal uncertainty include development time of interrelated technologies, substitutable technologies, and performance to specification. External uncertainty covers factors external to a given project, but affect the course and outcome that can be expected. Examples include rate of technological change in weaponry, changes in strategic requirements and shifts in government policy.

The USAF Risk Analysis report defines risk as the probability of an occurrence and uncertainty as incomplete knowledge. A risk assessment is where estimates are made of the risk associated with given alternatives and risk management as the actions taken to reduce risk. Risk analysis is considered the combination of risk assessment and risk management. It is the latter definitions which are most directly applicable to the acquisition process. As was shown previously, they use uncertainty to describe target, technical, internal program and process effects. They also use a network simulation to develop individual and joint risk profiles as the system progresses over time.

Harrison (20) defines risk, certainty, and uncertainty as follows:

risk - a common state or condition in decision-making characterized by the possession of incomplete information related to a probabilistic outcome.

certainty - an uncommon state of nature characterized by the possession of perfect information related to a known outcome.

uncertainty - an uncommon state of nature characterized by the absence of any information related to a desired outcome.

Harrison further contends that "genuine uncertainty is as common as complete certainty". The more common state of nature is incomplete or imperfect information, which means that the expected outcome contains an element of risk for the decision maker. There is no situation that deals with the future that can be completely known when the acquisition process lasts anywhere from 2 to 12 years. How can a program manager possibly forecast events that far in the future with any meaningful degree of accuracy?

Beverly, et al, (86) describe uncertainty in systems acquisition as the lack of knowledge in development requiring state-of-the-art technology. They apply risk based on historical phenomena for which probabilities can be established. On the other hand, certainty or uncertainty deals with the existence of know-

ledge. Uncertainty is greatest when knowledge is at its lowest level. Uncertainty would describe the situation where a new system is being developed which involved advanced state-of-the-art technology. The lack of knowledge, in turn, inevitably leads to errors in estimating, in design and ultimately in cost control. This leads to three kinds of uncertainty in weapons acquisition: design and technology uncertainty, scheduling uncertainty and cost uncertainty. They point out that there is conflict among goals because reduced design/technology uncertainty enhances performance while cost minimization tends to adversely affect both performance and schedule goals.

Martin (134) deals with uncertainty in terms of our inability to predict the future in the face of unknown variables. His taxonomy of uncertainty conditions represents a comprehensive treatment of the subject. He includes four basic categories of uncertainty as follows:

1. Environmental:

- a) natural factors
- b) social & political effects
- c) communication disparities
- d) time which results in distortions
- e) external to the project or exogenous
- f) internal approaches or endogenous

2. Functional:

- a) income/business risk
- b) financial/earnings risk
- c) technological uncertainty
- d) production inadequacies

3. Informational:

- a) unknowns of which contractor is aware
- b) unknowns that cannot be foreseen
- c) lack of knowledge
- d) unknowns that cannot be anticipated

4. Technical:

- a) uncertainty - no known probability distribution of events
- b) risk - outcomes can be described by a probability distribution
- c) certainty - predictable outcome determined
- d) subjective - probabilities derived independent of the problem at hand

Martin (134) describes a twenty year period in which measures to reduce cost growth were not effective. He recommends the use of entropy to measure the level of information in a system which is directly related to the uncertainty under which decisions have to be made. As entropy increases, so does uncertainty and what is needed is a means to increase information efficacy rather than increase choices or randomness. Thus, if order is complete (reduced

entropy) cost is known: whereas, if multiple outcomes are possible, cost is uncertain and difficult to control.

McNichols (138) presents a means for estimating the distribution of cost uncertainty where actual costs differ significantly from original cost estimates. He contends that cost overrun is a meaningless concept because all cost estimates rely heavily on subjective judgments and are subject to considerable uncertainty. He considers four basic requirements in the treatment of uncertainty. These include: generation of probability distribution for individual cost elements; generate a total cost by additive distributions; the probability density functions are then combined to form a compound distribution; finally the dependence or degree of correlation between cost elements is taken into account. The problem of uncertainty then is to determine a measure of the degree of difficulty or likelihood of achieving cost goals.

The descriptions of risk and uncertainty presented above illustrate the variety of approaches that can be taken. The relevant question, however, is how best can management deal with the problem of uncertainty in the acquisition process. Although it is commonly assumed that any major overrun signifies poor management, this premise fails to recognize that uncertainty is inherent in acquisition and that managers operate under severe time and resource constraints.

Even where the degree of uncertainty can be quantified, either by using past experience or by applying analytical techniques on the basis of a supportable theory, there is a significant probability of failure. In accepting risk, the trade-off must be clearly assessed. For example, economic growth is worth less to some manager (or their capital sources) than to others. Thus, arriving at a rational value of specific losses and benefits. Thus, there is a need for a "utility function" which identifies the financial consequences of a decision.

In view of the inherent uncertainty in the acquisition process, managers must consider: a) did the project warrant the resources and risks involved; b) were the alternatives rationally defined; c) were considerations given to the probable results of alternatives as to the failure of the project; d) were suitable steps to prevent failure or to hold cost to a minimum made available and e) was there adequate monitoring of events to detect deterioration of the situation in an early stage, and to limit the losses.

Clearly, managers take risks because they proceed in the face of possible failure. Unfortunately, the "degree" of uncertainty and the potential effects of unfavorable events are often difficult to determine. Many situations

involve potential events whose probability is not measureable. All too often the term "calculated risk" refers to a decision reached in recognition of factors known to be unfavorable but "not" susceptible to calculation. The future may even involve events of a totally unexpected or unknown type. Thus, in dealing with complex problems under limited time and resources, substantive errors in judgment can occur in unpredictable ways.

A CAUSAL BASIS FOR DEFINING UNCERTAINTY

Although uncertainty is defined as lack of knowledge about specific effects, it can be examined in terms of the factors that contribute to disruption and in turn attempt to understand the causal relations that lead to cost increase. The premise is that control of the variables contributing to uncertainty is an effective means for controlling cost. This is analogous to queuing theory where a knowledge of queue behavior and sequencing rules permits servicing the maximum demand with available resources. Delays are not eliminated; rather, they are reduced by adding capacity or modified by changing priority rules. Disruption in the acquisition process can be considered similar to queuing delays in limited capacity servers. By understanding which factors cause disruption, management can alter the expected cost growth by controlling those factors. Typical factors leading to disruption are shown in Table 8.

1. Delay: gaps in carrying out a program
2. Interruption: short delay
3. Stretch-out: slow down of program
4. Interference: delay by stoppage
5. Redesign: change scope, redo previous work
6. Work stoppage: partial interruption
7. Interdependencies: indirect delays
8. Shortages or errors: delay due to rework
9. Overlay: interferences & delay due to concurrency
10. Redirection of effort: disruptive effect of reorganization

TABLE 8 FACTORS IN DISRUPTION

Two key factors that are highly disruptive in the acquisition process involve concurrency and technological uncertainty. Concurrency is most often a result of customer urgency in attempting to meet tight deadlines. Delivery urgency enforced by competitive conditions exerts strong pressure on suppliers to commit to delivery dates which are inherently optimistic or

based on the assumption that no serious problems will develop. The plan becomes a matter of urgency when combined with some degree of technological uncertainty.

Delivery urgency can be disruptive even when the initial delivery cannot be eased, since planning is done and work initiated predicated on the original delivery date. A deferral in scheduled delivery causes added costs.

TECHNOLOGICAL UNCERTAINTY

As used here, technological uncertainty refers to two conditions. One is the highly abstruse demands at the very forefront of scientific knowledge or state-of-the-art. It also refers to a major gap between an organization's area of expertise and what is required to perform effectively. Rapid technological change can have a major financial impact on an organization which can be catastrophic and can be termed a "technical disruption."

Uncertainty occurs where conditions of rapid technological change exist simply because it is difficult to make valid judgments. Even experts have incomplete knowledge. Managers, in turn, must rely on the recommendations of technical people, and yet be able to detect errors and inconsistencies. Hence the manager's incomplete knowledge can be a limiting factor.

During a period of rapid technological change, there is usually intense competition, since a major advance by one enterprise reduces the business available to others. As a result, the amount of time available for testing and proving of new concepts and hardware is held to a minimum. Factors used to determine the state-of-the-art are shown in Table 9.

1. Size-number of interrelated components, physical volume
2. Complexity-difficulty in meeting performance requirement
3. Newness of technology-experimental state of technology
4. Percent proven technology-degree of newness
5. Experience in the field-work on similar programs
6. Percent new components-test and evaluation requirements
7. Interdependency of subsystems-types of linkages
8. Degree of precision-quality or cleanliness requirements
9. Special resources-testing, or tooling requirements
10. Definitive specifications-clarity in meeting requirements
11. Design flexibility-tolerance level, substitutes available
12. Required theoretical analysis-need to support proposed design

13. Degree difference from existing technology-life cycle of technology
14. Available knowledge in the field-amount of experimentation required
15. Infra-structure support required-degree of dependency on vendors

TABLE 9 FACTORS DETERMINING THE STATE-OF-THE-ART

An approach to determining the technological advance ratings was developed at the RAND Corporation (146) and is shown in Figure 8. The scale ranges from 0 to 20 where the newness of the design determines the advance in state-of-the-art. Examples of a number of military and commercial aircraft, as well as a number of different missiles is shown on the chart. The factors shown in Table 9 include the newness as well as the design requirements for determining the state-of-the-art. Thus, state-of-the-art for a given organization can be construed as the "ability" to produce a given design, in addition to the newness of the technology involved. (Shown page 41)

Uncertainty due to technological change often arises from the overlap or "concurrence" of development and production. The perceived necessity to initiate the ponderous and involved processes of production before there is real certainty as to the stability of the product design, places these at the mercy of any delays or changes which may occur in the design. And, such delays or changes are more likely to occur as the degree of concurrency increases.

Concurrency is inherently costly since it requires considerable effort and cost to establish production momentum, and sometime even more to shut it off or slow it down. A production organization is not very good at responding to the inherently sporadic character of a development program, and its floundering is dreadfully expensive.

It might seem obvious that the solution is to avoid concurrency, or at least to limit it to areas in which redundant or alternative courses of action offer an option with which to avoid real failure. Although this may be true, it is no simple matter to implement.

During rapid technological change, the pressure to take on new projects is greatest. But, doing so entails even greater risk than under conditions of technological stability. Unfortunately, there is no warning that "this" risk will turn out to be unacceptable. The effects are pervasive and far reaching, ranging from the ineffectiveness of familiar technical skills and operational procedures to the impact of recondite scientific laws on the design, construction, operation and maintenance of a new product.

In an all too common form, technological

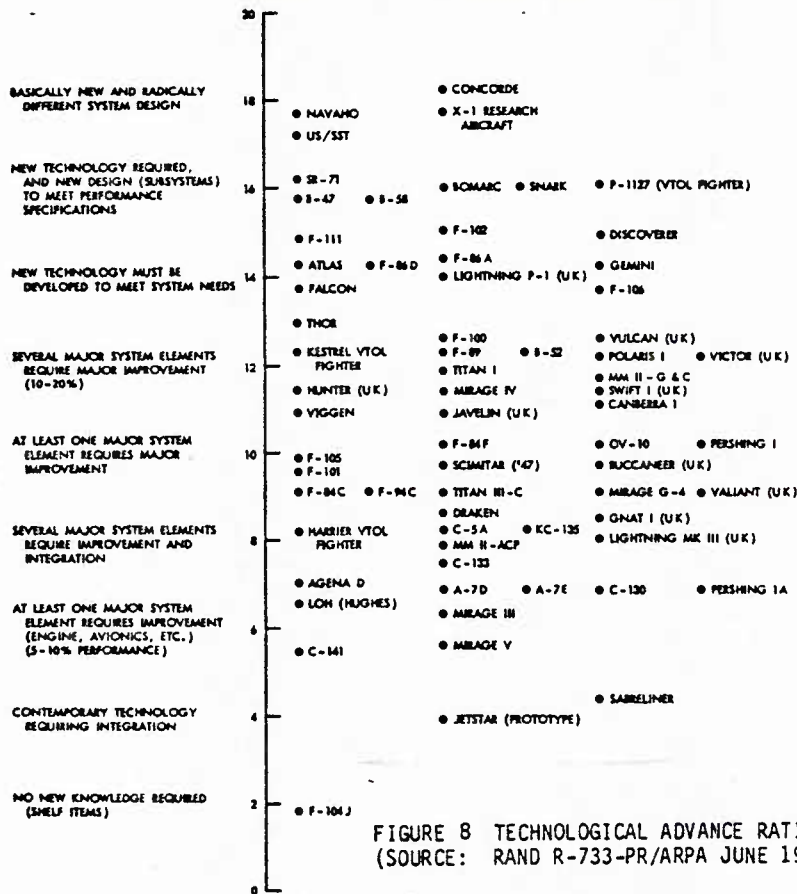


FIGURE 8 TECHNOLOGICAL ADVANCE RATINGS
(SOURCE: RAND R-733-PR/ARPA JUNE 1971)

	Lines & Body Plan	Hull Structure	Speed	Powering	Cargo	Arrangements	Machy.	Ballast	Fuel	Quarters	Cargo Handling	Weights & Distrib.	Seakeepg/Stabil.	Construction	Operation
Lines & Body Plan	X ¹	X ²										X		X	X
Hull Structure	X				X ¹	X	X	X			X			X	
Speed	X ¹			X								X			X
Powering			X			X		X						X	X
Arrangements-Cargo	X	X				X	X	X		X ¹	X	X		X	X
Machy.	X	X		X	X	X ¹	X	X	X	X	X	X		X	X
Ballast	X	X		X	X		X			X	X	X		X	
Fuel	X	X		X	X	X	X				X	X		X	X
Quarters						X ¹	X ¹				X			X	X
Cargo Handling					X	X	X				X			X	X
Weights & Distrib.		X ²										X ¹	X	X	
Seakeepg/Stabil.	X ¹		X ¹		X	X	X	X							

FIGURE 9 SHIP DESIGN INTERRELATEDNESS

disruption has the following characteristics:

- The enterprise embarks on a program requiring the delivery of a specific product within a specified time period.
- The product to be delivered is not fully designed, but is thought to involve only normal state-of-the-art, familiar to the organization.
- Unanticipated technological problems arise which require extensive time to resolve and result in substantial changes to the original product and to production.
- The changes generate confusion and increase costs substantially, and those increases are intensified by the need for skills and training and for additional management time.
- Intensive efforts must be made to minimize deviation from the original delivery schedule and product specifications. This further increases costs, as the natural confusion caused by change itself is compounded by the need to expend greater effort in the shrunken time now available for design and production, and by the need to invent new procedures to make better use of the time.

Much interaction occurs among the various stages and events of each situation, and the end result can be a cost overrun of enormous proportions.

INTERDEPENDENCY

If the degree of state-of-the-art is a driver of technological uncertainty, then interrelatedness is a major multiplier on cost of development and production. Interrelatedness of design boils down to the fact that a change in one component or subsystem affects many others, and of course this process can iterate further. Interrelatedness can also affect production and vendor activities, since a change in production methods or delivery cycle in one area or component (generated, or course, by design delays and changes) may affect production of other components or work in other areas. Again the process can become very complex with many ripple effects. In general, a product operating in a more advanced area of technology will be more subject to interrelatedness. Interrelatedness can be described in a matrix form as shown in Figure 9. (Shown previous page)

ORGANIZATIONAL SLACK

Two other factors compound the disruptive effect of concurrency: First; the level of resources effectively available to the project and second, the degree of external control over events. The level of resources comprises all types of resources -- technical, managerial, facilities, financial, etc. Adequacy of resources is measured by what might be termed "organizational slack".

This factor relates to the organization's experience in the basic technology involved. It provides an invaluable fund of knowledge and skill in handling the inevitable, unexpected problems which arise, and which could swamp an inexperienced organization. A second problem is the degree to which the task at hand fully engages all resources available over the time-frame of the project, which may leave inadequate reserves for use on unexpected problems. This inadequacy can be a critical flaw, given the intense time compression inherent in concurrent design and production.

Organizational slack, thus, defines the level or degree of unknowns that are internal to the system rather than the external exigencies. Factors related to internal uncertainty could be measured using dimensions such as:

1. The organization's ability to respond to new or unforeseen requirements.
2. The slack or flexibility that has been built into the organization.
3. Prior experience with the given technology.
4. Number of linkages of subsystem dependencies or interaction with other projects.
5. Percent of the project's subsystems being developed that are at the "state-of-the-art" of the technology.
6. The amount of time compression or tightness of schedules (concurrency).
7. Availability of or access to resources.
8. Maturity in the planning and control of operations, including computer systems and organization structure.
9. Amount of overlap of: development, design, and implementation.
10. Number of contractors or organizations involved in the project.

These factors contribute to a measure called, "Organization Response Capacity." That is, management's ability to cope with uncertainty. In turn, the delay, disruption, or slippage that can be anticipated would be measured by the relationship of this capacity to customer demand as shown in Figure 10.

Expected disruption is an exponentially increasing function which is dependent on the organizational response capacity, which in turn depends on the level of concurrency. Thus, when the level of concurrency approaches the response capacity, the delay increases. This formulation does not deal with uncertainty per-se, but whether the organization is able to cope with problems as they arise, or is able to anticipate problems. In turn, the amount of slack or flexibility in the organization determines the ability to respond to uncertain requirements. If management is operating with minimum slack, then any disruption causes a large delay.

(See figure 10 and Table 10 next page)

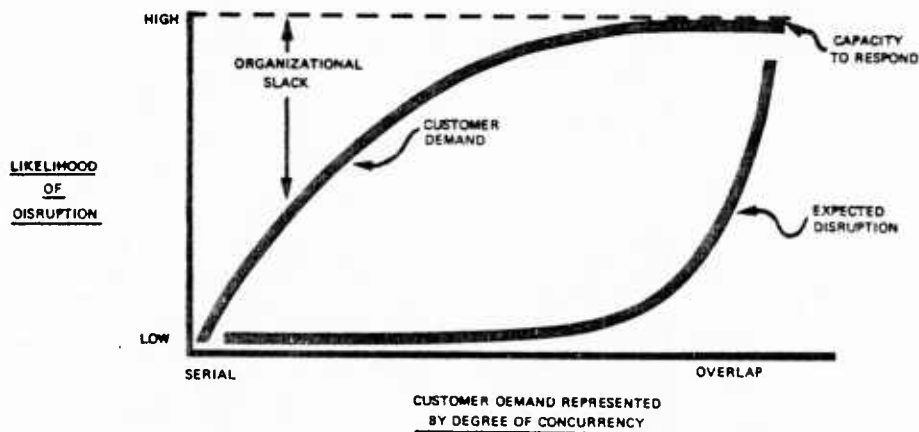


FIGURE 10 IMPACT OF CONCURRENCY ON DISRUPTION AND RESPONSE CAPACITY

Agency	Program			
	Planning	Development	Evaluation	Utilization
National Aeronautics and Space Administration: Goddard Space Flight Center	Highly directed with specific objectives	Reliance on internal staff for project selection Close monitoring	Regularly and frequently evaluated	Plan for utilization included in projects
National Science Foundation: Research Applied to National Needs (RANN)	General objectives and priorities	Project ideas generated externally Consultation with research community on project selection Partial monitoring	Regularly evaluated, but infrequently	Plan for utilization included in projects
Engineering, Mathematics, Physics Divisions	By disciplines or fields of inquiry	Support of individual scientists External mail review with feedback to reviewers Little monitoring	Program manager defends his project selection decisions	Little direct attention
Biological and Social Sciences	By disciplines (within these, by lines of inquiry)	Support of individual scientists External panel review of borderline decisions Little monitoring	Evaluation implicit in considering renewed or continued support	Little direct attention
National Institutes of Health	By disciplines, collections of similar subjects	Support of individual scientists Unsolicited proposals Dual panel review (greatest attention to evaluating proposals) Little monitoring	Evaluation implicit in considering renewed or continued support	Little direct attention
Office of Naval Research	By disciplines and directed at extracting most capable researchers	Seek new researchers No formal review of project ideas Monitor activities (once or twice a year)	Evaluation implicit in considering renewed or continued support	A part of the program manager's mandate

TABLE 10 - EXAMPLES OF PROGRAM MANAGEMENT
(SOURCE RAND - R-1375, APRIL 1975)

Another perspective of management practices is shown in Table 10 for four government agencies based on a RAND (54) study of R&D management. An examination of the findings reveals the considerable latitude given program managers in dealing with creative individuals needed in R&D programs. Given this kind of organizational environment, the accuracy of estimates is highly questionable. At best, the estimate becomes a target that permits a level of effort in attempting to achieve what are often elusive objectives or requirements.

Perry, et. al, in their study of acquisition strategies, (53) recommend that acquisition management use an incremental approach. This support was based on an analysis of 36 major DoD programs which revealed that high cost growth was due to:

1. Willingness to pay the price for having high technology with compressed schedules.
2. Over-optimism regarding the cost of coping with long term technology.
3. Little evidence that the programs had extreme urgency.
4. Little improvement in cost based on:
 - a) contractual approaches
 - b) complex management reforms
 - c) improved estimating
 - d) early identification and correction of cost growth

Despite these four factors, a number of programs had surprisingly good outcomes and were able to predict cost performance and schedule.

Using their findings, the authors suggest that an incremental strategy and control in the early phases of development would have the most effect on avoiding cost growth.

The incremental strategy recommend the following steps:

1. Resolve uncertainty early in the program
2. Avoid concurrency of development and production
3. Separate performance from reliability and maintainability
4. Require periodic reassessment, redefinition and readjustment regarding proposed changes
5. Conduct tradeoff studies to resolve restructuring

The benefits from an incremental approach to management would lie in greater predictability based on prototype demonstration and in uncovering difficulties early in program life. It would also encourage competition and transfer of technology as the need required.

Another consideration relating to organizational slack is presented in the study by Moeller (45) of the DSARC management review process to

determine its effect on the length of major system acquisitions. He found that although DSARC demands considerable time and generates a sizeable workload for the program office, there was no excessive delay in 11 of the 13 programs examined. His conclusion, therefore, was that regardless of how cumbersome the review process might be, it had no significant effect on the length of the acquisition cycle because the review was concurrent with the production activities. Rather, the primary contributor to lengthening the development process was lack of adequate funding or instability which caused stretch-outs. Another significant factor in lengthening the cycle was the lack of agreement on configuration and performance parameters. This lead to indecision or inconsistency in meeting technical requirements. There were a number of delays resulting from testing requirements. Two significant recommendations were the judicious use of concurrency, such as for logistics and more flexibility in the approach to acquisition.

ORGANIZATION PERFORMANCE

Another aspect of organizational slack relates to expected performance. Cochran (96) has identified key factors which contribute to disruption and which management can review in order to achieve more effective control:

1. CONTRIBUTORS TO TASK VARIABILITY

- a) Inadequate definition of product specification.
- b) Underestimating the degree to which "state-of-the-art" (SOA) must be advanced.
- c) Poor cost engineering or organization planning.
- c) Not allowing for the degree of uncertainty in meeting plans.
- d) Not anticipating the "backup" activities required in case the main approach fails.

2. DETERMINING DISRUPTION

- a) Review the source of rigidity in the delivery date.
- b) Analyze the SOA tradeoff surface.
- c) Determine areas where tasks were not anticipated.
- d) Define the degree of SOA advancement required, and the cost involved by area.
- e) Determine the risk elements involved and their effects
- f) Define specific cost increase relationships.
- g) Develop modeling techniques to conduct appropriate analysis.

Considering that industry is often confronted with untenable contractual procedures,

including perpetual specification change and rigid contracting requirements, as well as, unanticipated price changes, inflation, changes in the number of systems, and the impact of new technology, it is small wonder that acquisition managers are confronted with the requirements for effective means for handling uncertainty.

Cochran (96) also described the S-Curve patterns of labor hours as a cause of disruption leading to substantial cost overruns when development of a major new design is concurrent with production and under severe delivery pressure. Labor cost reflects the impact of design delays, growth, and changes in the production function. The S-Curve developed by Cochran is shown in Figure 11 and includes the effect of interruption which leads to forgetting and subsequent restarting of the program.

The disruption caused by the S-Curve effect generally continues well beyond the first units produced, because of the way in which production operates. The procedures, tools, and methods established during the start-up period inevitably carry forward to subsequent periods. Costs follow accordingly and managers generally acknowledge that it is harder to revise engrained organization practices than it is to start from scratch. Further, design growth and changes cause revisions to production methods and sequencing, and in facilities usage. If a change is introduced after production has been established, considerable time is required to fully implement the program. If design changes occur after the affected components have been completed, this requires rework and reinstallation, which involves extra cost. The cost of such work is dependent on the degree to which it is different from the position or sequence normally assigned to the original task. Such work also creates extensive interference with other on-going tasks, which can involve corresponding greater cost penalties.

Another cause of disruption carryover is the "queuing effect". For example, work still in process must be held up because of design delays, design changes, or the need to perform a sizable amount of rework. Inventory control demands frequent rearranging to locate items currently required from the shop, and other double handling affects units in process. In turn, the clogging up of valuable staging areas and even workspace may cause direct interference with follow-on units.

The repeated delays imposed on the production organization in the early stages of a new product cause deceleration of previous activities and rework with their many cost penalties. But beyond that, the relentless need to deliver on time causes a corresponding acceleration later, with its own cost penalties. The repeated cycles of deceleration-acceleration generates a pulsation which sweeps across every phase of

production, gaining momentum and leaving confusion and wasted effort in its wake. The effects on production procedures, facilities utilization and personnel deployment and morale are profound, and account for much of the cost overruns and schedule slippages encountered production. These effects are summarized in Table 11. (Fig. 11 & Table 11 shown next page)

DETERMINING A PATTERN OF DISRUPTION

The ability to define causal relations among variables in disruption and uncertainty is a first step in predicting cost overruns and in determining which actions a program manager should take to avoid cost growth. For example, Augustine (4) proposed using additional planning funds based on an assessment of risk. He contends that even the most capable program manager is not able to forecast all the problems that will be encountered in a development program spanning anywhere up to ten years. However, it is quite possible to forecast the "probability" that additional funds will be required. He recommended the use of TRACE (Total Risk Assessing Cost Estimate) as the basis for justifying the additional funding

One of the early attempts to deal with uncertainty was proposed by Marshak, Glennon and Summers (132). They indicate that where "component" interrelatedness is defined, one can predict the effects that are likely to occur. Under condition of uncertainty, low slack heightens interrelatedness and substantially increases the risk of redesign. Furthermore, the risk of redesign is sensitive to the degree that design reaches beyond past state-of-the-art and where there are requirements to use existing components which can strain the designer and lead to suboptimization. Based on three conditions describing component interrelatedness, one is in a position to predict potential disruption. When there is a high degree of close coupling or interrelatedness, the likelihood of design change is substantial. When there is loose coupling and engineering slack, which permits deviation to occur so that when components are redesigned the deviation does not influence the other components, there is less propensity to redesign. It is argued that the tightness of component interrelatedness can be traded off against uncertainty, and thus achieve more effective control.

Looking at the contract life cycle as consisting of two phase, the award and post-award, Martin, Glover and Lenz (136) have demonstrated that program information becomes more uncertain with the passage of time. The first phase of the acquisition cycle provides the basis for target cost, whereas the second phase with its lack of order related to program information contributes to cost growth. An entropy model developed by Martin (134) was

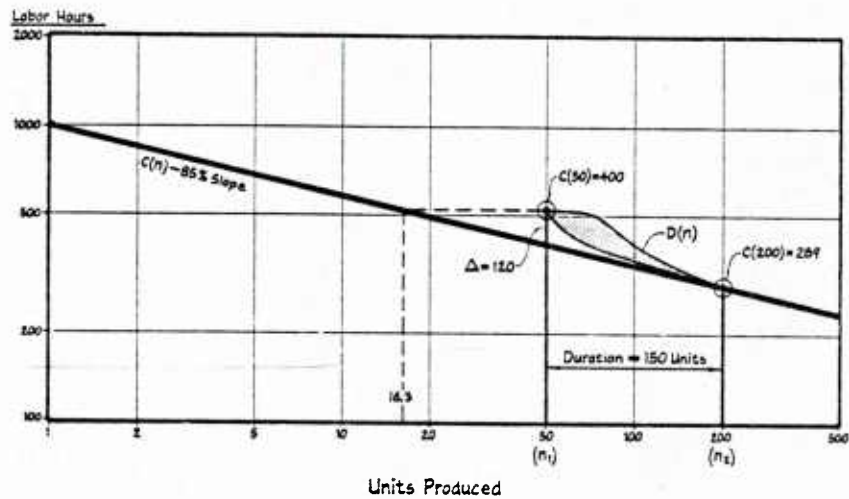


FIGURE 11 THE BASIC S-CURVE PATTERN (85% SLOPE)

Contributing Factor	Major Irregularity Produced					
	A	B ₁	B ₂	C	D	E
	Startup	Acceleration	Deceleration	Task Change	Interruption	Phaseout
1. Degree of man-paclog (production slope)				X	X	X
2. Position on unit sequence				X	X	X
3. Production Rate	X	X	X	X	X	X
4. Basic personnel efficiency and on-the-job training time	X	X		X	X	
5. Debugging of tools/methods	X			X	X	
6. Support services: supervision, materials, equipment, etc.	X	X		X	X	
7. Delays: tools, design, personnel, materials, etc.	X	X		X	X	
8. Task Changes						
o Progress: task reduction	X			X		X
o Configuration Changes	X			X		
9. Personnel: turnover, morale			X		X	X
10. Rate of learning: no. of crews, shifts, lines; parts used/unit	X	X	X			X
11. Task re-assignment				X	X	X
12. Work force increases	X	X				
13. Work force reductions			X			X
14. Lot size changes	X	X	X			X
15. Loss of learning				X	X	
16. Rework and retrofit	X			X		X
	11	7	5	11	10	9

TABLE 11 FACTORS CONTRIBUTING TO IRREGULARITIES

applied to predict final program cost as a function of target cost and disorder in information where: (See page 48)

The model was tested on the SRAM and F-5E aircraft. In the first case the actual cost of the SRAM development was \$439 million compared with the entropic cost model estimate of \$456 million. In the second case the results for the F-5E showed an estimated cost of 10.4 times greater than the actual cost. However, a cost growth of only 7% for the F-5E is unusual and could account for some of the difference. A second problem could have been the uncertainty assessment for computing the entropy value. Because of its potential, this approach of using entropy to predict final cost warrants continued investigation.

Another measure system complexity which contributes to determining the entropy in a system. Table 12 illustrates the impact of complexity on maintainability and availability. Complexity is indicative of the uncertainty related to potential disorder and resultant cost overruns. (See page 48)

RISK MODELS

Many causal relations currently applied utilize risk, rather than uncertainty to predict possible outcomes. Figure 12 shows the relationship between risk and uncertainty as related to causality. Models of known phenomena provide a more certain basis for prediction than random events which are used for estimating probabilities. Uncertainty, on the other hand, covers those areas that are ill-defined or where there is lack of knowledge of effects. (See page 49)

This approach can be extended to develop a risk profile that changes over time as shown in Figure 13 and Figure 14. (See page 49 & 50)

The paper by Admiral Freeman shows this profile approach in relation to the DSARC review process as shown in Figure 15. (See Page 50)

Morrow, Chapel and Worthing (141) developed a relationship between cost growth and "months before initial operational delivery" as a function of state-of-the-art. The high state-of-the-art projects are most sensitive to cost growth as shown in Figure 16. (See page 50)

The curves shown in Figures 17 and 18 relate the level of technological uncertainty to the program life cycle and advances in state-of-the-art. Figure 18 shows the probable impact of a stretch-out on the technological uncertainty. (See page 51)

Figure 19 attempts to relate state-of-the-art to interdependency and level of concurrency. The likelihood of disruption is shown as a function of varying levels of concurrency. The more complex the program, and the higher the

interdependencies the greater the likelihood of disruption. Thus, the likelihood of disruption increases with increasing concurrency. (See page 52)

Another version of the likelihood of disruption is shown in Figure 20 as a function of delivery urgency and technological uncertainty under differing levels of resource application. The higher the level of resource application, for a given delivery urgency and technological uncertainty, the lower the likelihood of disruption. The number of examples abound where alternate designs are produced in parallel to reduce the chance of failure. Expanding capacity, adding personnel or increasing the level of testing and evaluation are other examples of resource expenditures used to reduce uncertainty. (See page 52)

In regard to technological uncertainty, Duviol (15) recommends the use of technological forecasting to assess the risk in meeting the demand for increasingly advanced technology. He postulates that advances are extrapolations of current knowledge and that breakthroughs are rare. Even when breakthroughs do occur, such as the laser, it takes 8 to 12 years to incorporate them in new systems. He shows examples of engine weight, lift and fuel consumption all following smooth curves. Thus, the cost and benefit of new technologies can be based on an extrapolation of technology growth curves.

Regression models have contributed significantly to the understanding of causality in the acquisition process. For example, Leech and Earthrowe (126) have shown that the ratio of actual costs to estimated expenditures can be predicted based on a regression with actual size of the job. Using a sample of 64 jobs, they developed a regression curve, where $r = .955 + .009X$, and X = actual job size in man hours. As they point out, in every case a commitment was made to the customer based on an initial design. However, where the job is large, requires considerable technical innovation and the quantity ordered is small (no opportunity for learning) the design and development costs contribute significantly to the final cost. They recommend an investment portfolio approach to minimize the risk associated with design uncertainty.

It is well known that new technologies rarely are used for the entire system. Rather, they represent a small percent of all the subsystems and components. Where the manager maintains control over those components which utilize new technology, they are in a better position to effect the reduction of cost overruns. The use of the Pareto Law as a basis for determining which components contribute most to the technological uncertainty is shown in Figure 21.

The point C on the abscissa represents the

$$\text{Entropy} = \frac{\text{System Entropy}}{\text{Maximum Entropy}}$$

$$= \frac{\sum_{i=1}^n P_i \log P_i}{\log n}$$

where $0 \leq \text{Entropy} \leq 1$

and P_i = the probability of success or failure associated with the ith element of uncertainty.

$$\text{Final Cost} = \frac{\text{Target Cost}}{\text{Order in Information}} = \frac{\text{Target Cost}}{1 - \text{Disorder in Information}}$$

$$\text{Final Cost} = \frac{\text{Target Cost}}{1 - \text{Entropy}}$$

	Degree of Complexity	Not mission capable	Mean Flight Hours between failure	Maintenance man-hours per sortie
<u>Air Force</u>				
A-10	low	32.6%	1.2	18.4
A-7D	medium	38.6	0.9	23.8
F-4E	medium	34.1	0.4	38.0
F-15	high	44.3	0.5	33.6
F-111F	high	36.9	0.3	74.7
F-111D	high	65.6	0.2	98.4
<u>Navy/Marine Corps</u>				
A-4M	low	27.7%	0.7	28.5
AV-8A	low	39.7	0.4	43.5
A-7E	medium	36.7	0.4	53.0
F-4J	medium	34.2	0.3	82.7
A-6E	high	39.3	0.3	71.3
F-14A	high	47.1	0.3	97.8

TABLE 12 - COMPLEXITY, MISSION CAPABILITY, AND MAINTAINABILITY OF VARIOUS WEAPON SYSTEMS.

(Source: Armed Forces Journal International, May 1980)

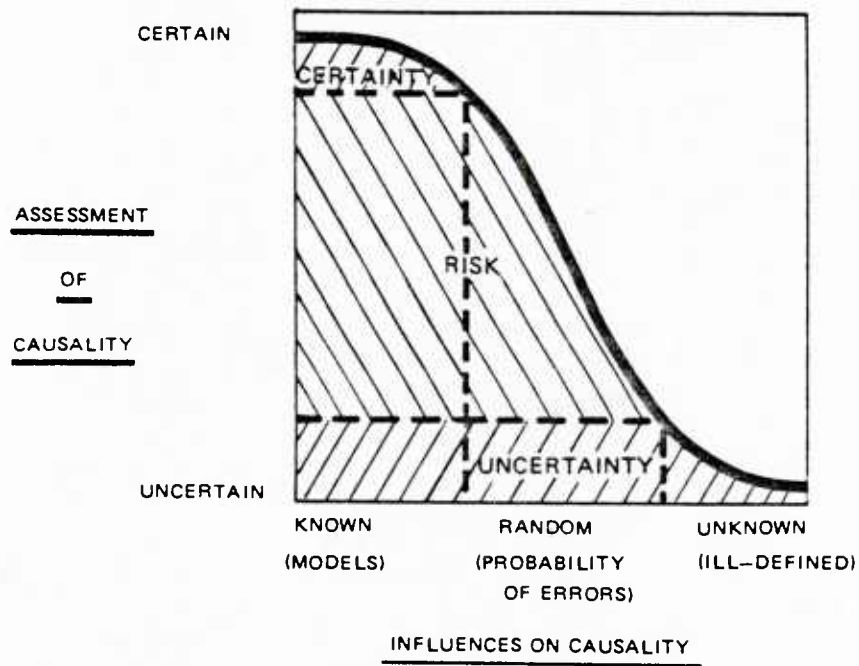


FIGURE 12 TAXONOMY OF CAUSALITY AND UNCERTAINTY

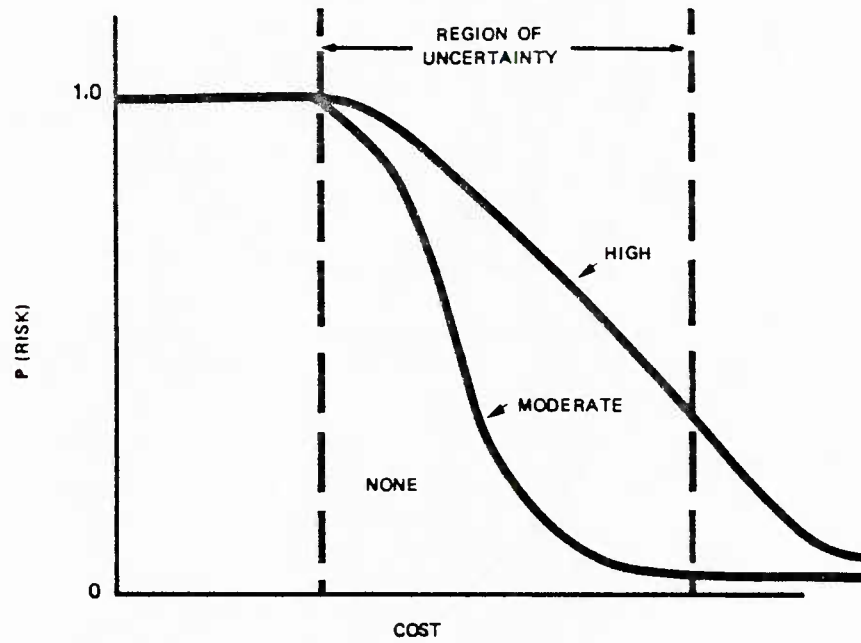


FIGURE 13 RELATIONSHIPS AMONG COST, RISK, UNCERTAINTY

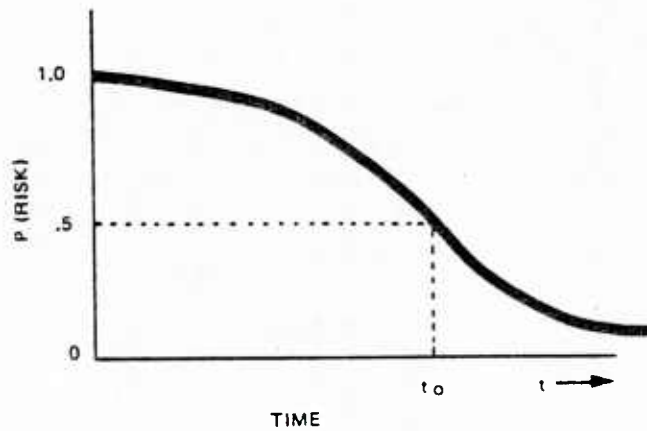


FIGURE 14 RISK PROFILE (TIME)

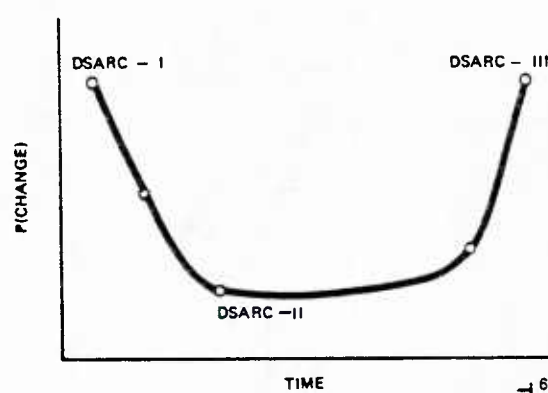


FIGURE 15 RISK PROFILE

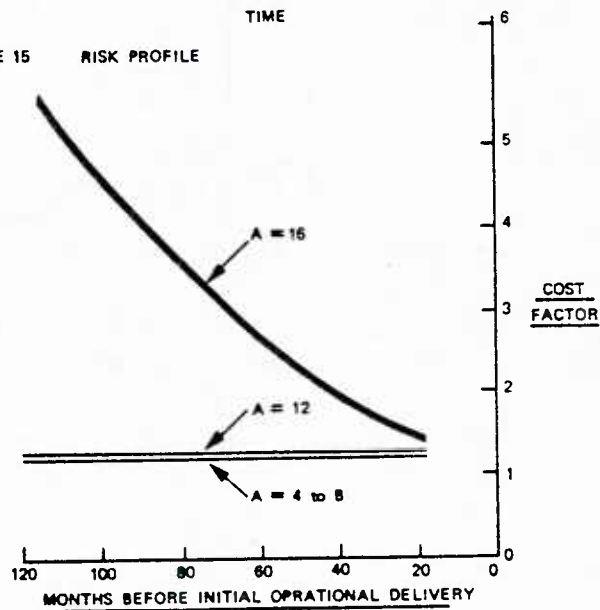


FIGURE 16

VARIAION OF COST GROWTH WITH PROGRAM DURATION
AND LEVEL OF TECHNICAL DIFFICULTY

SOURCE RAND R-2481-DOE, JULY 1979

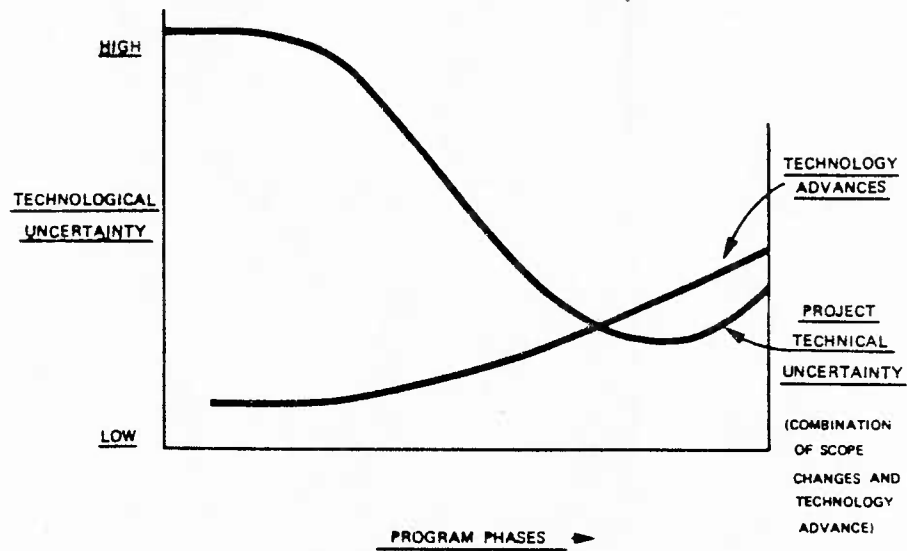


FIGURE 17 UNCERTAINTY VS PHASES

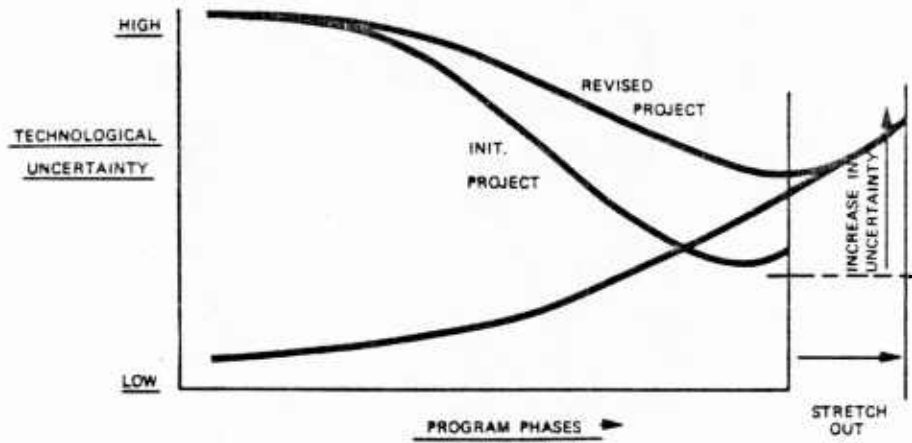


FIGURE 18 IMPACT OF STRETCH OUT

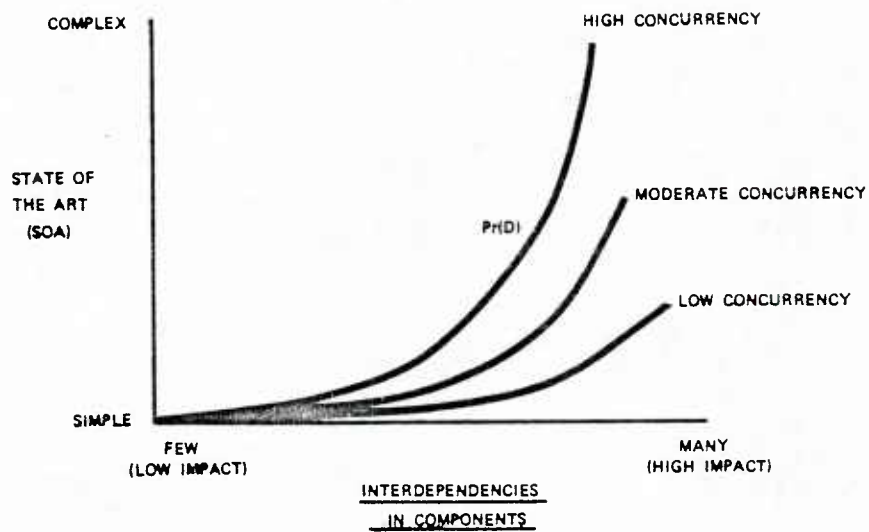


FIGURE 19 RELATION SOA TO CONCURRENCY

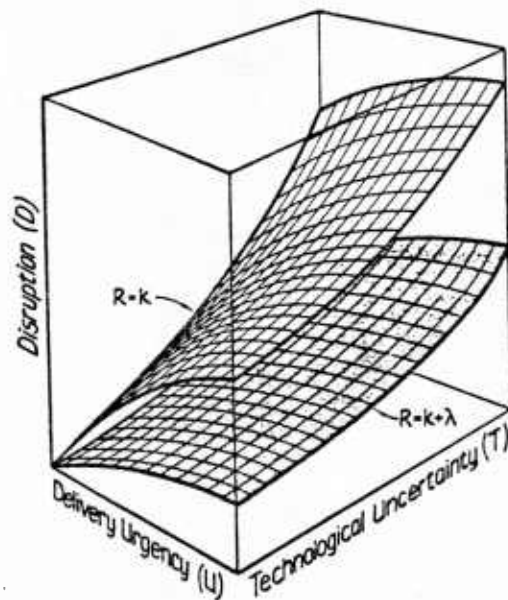


FIGURE 20 EXPECTED DISRUPTION

subset of components that contribute most to technological uncertainty in terms of system impact. Typically, 20% of the components contribute 80% of the problems encountered. The Pareto Law can be used as a basis for parametric estimating and provides a useful tool to control technological uncertainty.

(See page 54)

Because technological uncertainty impacts projects with advanced state-of-the-art. Reduction in development time is possible by maintaining a strong Research and Development (R&D) posture. New technologies can be tested and evaluated prior to incorporation in major systems and thus "avoid" the uncertainty. Considering that new technology is limited to a small percent of components, advanced or anticipatory development can contribute significantly to the reduction of technological uncertainty, reduced need for concurrency and ultimately reduced disruption. Thus, "demonstrated" technical capability could supplement before buy as an approach to the management of risk and uncertainty in major acquisitions.

This latter position is consistent with DoD 5000.3, dated April 1978 which states, "Test and evaluation shall be commenced as early as possible and conducted throughout the system acquisition process as necessary to assess and reduce the acquisition risk". It also concurs with OMB-A-109 which states, "When risks can be accommodated and progress indicates that a proof of concept demonstration is in order, the alternative system design concepts selected for consideration for competitive demonstration are to be submitted to the agency head for approval, along with other alternatives which were identified and evaluated." Although early prototyping offers a number of advantages, the maintenance of a basic technological capability consistent with emerging needs can effectively collapse the time span taken for major developments. In the commercial field IBM and Bell labs are examples of maintaining continuous, high technology, R&D capability which has payoff in terms of capability in developing new technology.

CURRENT APPROACHES TO ACQUISITION MODELING

This portion of the report will examine representative models that are currently being applied to the acquisition of major systems. For our purposes the types of models will be grouped into two major categories - probabilistic/stochastic models and general models. Within this framework several aspects of each of the models will be explored - namely, the basic approach of the model, how it is used, results of its use (post-mortem analysis will be included where available), the requirements for its use, and, the problems or limitations. The selection of the models chosen for analysis is not intended to be exhaustive, but rather indicative of the type of models

currently being used or proposed for use in the acquisition process.

The extension of the two groups of models leads to a proposed approach - the Causal - Integrative Model (CIM) - which is suggested as a means to deal with factors beyond those used by many of the current models.

Stochastic/Probabilistic Models

Within this category, three models will be discussed. These are - PERT, VERT, and a Risk Analysis Model presented by Admiral Freeman at the 1979 Symposium on Risk and Uncertainty.

PERT - Program Evaluation and Review Technique

PERT was originally developed in the late 1950's as a tool for managing large, complex engineering projects. Among the characteristics of PERT as a program management technique are:

- provides management with probabilistic estimates for best possible use of resources to achieve a given goal within time and cost limitations.
- helps management examine the uncertainties involved in programs by answering questions such as how time delays in certain elements influence project completion; where slack exists; and what elements are critical to meet completion date.
- provides a basis for evaluation of alternative approaches including manpower, material, capital requirements through utilization of a network analysis.

A set of basic requirements to meet the uncertainty aspects is as follows:

- a network of events and activities - Work Breakdown Structure - introduced with their associated risk or uncertainty.
- Events and activities are sequenced on the network under a highly logical set of rules which allow the determination of probability of delay or disruption on critical and subcritical paths.

The use of PERT provides the program manager a planning tool to create a major network. This can be used to analyze the interdependencies and problem areas which are neither obvious nor well defined by other techniques. PERT is also used to estimate the probability of meeting specified deadlines by examining alternative plans and evaluating the effect of changes in the program.

A major disadvantage of PERT is the cost in time and resources. Data collection, manpower, lag time to output, and computer resources, are some of the major problems. Maintenance of the program is also relatively expensive. Thus, PERT has been primarily used on large, complex systems where the cost is a minor part

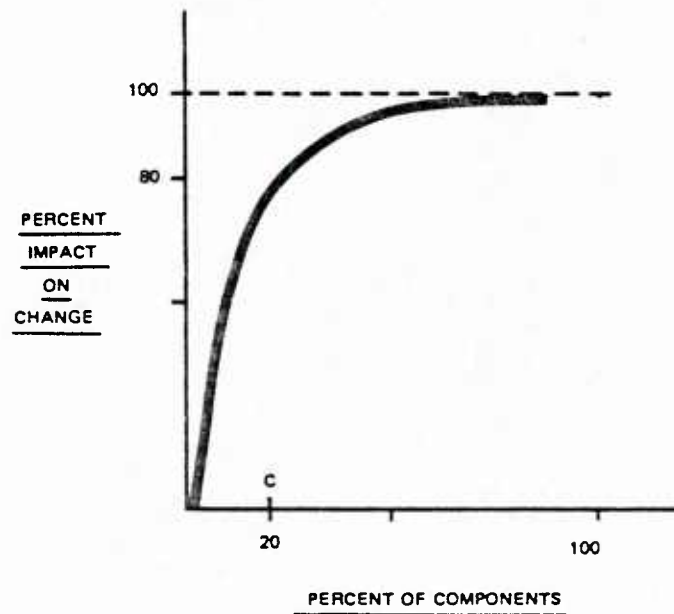


FIGURE 21 PARETO LAW

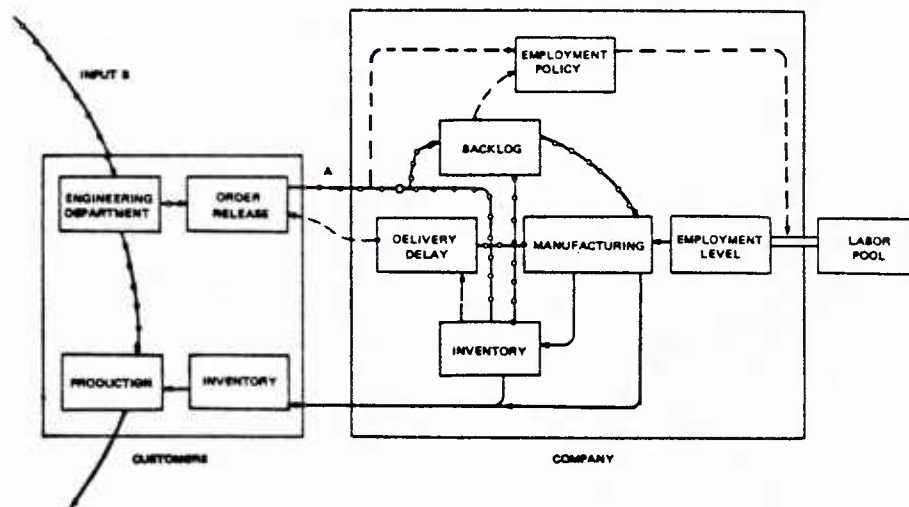


FIGURE 22 MAJOR SYSTEM DETAILS

SOURCE: INDUSTRIAL DYNAMICS P 2121

of total acquisition.

VERT - Venture Evaluation and Review Technique

VERT was developed in 1973 by Gerald Moeller (92) and has been used almost exclusively by U.S. Army program managers to determine the "best" balance among the three program parameters: cost, schedule, and performance. The model evolved from earlier methodological approaches such as GERT (Graphical Evaluation and Review technique), CPM (Critical Path Method), PERT (Program Evaluation and Review Technique), MATHNET (Mathematical Network Analyzer), and RISCA (Risk Information System and Cost Analysis). The short comings of these earlier models when compared with VERT was their failure to include the performance variables along with the cost and schedule variables in the total risk-analysis methodology. The VERT model corrects this problem.

The VERT approach is a general networking method that determines program risk analysis through two basic steps: construction of the graphically representative network and analysis of the network using the VERT software. The first step entails development of the ordered series of activities or subtasks that lead to a specific task. This network includes all aspects - including decision points - required to complete the event. If the problem is quite large and complex, lower level networks or subnetworks of the major subsystems are developed.

Once the network (or networks) is developed, the program is converted into the VERT software compatible terminology. The software allows for a variety of input capabilities that make it possible for decision events and activities occurring within the network to be described. Numerical values for a task's time, cost, and performance are assigned along with probabilities or decision rules based on a specified relationship. The process involves a Monte Carlo simulation in which the design of the network flow across the entire network or subnetworks from the start to an appropriate decision point leads to a trial solution of the problem being modeled.

The process is iterated as many times as the need warrants in order to create a large sample of possible outcomes concerning: slack time, completion time, cost, and performance. Frequency distributions, scatter diagrams, and probabilities of exceeding given values are also generated. Finally, pictorial histogram are generated for desired events, giving the program manager an integrated risk analysis for a particular point of interest in the program. Mann (131) reported in Defense Management Journal that "some minor problems have arisen with VERT, but none are considered major obstacles to its effective use." The problems center about the probability distributions.

Most data sets in VERT are triangular indicating pessimistic, optimistic, and most likely values. This factor reduces the flexibility of the model and the accuracy of the simulations. Another problem, according to Mann, is the inability to obtain expert estimates of the time and cost requirements. The experience is that most of the values obtained have been overly optimistic - which reduces the usefulness of this approach.

General Models

Within this category, types of models will be discussed - parametric cost estimation and dynamic modeling.

Parametric Cost Estimation

Parametric Cost Estimation is the primary costing methodology for DoD weapon system acquisition. This approach evolved from research by RAND Corporation in the late 1950's. The basic idea was to make accurate estimates of weapon system costs at the early stages of system design. This approach uses performance variables such as speed, weight, range, power, etc. to predict costs since estimates of these parameters are usually known early in the design phase. These estimates are based on historical data of previous or similar systems and utilize statistical relationships between cost and the performance parameters of these past or similar systems.

These statistical relationships, called cost estimating relationships (CER), take the form of an equation using cost as a function the performance variables and constant coefficients. McNichols (138) describes the relations in simplified format by:

$$C = f(X) = f(X_1, X_2, \dots, X_n)$$

where x_i denotes, a performance parameter. The total cost would then depend on each of the values of X_i based on data from historical or similar systems. McNichols criteria for selection of the variables is given by:

- The logical or theoretical relation of a variable to cost (thus implying that a real dependence between cost and the value of the particular variable or set of variables exists, subject to some random disturbance or uncertainty.)
- The statistical significance of the variable's contribution to the explanation of cost (thus implying that relevant cost experience exists to test and calibrate the postulated cost dependence - subject to measurement uncertainty.)
- The dependence pattern of the contribution made by a variable to the explanation of cost (thus the analyst must have sufficient confidence in the relationship that he is willing to extend it to estimate a new item - and different analysts will

have different degrees of confidence hence).

There are several advantages to the parametric cost estimation approach. First, since the method consists of a series of CER,s and requires aggregation, it is easily adapted to a computer. Output and turnaround for new estimates can be obtained quickly when compared with the detailed engineering approach. Second, sensitivity analysis is easily performed using this method. For any change in a given parameter, the corresponding change in cost is easily determined. Third, cost/benefit analysis or trade-offs are also easy to perform. Fourth, each time a later generation system is estimated, the historical data base already developed can be updated and used.

The approach is not without its disadvantages. First, the cost of computer resources is significant. Collection of the data is time-consuming as well as subjective. Second, keeping the database relevant is a major problem. Haese (117) states that the tremendous technological advances of weapon system state-of-the-art have tended to out-date cost data even before it is reported. Thus, cost data collected on the latest weapon system may not represent the cost of current technology. With changes from discrete components to integrated circuits, from compound metals to composite materials, etc. What, if any, historical technology is similar enough to any proposed weapon system to allow valid design and credible cost comparisons? Third, the relevance of the cost data base is equally influenced by differences in weapon system acquisition management philosophies, contractual approaches, contract types, and resources available. Fourth, the comparability of the cost data among contractor generated cost reports produces serious problems. Often, it is difficult to understand what the collected cost data represents.

Risk Analysis Model

RADM Freeman's risk analysis model allows various alternatives or systems to be objectively compared through aggregate risk analysis. The process begins with a segmentation of the various program functions into categories of reflecting the schedule, cost, and performance variables. Risk distributions, represented by utility functions, are used to determine utility values versus a change in one of the variables. For example, the question of "how much additional risk is presented by a change in performance variable A?" is answered. The next step consists of developing a Risk Matrix where the options (or alternative systems) are presented versus the criteria for choice. The summary risk or probability for each system/alternative can then be compared on a quantitative basis.

The term risk factor is presented in the form

of an equation:

$$R_f = 1 - P_s (1 - C_f)$$

Where: R_f = Risk Factor

P_s = Probability of Success

C_f = Consequences of Failure

With: $0 \leq P_s \leq 1$

$0 \leq C_f \leq 1$

If C_f the consequence of failure is interpreted to represent a utility function, then the risk factor curve will be defined as a utility function. The shape of this function will be in the form of Figure 20, previously described. If the system criteria and associated risks developed from the Risk Matrix earlier in the sequence were plotted in rank-ordered fashion, it too would be representative of Figure 20 (or, a negative Pareto function).

Dynamic Modeling

Computer-based dynamic modeling was developed by J.W. Forrester in the 1950's as an approach in helping to solve problems of complex, continuous systems. In his book, Industrial Dynamics (105), Forrester states that a dynamic model of a system should have the following characteristics:

- A statement of cause-effect relationship
- Simple mathematical relationships
- Be extendable to large numbers of variables without exceeding the computer limitations:
- Be able to handle "continuous" interactions in the sense that any artificial discontinuities introduced by solution-time intervals will not affect the results. It should, however, be able to generate discontinuous changes in decisions when these are needed.

A dynamic model is based on four factors that have improved understanding of complex systems.

- The theory of information-feedback systems.
- A knowledge of decision-making processes.
- The experimental approach to analysis of complex systems.
- The digital computer as a means to simulate realistic mathematical models.

Forrester contends that the development of a dynamic model should encompass the following steps:

- Identify a problem
- Isolate the factors that appears to interact to create the observed symptoms
- Trace the cause-and-effect information-feedback loops that link decisions to action to resulting information changes and to new decisions
- Formulate acceptable formal decision

policies that describe how decisions result from the available information streams

- Construct a mathematical model of the decision policies, information sources, and interactions of the system components
- Generate the behavior through time of the system as described by the model
- Compare results against all pertinent available knowledge about the actual system
- Revise the model until it is acceptable as a representation of the actual system
- Redesign, within the model, the organization relationships and policies which can be altered in the actual system to find the changes which improve system behavior
- Alter the real system in the directions that model experimentation has shown will lead to improved performance

He further states that dynamic models should be based on these premises:

- Decisions in management and economics take place in a frame work that belongs to the general class known as information-feedback systems.
- Intuitive judgment is unreliable about how these systems will change with time, even when good knowledge of the individual parts of the system is possessed.
- Model experimentation is now possible to fill the gap where judgment and knowledge are weakest - by showing the way in which the known separate system parts interact to produce unexpected and troublesome overall system results.
- Enough information is available for this experimental model-building approach without great expense and delay in further data gathering.
- The "mechanistic" view of decision making implied by such model experiments is true enough so that the main structure of controlling policies and decision streams of an organization can be represented.
- Industrial systems are constructed internally in such a way that they create for themselves many of the troubles that are often attributed to outside and independent causes.
- Policy and structure changes are feasible that will produce substantial improvement in industrial and economic behavior; and system performance is often so far from what it can be that initial system design changes can improve what causes losses in one area in exchange for gains in another.

Dynamic system model contain four essential features:

- Several levels or accumulations within the systems; e.g. - inventories; number of employees, work in process.
- Flows rates that transport the contents of one level to another.
- Decision functions that control the rates

of flow between levels.

- Information channels that connect the decision function to the levels concerned.

Figure 22 depicts an example of the interaction of the major components of a dynamic system. In Figure 22, the solid line represent the flow channels and the dashed lines represent information sources. Not shown in Figure 22 are all of the associated delays with the various levels (shown is the delivery delay). For example, delays associated with hiring and training employees, manufacturing delays, delays in receiving raw materials, and production delays associated with the various levels and flows.

(Shown on page 54)

Expansion of the concepts presented by Forrester into an acquisition model would present a clear picture of possible problems, areas of likelihood of cost overrun, and disruptions. Thus, the main advantage of dynamic simulation is that it forces managers to crystalize their decision-making processes. This function cannot help but lead to greater insights into program acquisition.

However, the approach is not without disadvantages. Among these are:

- In simulation, all relevant variables and phenomena must be quantified. The reduction of all descriptive knowledge to quantitative measures is not always valid.
- Dynamic simulation is found to be most useful in price-quantity problems, less useful in organizational design, and least-useful in product-market strategy.
- Dynamic simulation is not easy to apply. It is a complex technique that needs considerable data and knowledgeable people.
- There are problems in acceptance of the approach because it is often considered a research tool.

Causal Integrative Model (CIM)

An extension of the Forrester type model is shown in Figure 22 which describes the processes, flows, variables, feedback loops, delays, exogenous variables and key decisions as they are related to the four basic variables in the acquisition process. As noted in the report, acquisition models currently being used do not address all of these variables, thus, each model lacks some degree of completeness.

Referring to Figure 23, the Causal-Integrative Model can be used to determine how a change in economic uncertainty affects the level of environmental uncertainty which, in turn, affects mission, scope, and funding. These changes perturbate the system to effect changes in organizational slack, technological uncertainty, and customer urgency. Thus, a change

in one variable can be shown to cause changes in the others through the pervasive network of interdependencies. These changes in the key variable impact the acquisition cycle in ways that are not intuitively obvious without the aid of a dynamic model to point out the causal relationships.

The direction in acquisition management prompted by this report leaves several facets to be completed:

- . development of a computer-based model for use, such as the CIM,
- . testing of the model with a completed program,
- . validation of the model using current programs,
- . implementing the model for policy level decisions in acquisition management.

In order to extend the research described above, additional research is needed to construct the Causal-Integrative Model.

CONCLUSION

The material presented in this report has attempted to highlight important advances that have been made in improving the acquisition process. Because of the pervasiveness of the subject, of necessity, not all relevant research of applications can be included. Rather, what has been presented here can be considered as indicative of the current state-of-the-art in acquisition management and a baseline approach for future developments.

At the outset, the report emphasized the need for a causal basis for understanding the factors that affect cost overruns. A number of illustrations were presented that clearly identify that cost growth is a phenomena that is related to the acquisition of complex projects, both civilian and military. Furthermore, that four primary variables contribute to cost. These include environmental uncertainty, technological uncertainty, customer urgency and organizational slack. The discussion pointed out that control as currently practiced, is not sufficient to avoid cost overruns. A number of research reports were reviewed which cover reasons for cost overruns, including an extensive study done at the University of Southern California which identified 26 factors contributing to cost overrun. Among the key contributors to incurring higher than budgeted costs are the four primary variables in the acquisition process described above.

Having established a basis for understanding why cost overruns occur, the next section of the report dealt with the risk and uncertainty aspects of the problem. A number of authors were cited to help define the sometimes abstruse terminology used in the field. This material provided a foundation for the section on a causal basis for defining uncertainty

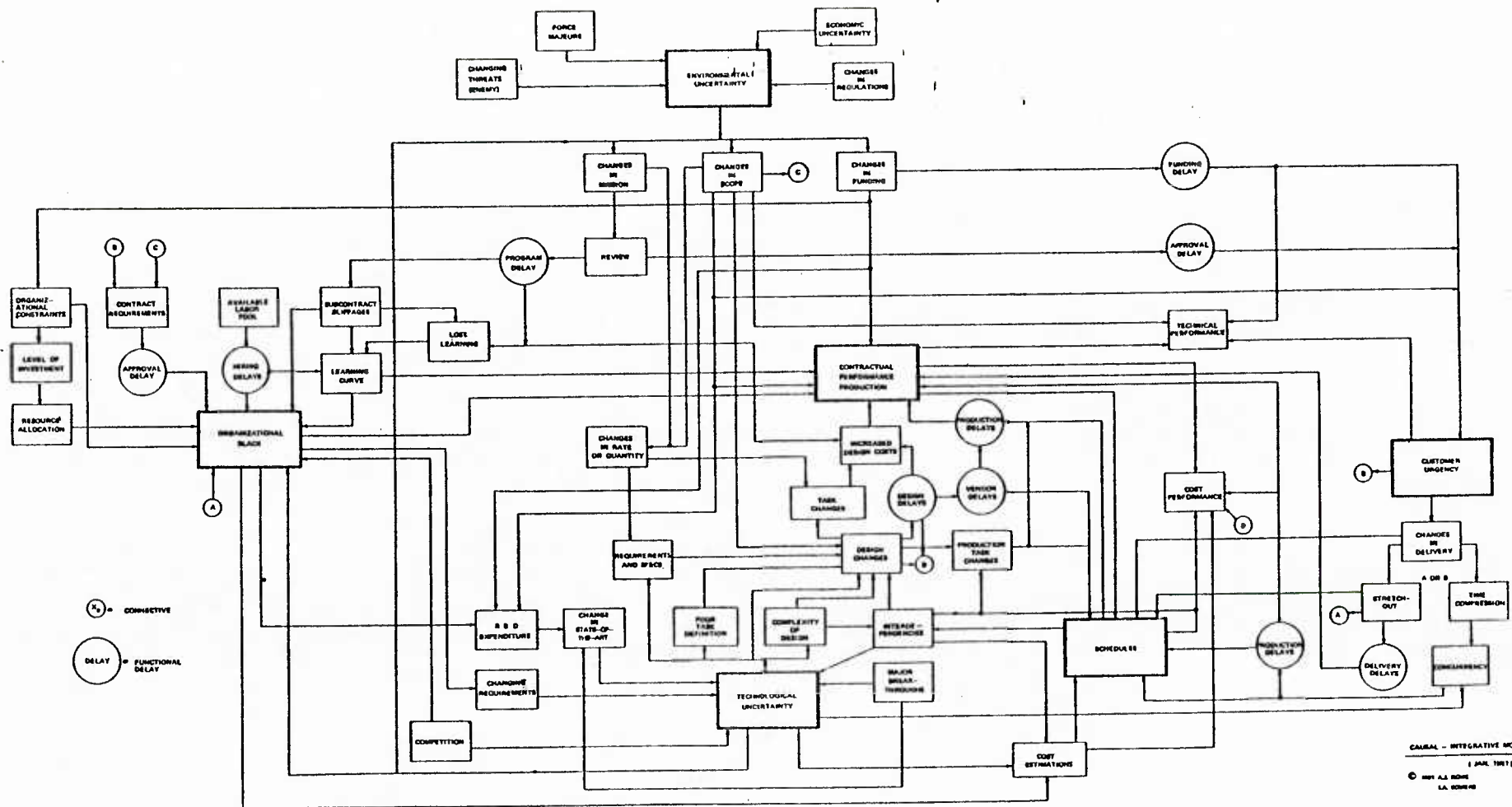
A number of studies were presented to help understand what causes uncertainty and how to approach it in the acquisition process. For example, it was pointed out that uncertainty and disruption cannot be eliminated, but rather can be controlled if there are causal models such as the RAND study relating cost to advance in state-of-the-art. Each of the four basic variables were examined in terms of developing models, measures or approaches to coping with the problems of uncertainty.

Given the foundation presented to this point, a set of causal relations among variables in disruption and uncertainty were examined in order to establish a "pattern of disruption". This was followed by the section on current approaches to acquisition modeling, including ones used for risk analysis.

The final section presented a "Causal-Integrative Model", which illustrates the complex relationships that exist among the variables that affect the acquisition process. Although this is a preliminary model, it provides a basis for integrating the approaches to date to managing the acquisition process. It includes many causal sub-models, such as concurrency, learning curve, disruption, etc. It also covers the dynamic interdependencies that exist and the treatment of risk and uncertainty as integral parts of the model.

Acquisition managers armed with more sophisticated tools can improve the effectiveness of their performance and thereby achieve the maximum potential cost control. Obviously, no set of tools or techniques is a substitute for management; however, the well informed manager can make decisions which have a greater likelihood of occurrence providing the bases used are sounder. The causal approach described in this report offers the potential for achieving this goal.

*Insert Bibliography after this



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BIBLIOGRAPHY A - METHODOLOGY AND THEORY

1. Allen, Wayne H., Should Cost/Will Cost/Must Cost: A Theory on cause of Cost Growth. U.S. Army Safeguard Office, Arlington, VA June, 1972.
2. Amdor, Stephen L., and Kilgore, Roy R. Quantitative Risk Assessment: A Test Case. Unpublished master's thesis, GSA/SM/74-1, School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 1974.
3. Anderson, David K. "Preparing for Production of a Major Weapon System" Defense Management Journal, Sept/Oct, 1979, p.20-24.
5. Augustine, Norman R. "Augustine's Laws and Major System Development". Defense Systems Management Review, Spring, 1979, p.50-76.
6. Balban, H. and Rettener, B. An Investigation of Contractor Risk Associated With Reliability Improvement Warranty. PRAM Program Office, Wright-Patterson AFB, OH. May, 1977. LD-41838A.
7. Busse, Daniel E., A Cost Performance Forecasting Model, ACSC-D370-77. Air Command and Staff College, Maxwell AFB, AL. May, 1977. AD/8019-568L.
8. Burt, David N., "Will Four-Step Solve the Problem?" Defense Systems Management Review. Winter, 1980. Vol 3. No.1 p.19-29.
9. Cheslow, Richard T. and Dever, James R. "Acquisition Costing in the Federal Government." Defense Systems Management Review. Autumn, 1979. Vol.2 No.4 p.7-16.
10. Clark, James C., Centralized Control: The Missing Ingredient in Multi-Service System Acquisition Management. ACSC-0415-79. Air Command and Staff College, Maxwell AFB, AL. May, 1979. AD/8D38-74DL.
11. Core, George N., Analysis of the Effectiveness of the Preproduction Evaluation Contract in Preventing Cost Overruns. CARCOM Intern Training Center, Texarkana, TX. May, 1976. AD/A024-818.
- Daly, G. G. et al. The Effect of Price Competition on Weapon System Acquisition Costs. Institute for Defense Analysis, Arlington, VA, 1979.
12. Davis, Guy W. The Dilemma of Uncertainties Associated with Cost Estimating in the Project Management Office, Defense Systems Management College, Ft. Belvoir, VA. May, 1976. LD-3642DA.
13. Defense Documentation Center, Cost Effective Analysis: Report Bibliography, DDC/818-78/01, Alexandria, VA, Apr., 1978. AD/A052-4DD.

14. Defense Technical Information Center, Cost Effectiveness Analysis, A DTIC Bibliography. report bibliography July 73-Feb 80, Alexandria, VA. July 1980. AD/A087 800.
15. Duvivier, G.F. "Technological Advances and Program Risks." Technological Forecasting and Social Change, Vol 2, No. 3-4, 1971. p-277-287.
16. Ellsworth, Roger W. USAF RDT & E Cost Growth: A Perspective, 630-79, Air Command Staff College, Maxwell AFB, AL. Apr, 1979. LD-45D86A.
17. Freeman, Rowland G., III. "Major Systems Developed: Lessons Learned." Program Manager's Newsletter, Jan/Feb, 1979, p.1-7.
18. Gibson, Robert G. "Concurrency". Defense Systems Management Review. Autumn, 1979, Vol 2. No.4 p.67-77.
19. Gordon, Harvey J. "The Role of the contract in Systems Acquisition." Defense Systems Management Review. Winter, 1980. Vol 3 No.1 p.30-42.
20. Harrison, EF, The Managerial Decision - Making Process. Houghton Mifflin Co., Boston MA, 1975.
21. Harvey, Thomas E. "Concurrency Today in Acquisition Management" Defense Systems Management Review Winter, 1980. Vol.3 No.1 p.14-18.
22. Hart, Steven L. and Ising, Terry R. 1977-1990 Technology Effects on NAVAIR Acquisition Management Concepts, NAFI-TR-2183, Naval Avionics Facility Indianapolis, IN. May, 1977. AD/BD18-391L.
23. Hill, Vaughn E. and Martin, Paul L. Life Cycle Costing: Its Promise and Problems. Air War College #5995, Maxwell AFB, AL. April 1976. LD-35957A.
24. Holland, Robert L., Role Definition in the Decision Making Process of Weapon Systems Acquisitions. Unpublished Master's thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH. Dec, 1970. LD-26233.
25. International Maritime Associates, Inc., A Study of Ship Acquisition Cost Estimating in the Naval Sea Systems Command, Executive Summary, Washington, D.C., Oct, 1977, AD/A046-976.
26. Jones, Julius E. An Analysis of Incentive Contracts With Respect To Risk. US Army Command and General Staff College, Ft. Leavenworth, KS. June 1971. LD-27535.
27. Kamrass, M. et al; Technical and Economic Analysis of Standardization and Independent Subsystem Development. Volume I. Institute for Defense Analyses, Arlington, VA. Dec., 1976. AD/AD4D-337.

28. Kelley, Albert J. "Can Weapon System Procurement be Managed?"
Defense Systems Management Review Autumn 1977, p.1-4.
29. Large, Joseph P., Bias in Initial Cost Estimates: How Low Estimates
Can Increase the Cost of Acquiring Weapon Systems. R-1467-PA/E.
RAND Corporation, Santa Monica, CA., July, 1974.
30. Launer, Robert L. et al. Cost-Growth-Effects of Contract Size,
Duration, Inflation, and Technology Level. Army Procurement
Research Office, Ft. Lee, VA. May, 1972. AD/746-620.
31. Lenox, Hamilton T. Risk Assessment Unpublished master's thesis,
GSA/MA/73-3, School of Engineering, Air Force Institute of
Technology (AU), Wright-Patterson AFB, OH, 1973.
32. Leon, Hayden L. Jr. The Ship Acquisition Process: an Inter-
organizational Perspective. Unpublished Master's thesis,
Naval Post Graduate School, Monterey, CA. March 1976.
LD-36971A.
33. Lev, Baruch, Financial Statement Analysis: A New approach,
Prentiss-Hall, Englewood Cliffs, N.J. 1974.
34. Lewis, Edwin H. and Pearson, Eugene, D. The Air Force Cost
Estimating Process: The Agencies Involved and Estimating
Techniques Used . Unpublished thesis, Air Force Institute of
Technology, Wright-Patterson AFB, OH. June, 1977. LD-39962A.
35. Lilce, Ralph W., Total Risk Assessing Cost Estimate (TRACE): An
Evaluation . U.S. Army Research and Development Command.
St. Louis, MO. Feb, 1979. LD-44065A.
36. Magee, Terry E. Differences in Aircraft Acquisition Management
Practices Between the Air Force and the Navy. Unpublished
thesis. Naval Postgraduate School, Monterey, CA: 1977
AD/A042-303.
37. March, Robert T. "The Impact of Today's Electronics Technology on
Systems Acquisition." Defense Systems Management Review ,
Summer 1979, p.97-102.
38. Mariutto, William F., Managing Cost Overrun Engineering Change
Proposals . Army Material Command, Texarkana, TX. Apr., 1975.
ADA009-183.
39. Marks, Kenneth E. An appraisal of Models Used in Life Cycle
Cost Estimation for USAF Aircraft Systems. Santa Monica, CA:
1978. RAND Corporation.
40. McLeod, Hugh S., The Accuracy of Air Force Weapon System Cost
Estimates as a Function of Time . Unpublished Master's thesis.
Air Force Institute of Technology, Wright-Patterson AFB, OH.
June, 1976. AD-A030-240.

41. Merrow, Edward W. A Review of Cost Estimation in New Technologies: Implications for Energy Process Plants . R-2481ODE. RAND Corporation, Santa Monica, CA. July, 1979.
42. Metcalf, Joseph. Cost-Overruns in Military Hardware: An Analysis of Cause . U.S. Army War College. Carlisle Barracks, PA. March, 1971. LD-26399.
43. Mills, Brian S. Understanding and Evaluating Life Cycle Cost Models (second edition). Air Force Systems Command, Wright-Patterson AFB, OH. March, 1977. LD-45159A.
44. Moeller, William G. Affordability For Major System Acquisitions . Washington: Logistics Management Institute, 1980.
45. Moeller, William G. et al. Accelerating the Decision Process in Major System Acquisition , Washington: Logistics Management Institute, 1979.
46. Montgomery, Douglas C., et al. Application of Decision/Risk Analysis in Operational Tests and Evaluation , Georgia Institute of Technology, GA, Sept., 1975. AD/A024-205.
47. Nelson, J.R. Life-Cycle Analysis of Aircraft Turbine Engines . R-21D3-AF, RAND Corporation, Santa Monica, CA. November, 1977.
48. Nelson, J.R. Performance/Schedule/Cost Tradeoffs and Risk Analysis for the Acquisition of Aircraft Turbine Engines: Applications of R-1288-PR Methodology . R-1781-PR. RAND Corporation, Santa Monica, CA June, 1975.
49. Oder, F.C.E. "Affordability and the Acquisition of Major Defense Systems". Defense Systems Management Review . Winter, 1980 Vol.3 No.1 p.7-13.
50. Ostronski, George et al, Simplifying Contracts for Commercial Systems: A Case Study of DoD Acquisition of Commercial Systems and Components , Don Dowle Assoc., Inc, Arlington, VA. Jan., 1980. LD-46487A.
51. Padgett, Thomas C. An Examination of the Relationships Between Inflation and Cost Overruns in Defense Contracts and the Adequacy of Various Types of Price Indexes in Explaining these Relationships . Unpublished dissertation, Air Force Business Research Management Center, Wright-Patterson AFB, OH. March, 1975. LD-31618A.
52. Pearce, Michael A., Prototyping: A Strategy for the Acquisition of Naval Aircraft . Defense Management Systems College, Ft. Belvoir, VA. Nov., 1976. AD/A035-357.
53. Perry, Robert L. et al, System Acquisition Experience RM-6072-PR, RAND Corp., Santa Monica, CA. Nov., 1969.

54. Press, S. James, et al Methodology for Subjective Assessment of Technological Assessment . R-1375 RAND Corporation, Santa Monica, CA. Apr., 1975.
55. Price, Joseph S and David, James C. Successful Communication in Full-Scale Engineering Development Statements of Work . Air Force Institute of Technology, Wright-Patterson AFB, OH. June, 1980. LD-47300A.
56. Proceedings, Seventh Annual Acquisition Research Symposium. Hershey, PA, May 31 - June 2, 1978.
57. Proceedings, Eighth Annual DOD/FAI Acquisition Research Symposium. Newport, RI, May 4-6, 1979.
58. Proceedings, Ninth Annual DOD/FAI Acquisition Research Symposium. Annapolis, MD, June 9-11, 1980.
59. Pyne, Ernest L. and James J. Lindenfelser. "USAF Trends in Weapon System Acquisition". Program Managers Newsletter , Oct., 1977, p.17-19.
60. Quade, E.S.; A Critique of Cost-Effectiveness . P-5524. RAND Corporation, Santa Monica, CA. Nov., 1975. ADA022-195.
61. Richardson, John H. "Defense Systems Acquisition: Working Toward Improving Process." Program Managers Newsletter , Oct. 1977, p.12-16.
62. Sellers, Benjamin R. Competition in the Acquisition of Major Weapon Systems . Unpublished thesis. Naval Postgraduate School, Monterey, CA 1979. AD/A078-268.
63. Sidney, W.A. The Defense Systems Acquisition and Review Council: A Study of Areas of Consideration Affecting the Functions and Process of Defense Major Systems acquisition . Unpublished report, University of Southern California, Los Angeles, CA. Sept, 1976. LD-9210A.
64. Spencer, David T. "Alternatives for Shortening the Acquisition Process." Defense Systems Management Review . Autumn, 1979 Vol.2 No.4 p.36-59.
65. Tateyana, Joseph T., A Defense Systems Acquisition Management Taxonomy and Inventory of Official Acquisition Management Documents . Defense Systems Management College. Ft Belvoir, VA, May, 1977. AD/A044 95B.
66. U.S. Air Force Audit Agency, Acquisition of Selected Surveillance and Control Programs, Norton AFB, CA, Jan, 1980. LD-45893A.
67. U.S. Army Material Development and Readiness Command, Acquisition Strategy Development , in-house study, Alexandria, VA. Sept., 1980. LD-46766.

68. U.S. Congress. Congressional Budget Office. Shaping the General Navy of the Eighties: Issues for Fiscal Years 1981-1985 . U.S. Govt. Print. Off. Washington, D.C.
69. U.S. Congress. House. Committee on Government Operations. Inaccuracy of Department of defense Weapons Acquisition Cost Estimates . Hearings before a subcommittee, 96th Cong., 1st sess. June 25 and 26, 1979. Washington: U.S. Govt. Print. Off., 1979.
70. U.S. Congress. House. Inaccuracy of Department of Defense Weapons Acquisition Cost Estimates . Report of the Committee, 96th Cong., 1st sess. Nov. 16, 1979. H. Rept. 96-656. Washington: U.S. Govt. Print. Off., 1979.
71. U.S. General Accounting Office, FAA has Not Gone Far Enough With Improvements to its Planning and Acquisition Processes. PSAD-80-42. Washington, D.C. June 4, 1980.
72. U.S. General Accounting Office, Financial Status of Major Federal Acquisitions September 30, 1978 PSAD-79-14, Washington, D.C. January 11, 1979.
73. U.S. General Accounting Office. Impediments to Reducing the Costs of Weapons Systems , PSAD-80-6. Washington, D.C. November 8, 1979.
74. U.S. General Accounting Office. Implications of Highly Sophisticated Weapon Systems on Military Capabilities . PSAD-80-61. Washington. D.C. June 30, 1980.
75. U.S. General Accounting Office. Implementation of Major System Acquisition Process-A-109-Is Inconsistent Among Civil Agencies. PSAD-79-89. Washington, D.C. August 14, 1979.
76. U.S. General Accounting Office. Issues Identified in 21 Recently Published Major Weapon System Reports . PSAD-80-43. Washington, D.C. June 12, 1980.
77. U.S. General Accounting Office, Lessons Learned from Constructing the Trans-Alaska Oil Pipeline . EMD-78-52. Washington, D.C. June, 1978.
78. Venzke, Gene A., Implementation of Risk Assessment in the Total Risk Assessing Cost Estimates (TRACE) . Unpublished thesis, U.S. Army War College, Carlisle Barracks, PA. May 1977. LD-39206A.
79. White, Richard P. and Myers, Myron G. Competition in DoD Acquisitions . Logistics Management Institute, Washington, D.C. May, 1979. LD-45320A.

80. Air Force Business Research Management Center, Semiannual Business Research Report . Wright-Patterson AF8, OH. Periodical Report.
81. Allen, Wayne H., Should Cost/Will Cost/Must Cost: A Thory on the cause of Cost Growth, Office of the Assistant for cost Analysis, U.S. Army Safeguard system office, Arlington, VA. June, 1972.
82. Arvis, Paul F. Business/Procurement Strategy , US Army Procurement Research Office, Ft. Lee, VA. Jul 1980(est.) LD-41596.
83. Babiarz, Anthony S., and Gredras, Pekar W. A Model to Predict Final Cost Growth in a Weapon System Development Program . Unpublished master's thesis, SLSR 49-75B, School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AF8, OH, 1975.
84. Baker, B.N. Improving Cost Estimating and Analysis in DoD and NASA Unpublished OPA dissertaion. George Washington University. Jan., 1972.
85. Betaque, Norman E., Jr., et al. Manpower Planning for New Weapon Systems . Logistics Management Institute, Washington OC, 1978.
86. Severly, J.G, Bonello, F.J. Davison, WI "Economic and Financial Perspechioes on Uncertainly in Aerospace Contracting", paper presented at the 2nd symposium at the on management of Risk and Uncertainty in the Acquisition of major Programs. USAF Academy, February, 1981.
87. Blandin, J.S. and Brown, W.B. Uncertainty and Management's Search for Informatin. IEEE Transactions on Engineering Management . Vol EM-24 Nov., 1977. p.114-119.
88. Brown, R.A. "Probabalistic Models of Project Management with Design Implications," IEEE Transactions on Engineering Management . Vol EM-25, May, 1978. p.43-49.
89. Burstein, A.W., Cost Estimating Research Methodology , in-house study, Naval Air Oevelopment Center, Warminster, PA. On-going. DTIC Accession number: DN181022.
90. Burt, J. M., "Planning and Dynamic Control of Projects Under Uncertainty", Management Science , Vol 24. Nov., 1977 p. 249-258.
91. Chapman, C.8. "Large Engineering Project Risk Analysis", IEEE Transactions on Engineering Management . Vol EM-26 Aug, 1979 p.78-86.
92. Cockerham and Associates, Inc.; U.S. Army Total Risk Assessing Cost Estimate (TRACE) Guidelines . Hopewell, VA, Dec. 1976. AO/A036-327.

93. Cochran, Edward B., Patz, Alan L., and Rowe, Alan J. "Concurrency and Disruption in New Product Innovation," California Management Review, Vol. XXI No.1 Fall, 1978. p.21-33.
94. Cochran, Edward B., and Rowe, Alan J. "The Sources of Disruption to Project Cost and Delivery Performance", Proceedings of Eighth DoD Symposium on Acquisition Research. West Point, NY 1978.
95. Cochran, EB. Production Planning Costs - Using the Improvement curve, Chandler Publishing Co. 1968.
96. Cochran, EB. "Measuring and Predicting Production Disruption costs Due to Design Uncertainty and Delivery Urgency" Proceedings of Ninth Annual DoD/FAI Acquisition Research Symposium June, 1980.
97. Cooper, Virgil L., An Investigation of the Software Allocation Process in the Acquisition and Management of a Major Defense system, Unpublished Master's thesis, AFIT/GSM/SM/795-2, Air Force Institute of Technology, Wright-Patterson AFB, OH, Sept., 1979, AD/A076-0978.
98. Corley, Parris L. and Roscoe, Arthur J., Cost Control in Air Force Systems Acquisition. ACSC-5560 Air Command and Staff College, Maxwell AFB, AL. April, 1975. AD/B003-9366.
99. Coyle, R.G. Management System Dynamics, John Wiley & Sons, Ltd. London, 1977.
100. Cummins, J. Michael, Incentive Contracting for National Defense: A Problem of Optimal Risk Sharing. Ph.D Dissertation Northwestern University, Evanston, IL. Aug., 1976.
101. Dienemann, Paul F. Estimating Cost Uncertainty Using Monte Carlo Techniques. Santa Monica, California: The RAND Corporation, 1966.
102. Drake, Hudson B. "Major DoD Procurements at War With Reality" Harvard Business Review Jan.-Feb., 1970. p.119-140.
103. Dye, John H., Methodology Investigation: Risk/Cost Benefits Associated with Elimination of R and D Test Phases, APG-MT-4475 Aberdeen Proving Ground, MD, June 1974, AD/B000-129L
104. Edwards, Ward; John, Richard; and Stillwell, William, Research on the Technology of Inference and Decision, Decisions and Designs, Inc. McLean, VA, Nov. 1977. AD/A056-921.
105. Fabian, Felix M., Jr. and Franck, Raymond E. Jr. "A Portfolio Approach to Systems Acquisition." National Contract Management Quarterly Journal. 1st Qtr 1978, p.97-113.
106. Forrester, Jay W., Industrial Dynamics, MIT Press, Cambridge, MA., 1961.

107. Frischhoff, Baruch; The Art of Cost-Benefit Analysis, Decisions Decisions and Designs, Inc., McLean, VA. Feb, 1977. ADA041-526.
108. Frysinger, Thomas C., A Production Entry Approach to Weapon System Acquisition, ACSC-0975-75, Air Command and Staff College, Maxwell AFB, AL. May, 1975. AD/8005-367L.
109. Gansler, Jacques S. "A new Dimension in the Acquisition Process." Defense Systems Management Review, Autumn 1977, p.6-12.
110. Glover, William L., and Lenz, John D. A Cost Growth Model for Weapon System Development Programs. Unpublished master's thesis, SLSR-22-748, School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 1974.
111. Graves, S.B. A Monte Carlo Risk Analysis of Life Cycle Cost Prediction, unpublished Master's Thesis, Air Force Institute of Technology, Wright-Paterson AFB, OH Sept., 1977 AD/AD21-677.
112. Grayson, C. Jackson, Jr. Decisions Under Uncertainty. Boston: Harvard University, 1960.
113. Grayson, Anthony A. and Landos, Harold J., A Methodology for Subjective Assessments of Probability Distributions, Unpublished master's thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH. Sept. 1976. (Contains an extensive bibliography.)
114. Greenberg, J.S. "Risk Analysis----in Space Mission Decision Making". Astronautics and Aeronautics, Vol 12, Nov., 1974. p.48-57.
115. Greicken, J. and Milne, J.F., Prediction and Control in Program Management, Naval Air Systems Command, Washington, D.C. Feb, 1978. LD-42D4DA.
116. Grimm, Richard W, Using Cost Analysis to Break the Overrun Habit. Defense Systems Management College, Ft. Belvoir, VA. May, 1977. AD/A042-935.
117. Haese, Edward J. "How Useful Are Historical Costs?" The Air Force Comptroller. July, 1977 p.34-36.
118. Harman, Alvin J. A Methodology for Cost Factor Comparison and Prediction. Santa Monica, California: The RAND Corporation, 1970.
119. Harman, Alvin J., Measurement of Technological Innovation by Firms. P-5496. RAND Corporation, Santa Monica, CA. Sept. 1975. AD/A021-712.
120. Henry, Douglas D. A Statistical Analysis of the Effectiveness of Program Initial Conditions As Predictors of Weapon System Acquisition Program Success, unpublished Master's thesis, Naval Postgraduate School, Monterey, CA. Dec., 1976. LD-39497A.

121. Higgins, J. Alan. An Outlook on Future Weapon Systems Acquisition, Defense Systems Management College, Ft. Belvoir, VA. Nov., 1977. LD-41076A.
122. Jenkins, Gwilym H., Jr. Decision Criteria for Cost-Plus-Award-Fee Contracts in Major Systems Acquisitions. Unpublished thesis. Naval Postgraduate School Monterey, CA, 1979. AD/A070-092.
123. Jewell, William A., Planning and Control Under Risk, U.S. Army Research Office, Research Triangle Park, NC. Aug. 1976. LD-39261A.
124. Jones, Harry, and Twiss, Brian C. Forecasting Technology for Planning Decisions. Petrocelli Books, Inc. New York, N.Y. 1978.
125. Keefer, D.L. "Allocation Planning for R&D With Uncertainty and R&D With Uncertainty and Multiple Objectives," IEEE Transactions on Engineering Management, Vol EM-25. FEB., 1978 p.8-14.
126. Leech, DJ, and Earthrowe, D.L. "Predicting Design Costs," Aeronautical Journal. Sept. 1972.
127. Lincoln, James B. Managing Total Acquisition Time: A New Priority for Major Weapon Systems. Defense Systems Management College, Ft Beloir, VA. May, 1977.
128. Linton, P. Models of Systems Cost Effectivness. in-house study, Naval Air Development Center, Warminster, PA. On-Going DTIC Accession Number: ON081489.
129. Lochry, Robert R. et al, Final Report of the USAF Academy Risk Analysis Study Team, US Air Force Academy, CO. Aug. 1971. AD/729-223.
130. Lowell, David H. System Acquisition: A Presentation of Philosophical Approaches and Need Determination for Air Force Planning Consideration. Air War College, Maxwell AFB, AL. Apr., 1976. LD-38604AZ.
131. Mann, Greg A. "VERT: A Risk Analysis Tool for Program Management" Defense Management Journal. May-June 1979. p. 32-36
132. Marschak, Thomas, et al, Strategy for R&D: Studies in the Microeconomics of Development. RAND Corporation, Santa Monica, CA. 1967.
133. Martin, David P and Kaffenberger, Susan A. A Dynamic Policy Model of the Department of Defense Acquisition Process. Unpublished thesis. Air Force Institute of Technology, Wright-Patterson AFB, OH. June, 1979. LD-44970A.

134. Martin, Martin D., A Conceptual Cost Model for Uncertainty Parameters Affecting Negotiated Sole Source Development Contracts . PhD thesis. University of Oklahoma, Norman, OK. 1971. AD/A035-482.
135. Martin, Martin D., Leng, Joseph D. and Glover, William L., "Uncertainty Analysis for Program Management," Project Management Quarterly , Vol. VI, No.3 (1975), pp. 15-18.
136. Martin, MD, Glover, WL, and Lenz, JO, "The Status on Uncertainty Measurement for the Development Contract," National Estimating Society Journal, Fall, 1977.
137. McIver, D.W. et al A Proposed Strategy for the Acquisition of Avionics Equipment . R-1499-PR. RAND Corporation, Santa Monica, CA. Dec, 1974.
138. McNicols, G.R. On the Treatment of Uncertainty in Parametric Costing . Unpublished PhD dissertation, George Washington University, Washington, D.C. 1976.
139. McNichols, Gerald R., "Treatment of Uncertainty in Life Cycle Costing". Proceeding IEEE 1979 Annual Reliability and Maintainability Symposium . p.56-61.
140. Merrifield, D. Bruce, Strategic Analysis, Selection, and Management of R and D Projects. AMACOM, New York, N.Y. 1977.
141. Mitchell, Terrence R., Uncertainty and Decision-Making , Washington University Dept. of Psychology, Seattle, WA, Sept. 1979 AD/A074-D72
142. Morris, John M. et al. Aggregating and Communicating Uncertainty . Pattern Analysis and Recognition Corporation, Rome, N.Y. Apr., 1980. AD/A086-987.
143. Dsterhus, Damond L. and Lawson, Diann. A Conceptual Model of the Department of Defense Major System Acquisition Process. Unpublished thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH. June 1978. LD-43088A.
144. Dstwald, Phillip F. Cost Estimating for Engineering and Management . Prentice-Hall, Inc. Englewood Cliffs, NJ. 1974.
145. Peck, Merton J., and Frederic M. Scherer. The Weapons Acquisition Process: An Economic Analysis . Boston: Division of Research, Graduate School of Business Administration, Harvard University, 1962.
146. Perry, Robert et al. Systems Acquisition Strategies , R-733-PR/ARPA, RAND Corporation, Santa Monica, CA. June, 1971. AD/73D-921.

147. Peterson, Stephen P. Numerical Methods for the Evaluation of Potential Research and Development Contractors . Texarkana, TX: Army Materiel Command, 1975.
148. RAND Corporation, Laser Systems Cost Analysis Study , On-Going Study, Santa Monica, CA. DTIC Accession Number: DF169840.
149. Riple, J.C. Jr Technical Risk Management in Advanced Technology Development . PhD dissertation. University of California, Los Angeles, Los Angeles, CA. 1977.
150. Riverside Research Institute, Investigation of Cost and Schedule Implications of New Technology in Support of BMD/Critical Functions . On-Going Study, New York, N.Y. DTIC accession number: DA058783.
151. Roesch, N. and sage, AP, "Systems Engineering Methodology for Defense System Acquisition" Proceedings of Ninth annual DOD/FAI acquisition Research Symposium. June, 1980.
152. Ross, Frank W., A Cost-Effectiveness Model: Choice Through Preferences . Army Aviation Systems Command, St. Louis, MO., Feb, 1975. AD/A006-205.
153. Sapp, R.S. The Procurement Process and Program Cost Outcomes: A Systems Approach . PhD dissertation, Purdue University, Lafayette, IN. 1971.
154. Simpson, F.S. Measurement of Technical Performance in Weapon System Development Programs: A Subjective Probability Approach. RM-5207-ARPA. Santa Monica, California: The RAND Corporation, 1968.
155. Slay, Alton D. "Working to Improve the Defense Acquisition Business." Contract Management , Oct., 1979, p.6-9.
156. Smith, Giles K. Air Force Acquisition Options For the 1980s: a Briefing on Study Plans . RAND Corporation, Santa Monica, CA. 1979 N-124-AF.
157. Sobel, S. A Computerized Technique to Express Uncertainty in Advanced System Cost Estimates . Bedford, Massachusetts: The Mitre Corporation, 1965
158. Solinsky, Kenneth S. "Controlled Competition for Optimal Acquisition". Defense Systems Management Review . Spring, 1980. Vol.3 No.2 p.47-55.
159. Spencer, David T. Alternatives For Shortening the Systems Acquisition Cycle: Milestone 0 to DSARC II. Unpublished research paper. Air Command and Staff College, Air University, Maxwell AFB, AL, 1979.

160. Stanley, William L. and Miller, Michael D. Measuring Technological Change in Jet Fighter Aircraft . R-2249-AF. RAND Corporation, Santa Monica, CA, Sep., 1979.
161. Stiles, Charles. "Formulating Improved Figures of Merit in Aircraft Acquisition". Defense Management Journal , 1st Qtr 1980, p.56-60.
162. Summers, Robert. Cost Estimates as Predictors of Actual Weapons Costs: A study of Major Hardware Articles . Santa Monica, California: The RAND Corporation, 1965.
163. System Development Corporation. Risk Assessment Methodology . Rept-SDC-TM-WD-7999/001/003 McLean, VA. July, 1979. ADAJ72-249.
164. Thomas, Thomas N., VERT- A Risk Analysis Technique for Program Managers. Defense Systems Management College. H. Belvoir, VA. May, 1977. LD-40483A.
165. Timson, F.S. and Tihansky, D.P. Confidence in Estimating Airframe Costs: Uncertainty Assesment in Aggregate Predictions . R-903-PR RAND Corporation. Santa Monica, CA Oct 1972.
166. U.S. General Accounting Office, A Range of Cost Measuring Risk and Uncertainty in Major programs --- An Aid to Decision-Making , PSAD-78-12, Washington, D.C. Feb. 2 ,1978.
167. U.S. Government, Department of Defense Directive Number 5000.1, Major Systems Acquisition . Washington, D.C. Jan 18, 1977.
168. U.S. Government, Department of Defense Directive Number 5000.2, Major Systems acquisition Process , Washington, D.C. Jan 18, 1977.
169. U.S. Government, Office Management and Budget, OMB Circular A-109, Major System Acquisitions . Washington, D.C. April 5, 1976.
170. Vemuri, V., Modeling of Complex Systems: An Introduction . Academic Press, New York, NY. 1978.
171. Wales, Norman, The Pentagon 'Four-Step' , Mitre Corp., Bedford, MA, March, 1978. AD/A053-963.
172. Yanke, Michael A. Methodology for Estimating Jet Engine Costs Early in Weapon System Acquisition , Contract Management Division, Kirtland AFB, NM. Aug, 1976. LD-37184A.
173. Zabinsky, J.M. et al, Design Definition Study of a NASA/Navy Lift/Cruise Fan Technology V/STOL Airplane: Risk Assessment Addendum to the Final Report . Boeing Commercial Airplane Co., Seattle, WA. June, 1975.

APPENDIX

As an adjunct to the research report, a survey of various government agencies, military services, contractors, and university faculty was conducted. The goal of the survey was to summarize methods currently being used or proposed to be used in the analysis of risk and uncertainty in major program acquisitions. As expected, many of the approaches relied on DoD Directives 5000.1 and 5000.2 along with DMB Circular A-109.

The following comments were either excerpted directly from the returned questionnaire or were summarized by the authors.

- . This respondent is not involved in the acquisition process, but does perform economic analyses in support of it. Encouraged in the use of sensitivity analyses or "what if" types of approaches. The prime tool is the net present value approach (NPV) of different investments using inputs concerning major uncertainties. If changing the risk changes the rankings of the NPV analysis, the factor is considered sensitive for subsequent analyses.

Also included from the respondent was a copy of proposed legislation HR 8303 dated October 2, 1980. This bill would establish coordinated program under the direction of the Office of Science and Technology Policy for improving and facilitating the use of risk analysis by those Federal Agencies concerned with scientific and technological decisions as related to human life, health, and protection of the environment. The bill would require that research be done to meet the objectives defined within the bill. These objectives deal with establishing criteria and methods for risk analysis.

- . Several different techniques are used by this group. These include:
 - . establishing management reserves for contingencies
 - . cost and schedule variance reporting using C/SCSC (Cost/Schedule Control System Criteria)
 - . use of program "baselines" which establish program cost-levels to carry out the program

Noted that formal approaches on risk and uncertainty are limited in usage within DoD

- . A bidding division provides the corporate offices with details of the customer's request for proposal (RFP) for independent review and comment. Discussions ensue on high risk areas on how to minimize the risk through contract terms or price considerations. Corporate level approval is obtained via a proposal/pricing review meeting where risks and treatments of risk are

discussed. Corporate approval usually carries certain qualifying guidelines. Any departures from these guidelines during competition must be reviewed and approved.

- . Risk assessment (reduction?) is considered and incorporated as follows:

- . Need for a validation period for critical components/segment
- . Need to maintain multiple sources through the validation plan, and through full scale development if risks are sufficiently low
- . Extent of testing (number and types) with rules for operational evaluation testing being employed
- . Extent of testing and demonstration prior to committing to production
- . Type of contract (cost vs. fixed price) and type of incentive to recognize risk and drive contractual efforts towards technical solution

Mainly employs Dod 5000 series.

- . Describes a general management approach for addressing Dod's affordability problem in the procurement funding area LMI report RE903 "Affordability for Major Systems Acquisitions" Jan 1980. The affordability analysis procedure is based on the use of an affordability matrix for the procurement analysis of each service. The matrix allocates forecasted procurement resources to programs for a 15-year period based on program priority and cost, thereby establishing a 15-year baseline procurement program for each service. This procedure could lead to stable funding for high priority programs and identification of unaffordable procurement programs.

- . Computer-based approach that used a prior established upper and lower bounds costs for subsystem. (eg. airframe engine control & guidance, etc.). A beta distribution is fitted to the upper, lower, and most likely estimates of costs. Subsystem costs are then aggregated using Monte Carlo Simulation.

- . Study under way (Study completion date in 1981)

- . DoD funded study involves interviews with strategic planners and procurement managers regarding the process and content of strategic planning efforts by prime contractors to identify sources of material, product and technological risk among lower tiers of the industrial base and develop proactive, entrepreneurial programs to help reduce that risk. Desired output is a viable and responsive multi-tier industrial base for major problems. Specific risk issues involve critical materials

and capacities, manufacturing technologies, and interorganizational technology transfer.

- Developed a method of first order evaluation of a system cost which is applicable in the first months of a concept development effort. The method identifies the major contributors to cost and the factors that influence them. Reduction of cost risk requires knowledge of where the risks are. This approach developed by the respondent provides the identification of the risks within "reaction time". Utilizes engineering estimates (vs. parametric).
- Offers two methods: a) parametric cost estimation technique, and b) statistical sampling.

The parametric estimate utilizes "degree of analogy" as measured by Mahalanobis distance (defined as the distance between two multivariate populations. The two populations are the predictor variable space and the historical variable space). The approach selects a data base and appropriate predictor variables to predict the cost of a major program based on historical costs of related programs.

The statistical sampling approach is constrained to sole source pricing. It uses a suitably selected sample of proposals from a sole source to price out an entire backlog. It is shown that classical statistical procedures are vulnerable to gamemanship and this new approach is invulnerable to this since the user controls the risk with sample size and sample stratification.

- Preliminary study that analyzes acquisition costs as a function of production rate and the quantity produced.

Appears to pick up cost growth as related to customer urgency (production rate) and scope changes (quantity produced).

- Program using cost, technical, and schedule analyses in support of development and full production of a battlefield system.

In-house and external agencies perform analyses at prescribed stages in the acquisition cycle (See Dodd 5000.1,.2). These analyses use the appropriate analytical tools for the stated study objective including C/SCSC (Cost/Schedule Control System Criteria), VERT (Venture Evaluation and Review Technique - a quantitative "CPM" - type of approach) and other operations research systems analyses techniques.

- Uses an approach called PROMAP. This approach is a network analysis technique

similar to PERT and CPM but is probabilistic rather than deterministic like CPM and PERT. PROMAP is a simulation program to aid in decision-making regarding risk in the areas of cost and schedule (does not look at technical risk or address causality).

- The methodology is being used to reduce risk and uncertainty on program costs and schedules (again, lacks technical risk) through application of the Draft RFP. Potential contractors are encouraged to challenge requirements that are considered significant "cost drivers" and to suggest revisions to performance, schedule, or other contractual requirements that could enhance program/project performance.

In addition to the DRFP, Business strategy panels are convened prior to the issuance of a formal RFP. The panel discusses acquisition problems, desired type of contract (FPI, CPFF, etc.) and other relevant aspects to this point in the cycle.

Based on overall risk assessment, the type of contract is determined (incentives, fee sharing, etc.) which may be influenced to some degree by the contractor.

- Uses C/SCSC which required detailed planning of work tasks by cognizant people at the operational level in terms of anticipated resources to be anticipated to be expended for successful completion (C.O.P. cost to complete).

Looks at variance of cost and schedule and performance against the current plan. Identifies causes of variances to the plan, impacts of variances, recommends action, and probable new plan. Manages risk on an exception basis.

- Because of the variety of programs, respondent indicates that no standard approach is desirable. Instead, each program is handled as a case-by-case approach where management reviews the risk and uncertainty prior to the commitments and at intervals throughout program life. The intervals are pre-established but reviews can occur upon indication of a potential change in risk caused by either internal or external reasons. At critical points, these reviews are made with the inclusion of ad hoc groups of individuals not directly associated with the program.
- The approach is to consider uncertainty ubiquitous, and to treat it descriptively, as a characteristic of variables of interest. Develops the term "Parametric Factor Evaluation" (PFE) as a process of identifying variables of interest describing the nature or form of the uncertainty of

concern, and for examining available information to arrive at the required or desired decision.

- . Manages risk and uncertainty in the acquisition of major programs by various methods and techniques authorized by Defense Acquisition Regulations (DARs). The regulations provide the use of various types of contracts depending on the degree of risk and uncertainty (did not state how the degree is obtained). In addition various forms of escalation clauses are utilized in long term major contracts to cope with uncertainty and degree of inflation as well as labor and material cost increases.
 - . Risk and uncertainty are assessed at the outset of every program. They are judged mostly by experience on previous programs and how far current technology would be extended in each approach considered. Cost and schedule risk are tied directly to performance goals and difficulty of achievement vis-a-vis current technology.
 - . Describes three approaches currently being used:
 - . SCARA - Schedule/cost Risk Assessment which is a detailed program simulation model used to predict budget requirements.
 - . Estimate at completion: statistical curve fitting routine based on historical program cost and schedule data, used to predict program budgets and/or schedules.
 - . Parametric Cost Estimating: Models are used to attempt to accurately predict program runout costs.
 - . Describes a conceptual approach that:
 - . Uses a triangular frequency distribution to describe risk profile of each major cost element
 - . Convoluting these individual risk profiles into an overall risk profile for the program
 - . Uses the overall risk profile to establish the negotiation position for high risk (low definition) programs
 - . Manages program risk in shipbuilding by:
 - . Providing for adequate design schedule and iterate design;
 - . introducing shipbuilder and contractor support early in the program;
 - . commencing testing early at land-based engineering facilities;
 - . commencing detailed design before the lead ship contract is awarded;
 - . using cost reimbursement contracts in initial stages;
 - . using a lead yard-follow yard concept with the ship builder to ship builder to contractor liaisons relationships (in-yard or in-facility)
 - . bounding physical parameters for developing items.
 - . Just completed study resulted in this approach to assess the feasibility of developing an analytical model for use in selecting an acquisition strategy. Probability distributions of key parameters are determined by combining subjective assessment with information contained in an historical data base. From these, the expected result of pursuing a particular acquisition strategy is assessed through attributes addressing time, cost, affordability, technical risk, etc., together with the uncertainties associated with each. Tradeoffs among the varying attributes are accomplished by developing a multiattribute utility model tailored to reflect the needs and constraints of a particular program.
 - . Risk analysis program which is a basic Monte Carlo simulation model with input distributions from uniform to Weibull. Utilizes methods/techniques as established by the federal government in such documents as:
 - .OMBA-109
 - .DoDD 5000 Series
 - .USAF 7000 Series
 - .USAF ASCP 800-19
- Also utilize parametric analysis, C/SCSC
- . Apply project risk estimates as developed from the company's experience in marketing, designing, manufacturing and adjusting expected cash flows accordingly by adjusting discount rate, or, if possible, using certainty equivalent method of adjusting cash flows directly, so as not to compound effect of risk adjusted discount rate. Expected net present values of cash flows determines desirability of project under projected risk.
 - . Methodology involves use of Award Fee Type incentive for fixed price follow-ship contracts in order to encourage contractors to finish contracts on time, with high quality, within cost goals.
 - . A performance Measurement System is used based on the use of earned value of work performed. The system uses a computer data base developed by each using organization and program. The data is evaluated for schedule and cost variances for current and ITD periods of performance and at completion variance.
 - . In April 1976, the Office of Management

and Budget issued OMB Circular A-109 for the acquisition of major systems. The circular required that each federal agency adopt new procedures for early and complete evaluation of alternatives identified through the competitive process. One of the key objectives of the Circular is managing risk and uncertainty so that it remains within tolerable levels. This objective is met in several ways. First, in the development of an acquisition strategy, the project manager must recognize and make accommodations for risk and uncertainty that assures the proper relationship of risk sharing between Government and Contractors and establish a management system for identifying, analyzing, and evaluating risk throughout the acquisition process. Secondly, A-109 employs the use of short-term parallel contracts to further explore proposed alternatives and reduce the technical uncertainties. During contract performance emphasis is placed on the measures taken to progressively reduce risks. Finally, throughout the remainder of the process the head of the agency must assure himself that the risks have been evaluated and accommodated before approving the continuation of the acquisition at the key decisions points--selection of alternatives and approval to advance to test/demonstration, commitment to full-scale development, and commitment to full production, as appropriate.

Within GSA this A-109 approach is applied to major public buildings and ADP/Telecommunication system acquisitions whose estimated value is \$25 million or greater. Specific guidance for the acquisition of each type of acquisition has, or is, in the process of being developed.

BEHAVIORAL ASPECTS OF DECISIONS UNDER UNCERTAINTY
DURING WEAPON SYSTEMS ACQUISITION

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ABSTRACT

This paper addresses the results of a survey of the available sources of information concerning the behavioral aspects of decision-making, uncertainty, and risk analysis in the Department of Defense (DoD) acquisition process. The authors were able to determine that very little information exists that directly addresses small group behavior as related to the subject, that there is disagreement concerning optimizing group performance, and that better risk analysis data could be obtained if the group members were adequately trained and held responsible for the group decisions.

INTRODUCTION

There is a great deal of uncertainty associated with each stage of the acquisition process within the DoD. This uncertainty exists primarily in the areas of cost, schedule, and performance. Inability to successfully forecast in these areas has led to sometimes severe criticism of the acquisition process, in many cases creating adverse public opinion and a negative effect on U.S. defense capabilities. Current DoD policy requires that these uncertainties be continually considered throughout all phases of the acquisition process and that risks be minimized before a production decision is made. Department of Defense Directive (DODD) 5000.2 states "The program manager shall take positive action to continually assess program risk areas and to make or propose trade-offs in performance, cost and schedule to achieve the best balance." Also, "Contract type shall be consistent with the system program characteristics and shall give particular emphasis to the issues of risk and uncertainty to the contractor and government." The uncertainties involving the technological unknowns associated with the weapons system acquisition process require the manager to face more risk in his decision-making than exists in other areas of management.

It is appropriate at this point to define risk as it is used in relation to the acquisition process. It is "The probability that a planned event will not be attained within constraints (cost, schedule, performance) by

following a specified course of action." [1]

Much work has been done and continues to be done in the area of development of tools for assessing risk and for performing risk analysis. However, there is another very important aspect of decision-making under conditions of risk and uncertainty: the behavioral aspects associated with the decision-maker and his staff in the decision-making process under conditions of risk and uncertainty. Concern over this aspect led the Air Force Business Management Research Center to contract with the University of Dayton to conduct a penetration study in this area.

STUDY RESULTS

The objective of this study was to conduct a survey of the available sources of information in order to identify sources of knowledge and information about the behavioral aspects of decision-making, uncertainty, and risk analysis in the Department of Defense acquisition process. Throughout the survey, an effort was attempted to emphasize those topics and sources that can be directly related to the risk analysis and decision framework of the weapons system acquisition process as defined in DODD 5000.1 and DODD 5000.2. In addition, the study concentrated specifically on those topics and sources of information that address individual and small group behavior in the uncertain decision environment.

As a result of this contract effort, the study team also developed a catalog of sources of knowledge and information for use by acquisition managers and their staffs to improve their understanding of individual and small group behavior in the uncertain decision environment. This catalog is included as a part of the contract and addresses, in alphabetical order by author and/or topic, those articles that may be of interest to acquisition managers. In each case, in addition to the title, author, and source of the document, a complete abstract is provided in the catalog.

The contractor utilized the Defense Technical Information Center and the DIALOG Information

Retrieval Service from Lockheed Information Systems to provide listings and abstracts of appropriate documents. Key words used by the study team included risk, risk analysis, decision-making, uncertainty, small group behavior, group decision-making, etc., as entering arguments into the data bases. The remainder of this paper considers some of the more important observations derived from the literature review.

It was determined that in almost all cases in the weapons system acquisition process the opinion of experts based upon their experience is critical to the measurement of risk and uncertainty. These factors of risk and uncertainty as measured by expert opinion contribute to the subjective probability that an event will occur with a specific probability. Several authors were quite concerned with the reliability of so-called expert 'testimony'. Several others were very concerned about the ability to determine the relative accuracy of these estimates and none were able to suggest methods of determining the adequacy of the expert opinion. In fact, H. M. Parsons concluded that the reliance on system designers for the opinion and preferences of experts is foolhardy. Such experts may provide suggestive leads but are not reliable guides as demonstrated by repeated disagreement with objective data. In several technologies, the aggregated group opinion or consensus is used as the value to be entered in the risk analysis model. It is questionable whether or not this group response can be aggregated in a meaningful manner. There is no way to evaluate the aggregated group response. This creates some serious difficulties because generally group opinions are used as entering arguments in risk analysis models. There is evidence that external pressure to conform to the popular or top-level management preferences or a desire to avoid rocking the boat may seriously affect the group decision-making process. The impact of the leader upon the group was discussed by several authors and was generally agreed upon to be one of the most serious difficulties in evaluating the parameters for the risk assessment models. Another area that impacts on the accuracy of the subjective probabilities is the accountability of the participants. It was suggested that lacking accountability, a participant cannot blame nameless others for any findings he does not like. Several authors conclude that valid techniques to collect subjective judgments are neither available nor are they likely to be developed in the immediate future. Several also mentioned that at the present time a complete, well-documented, real-life case study of a major development program is still very much needed to bridge the credibility gap between practice and theory in the area of risk analysis.

There is even difficulty in developing subjective judgments within the contractor organiza-

tions. The contractor may have difficulty in getting his own experts to accurately transmit their perceptions upward to their superiors, if they perceive these values to be 'out-of-line'. If it is difficult for the contractor to develop subjective probabilities, it becomes impossible for the system program office who is responsible for the overall performance to evaluate the validity of these subjective probabilities. As time passes in the weapons acquisition process, there is indication that, should the contractor performance be below what is expected, the contractor may show great reluctance to provide unfavorable information to the system program office, especially in the situation like the A-10 where a company's virtual survival as a prime contractor may depend upon an impending production decision. Given that the data from the contractor is subject to wide variability--depending upon the level of expertise, the background in decision analysis, the background of the so-called experts in probability theory, the management philosophy of the company, and the importance of the contract--it is unlikely that the system program office would receive from the contractor highly credible data. If unacceptable data is received from the contractor, it is extremely difficult for the system program office to develop acceptable estimates for the risk analysis programs.

Presently, the decision-making systems or risk analysis programs are designed for the user and this would include, of course, the contractor and the system program office personnel rather than for the task at hand. Several authors indicate that it might be more cost-effective to develop specific risk analysis programs for specific programs based on the relative experience of the personnel at the contractor office, the system program office, and at the decision-making level.

Regardless of the sophistication, elaboration, or expertise of the scientists and engineers who are providing the scientific data that is entered into the risk analysis models, there is no indication at the present time that the modeling techniques are capable of handling irrational acts either by man or by nature. For instance, to have predicted that the United States would currently have 52 persons hostage in Iran, a friendly country only two years ago, is a problem that would probably not have been modeled two years ago. Pending Congressional findings, alterations that may delay production as much as 12 months with the associated rise in cost are difficult if not impossible to model in an objective manner. These particular difficulties have led many to believe that would be foolhardy to expect a valid risk analysis for every major program and therefore at the present time there are indications that in order to comply with the Department of Defense requirements many pro-

gram offices are merely giving risk analysis formal lip service.

Many authors were concerned about having experts assign particular values in the risk models when the personnel who were assigning these particular values had no particular stake in the results. Similarly, they were concerned with the values that would be utilized by those whose very jobs and/or careers could be significantly affected by the decision concerning a particular weapons system. In the area of weapons acquisition, specifically, there was a great amount of data that indicated that the experts were constantly overly optimistic.

In the area of small group behavior, it is interesting to note that a decision made by a particular group at a particular time on a particular subject could be altered at a later time on a similar subject. There appears to be a number of outside, interactive forces that can impact upon the decision arrived at by a single group. As far as group decisions, it is generally conceded that group decisions are better than individual decisions. This is based primarily on the group dynamics and the interaction of the participants within the group. Additional data supports the synergism of group dynamics. Several authors show how to improve this synergism and almost all agree that the groups are more risky than the individuals. However, there are presently no formal screening or evaluation procedures or computer programs that can evaluate the decisions made by the individual groups. In developing group solutions, there is a great dependence upon the group members asking the right questions and then being able to answer these questions in a scientific manner. Again, given the fact that the right questions are asked and the right answers are given, there is difficulty in measuring the effectiveness of these particular numbers as applied to the risk analysis process. There are indications that individual group members may concern themselves more with reaching consensus than with the quality of the agreed judgment. Various factors--such as individual dominance through personality characteristics or rank or position within the organization--may influence the judgment of the individuals in the group and therefore the group consensus. This is particularly of interest since the individual characters in the drama are irrelevant to the task and/or the evaluations or numbers that are to be provided for the risk analysis. The researchers investigated several behavioral interaction techniques including the Delphi method, the nominal group technique, the modified nominal group technique, the consensus technique, and the no interaction technique. Authors differ as to which provides the best group solutions. Some favor the Delphi method and some the nominal group technique. In order to improve the group consensus--and here when

we speak of the group consensus, we are talking about a group of experts--it was suggested that possibly the training of these experts in probabilistic thinking could lead to significant improvement in their quantification of uncertainty. One author seemed to indicate that interaction tends to increase the certainty of the group, decreases the calibration, and decreases disagreement among group members. However, in many instances, simple averaging of individual assessments without any group interaction may be the most desirable, simply because it is the easiest to use.

CONCLUSION

The authors were able to determine that there was very little information that directly addressed the small group behavior in uncertain decision environments such as the acquisition process. There was great disagreement among experts concerning the validity of the different group dynamics processes. All generally agreed that better data for risk analysis models could be obtained if personnel could be trained in probabilistic methods and would be held responsible for the decisions that resulted from the output of the group analysis.

REFERENCES

1. Col. Robert R. Lochry et al, "Final Report of the USAF Academy RISK Analysis Study Team," Colorado Springs, CO, August 1971.

AN EVALUATION OF THE DEFINITION, CLASSIFICATION AND STRUCTURE OF PROCUREMENT RESEARCH IN THE DOD

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INTRODUCTION

Extensive research has been accomplished in the name of procurement research over the past few years but no definitive, delimited concept has evolved as to what constitutes procurement research (15). A review of the early Department of Defense (DOD) Procurement Symposia "Proceedings" indicated that professionals in the field of procurement called for a definition of the term "Procurement Research" as well as the classification of its characteristics into a model to provide more efficient use of resources. The need existed to clearly define procurement research and to classify its characteristics into a useable conceptual model. Consequently, a study was initiated at the Air Force Institute of Technology to accomplish these goals (4).

Research has been viewed by many in the field as a key to alleviating both existing and future procurement problems (2:1). Senator Stennis, Chairman of the Senate Committee on Armed Services, and Congressman Price, Chairman of the House Committee on Armed Services, reiterated this widely held belief in a joint letter to Former Defense Secretary Schlesinger:

"We recognize the value and importance of procurement research as a means of improving the procurement process-one of the most crucial tasks in Government (10)."

Even though there is a general consensus as to the importance and possible impact of research on the procurement process, procurement research as a discipline has not been clearly defined in existing literature and practice. Also, there is little agreement among the agencies performing this research as to what constitutes procurement research (1:2). There have been several indications as to a possible scope for procurement research; for example, J.M. Malloy, then Deputy Assistant Secretary of Defense for Procurement, described procurement research as essentially "a systematic approach" that follows the scientific method (8:215). However, there has not been a concerted effort to adequately describe what should be included. The result has been that research efforts are categorized as both tentative and diffuse (11:4).

Robert Judson, then Deputy Director of Commission Studies, Commission on Government Procurement (COGP), stated that procurement research's

". . .first order of priority . . .is to construct . . .a model so that we can share a consensus on procurement problems, . . .a comprehensive studious critical conceptual model for the acquisition process that will give us insights we do not now possess that will help us identify what we don't know (6:93)."

The importance of procurement research and the necessity of defining its role in government acquisition was reaffirmed in an interview with Robert F. Trimble, then Assistant Administrator, Office of Federal Procurement Policy (OFPP) for Contract Administration. He discussed procurement research as follows:

"I've long had an interest in procurement research. I think that it (an attempt to define and classify procurement research) is one that is particularly important because I have seen a considerable amount of confusion regarding what constitutes procurement research. I believe that this matter needs to be clarified so that we can more efficiently utilize the manpower resources that we have in this particular area (15)."

BACKGROUND

In the past, specific areas in procurement research have not been clearly delimited, thus, a historical background must concentrate on the procurement organizations which have developed during the past twenty-five years. The evolution of procurement research has been characterized by changes in organization and procedures. Research, per se, has not been emphasized; rather, the emphasis has been on the changes in DOD and Air Force procurement organization which resulted from the need for better procurement methods. The lack of a clear definition of just what procurement research includes made this approach necessary.

In the 1950's, various attempts were made to have money through reorganizing and centralizing purchases of common items. The inertia of old techniques was slow to yield to change; moreover each military

service was "isolated" from the others as far as procurement methods. In the 1960's, some efforts were made to exchange procurement information and to evaluate decision-making during the acquisition process. New approaches were being utilized to improve the management information flow. In the 1970's, many changes occurred in the formal acquisition process. After many long years of inefficiency and redundancy, the national procurement policy, education, and research are becoming centralized and coordinated under the Federal Acquisition Institute (FAI).

Mr. Robert Judson, then Deputy Director, Commission Studies, Commission on Government Procurement (COGP), in an address to the second DOD Procurement Symposium in 1973 made a challenge to the procurement profession. He said:

"You, gentlemen, have a golden opportunity to redirect procurement research to achieve new goals of excellence. First let's do our research on the problems of research before we lose the chance to make procurement what we want it to be (6.99)"

This challenge was re-emphasized by Dr. John J. Bennett, then Acting Assistant Secretary of Defense (Installations and Logistics) in the Defense Management Journal, July 1975:

"Procurement research is not yet a household phrase in the Department of Defense... It needs a great deal of attention from management and those people actually engaged in procurement projects (2:1)"

In summary, the important events in the evolution of procurement research start with the Second Hoover Commission in 1953 and continue up to the present time. Key events in procurement reorganization in the 1960's include the reorganization of Air Force Systems Command and Air Force Logistics Command, the Hershey Procurement Pricing Conference, the establishment of the Army Procurement Research Office, and the Commission on Government Procurement. The significant events (thus far) during the 1970's include the six DOD Procurement Symposia, the establishment of the Air Force Business Research Management Center, the addition of a Graduate Procurement curriculum to the Air Force Institute of Technology, School of Systems and Logistics, and a Systems Acquisition Management curriculum to the Naval Postgraduate School, the establishment of the Office of Federal Procurement Policy, and the founding of the Federal Acquisition Institute.

BASIC STUDY OBJECTIVES

The following research objectives of the study are germane:

1. To define procurement research so that a common foundation can be used when discussing this subject.
2. To classify procurement research efforts and functions into various areas and to identify those areas that are most frequently investigated.
3. From these classifications, to suggest a detailed algorithm¹ which can be used for deciding if an effort is procurement research.

METHODOLOGY

A literature review was initiated. It disclosed an increasing interest in the area of procurement research and in defining procurement research, but no suggestions were made as to how this specific area of research should be defined or how it should be classified from a taxonomical standpoint. A search disclosed that content analysis provided a rigorously subjective technique for grouping various procurement efforts: by division of scientific study, by breadth of application, by degree of control, by level of outcome, by level of effort, and by placement in the acquisition and procurement processes.² Through a system of summarizing and categorizing, these various groups were used to suggest a definition for procurement research.

The basic research design was divided into five areas:

1. Classifying procurement research efforts and functions into categories and sub-categories.
2. Identifying the areas of procurement research that were mostly frequently investigated.
3. Defining procurement research in terms of characteristics which were evidenced in the study.
4. Suggesting a taxonomy of procurement research.
5. Designing a procurement research algorithm for evaluating research.

The first three areas of the research design were planned to answer the first and second research objectives. The fourth and fifth design areas were planned to answer the second and third objectives.

The first design area was planned to identify specific scientific and research characteristics of procurement research as evidenced in the "Proceedings". Through content analysis, the articles of the

The results of the content analysis are limited to the actual sub-population itself, but the sub-population of the "Proceedings" represents an important cross-section of recent DOD procurement research experience. Information derived from the analysis of this sub-population can suggest important characteristics and relationships of other procurement research efforts.

The areas of emphasis in the procurement research of the "Proceedings" were identified in the content analysis. Procurement research was characterized as a social science with abstract science combined more often than not. Its structure is delimited in Figure 1. Efforts were primarily applied to solving problems. The research was primarily accomplished through a selected aggregation of information (library) and the level of outcome was descriptive. In the sub-population, the level of effort was primarily a professional paper/research monograph. The relationship of procurement research with the acquisition process or were not concerned with acquisition process at all. Emphasis in the procurement process was primarily in the pre-award phase with many articles dealing with more than one phase.

The definition of procurement research and the classification of the characteristics of procurement research were combined with the information from the literature review to develop the taxonomy. The emphasis for the taxonomy has been to cover all possible areas of procurement research as suggested by various information sources. (See page 82)

The procurement process is the foundation upon which procurement research is based (see figure 2). Procurement research can involve both the procurement and acquisition processes and their interrelationship. Therefore, to construct a taxonomy of procurement research focusing primarily on the procurement process, it was necessary to build a model of this process. Since procurement research is concerned with the procurement process and the procurement process as an integral part of the acquisition process, a taxonomy of the procurement process can serve as a foundation for a taxonomy of procurement research. The areas and issues pertaining to these processes, therefore, also pertain to procurement research. These areas and issues, as related to the procurement process were the focal point of this research and the descriptors of the research taxonomy. Content analysis provided the general characteristics of procurement research and a partial structure of the procurement processes. However, to complete the taxonomy of the process, it was necessary to conduct interviews and make literature reviews.

The taxonomy was constructed to display five levels of the procurement process. The first level is the procurement process. The second level is the three phases (Pre-Award, Award, and Post-Award). The third level is comprised of the cycles that make up each of the phases. The fourth level is a continuum of events (Procurement Continuum) that describes the necessary actions pertinent to the life of a "Procurement". The fifth level, the lowest level presented, is composed of a number of issues related to each of the events. (See Figure 3 page 83)

The research effort was adjusted as the researchers discovered new information that impacted the definition and the taxonomy. The taxonomy developed by the researchers is outlined in Figure 4. Lastly, an algorithm was developed (See Figure 5) which followed the format of a decision flow chart with eight decision points, all of which (except one) must be answered with an affirmative response before an effort can be considered procurement research. These eight decision points are as follows:

1. Is the effort concerned with satisfying a perceived DOD need? Is the effort attempting to solve a problem, provide insight into an issue, or describe a

(See pages 84 - 8)

problem with the DOD? If it is not, it should be considered for further research.

2. Is the research effort concerned with the acquisition process? If the answer to this is negative, a second question is asked, "Is the research concerned with the procurement process?" (See Figure 4 and Table 3.) If the answer to this is positive, the effort is retained for further analysis.

3. Is the research concerned with the procurement process? Here, the efforts judged affirmatively, using question 2, are analyzed according to the procurement taxonomy and questions set forth in Table 3.

4. Does the effort suggest a method for improving the knowledge associated with the procurement process? Three general questions can be asked of the research effort.

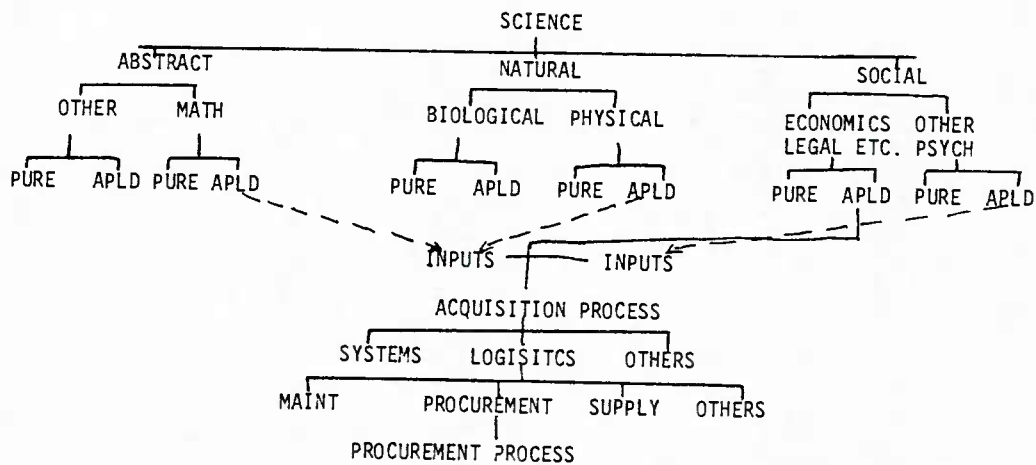


FIGURE 1. THE DELIMITATION OF PROCUREMENT RESEARCH

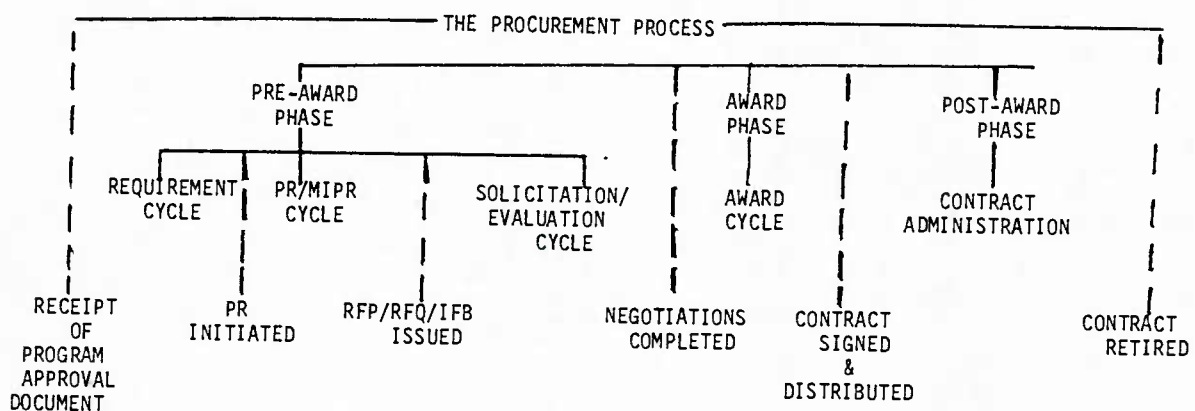
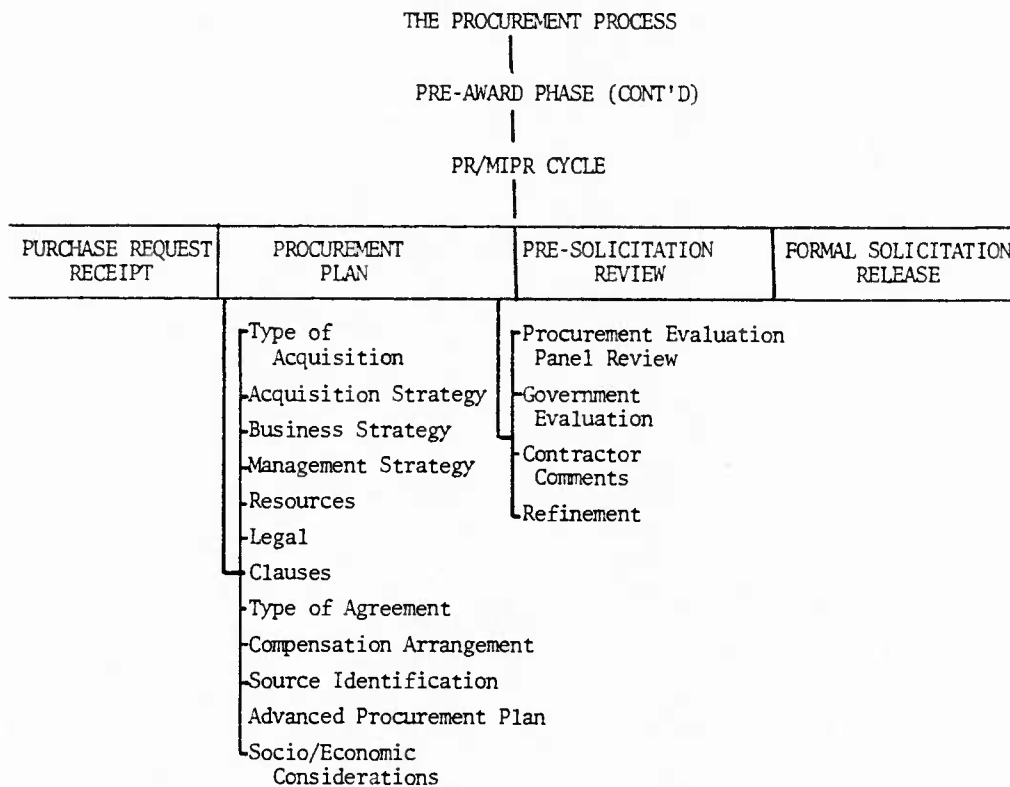
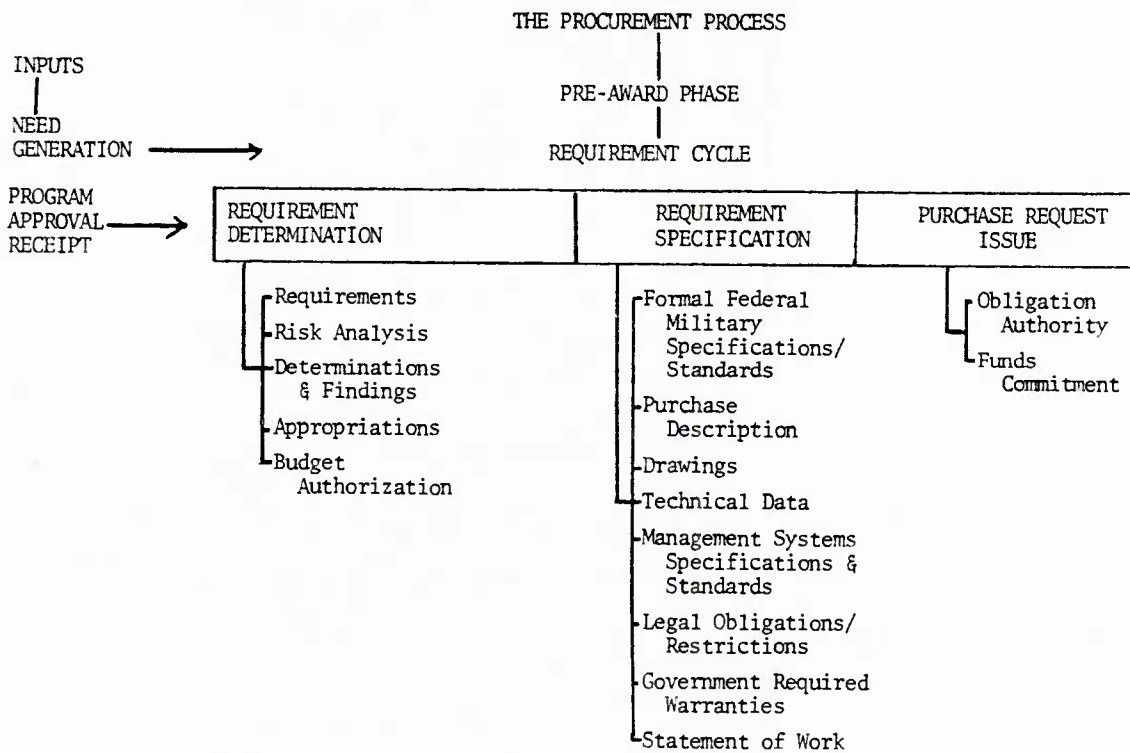
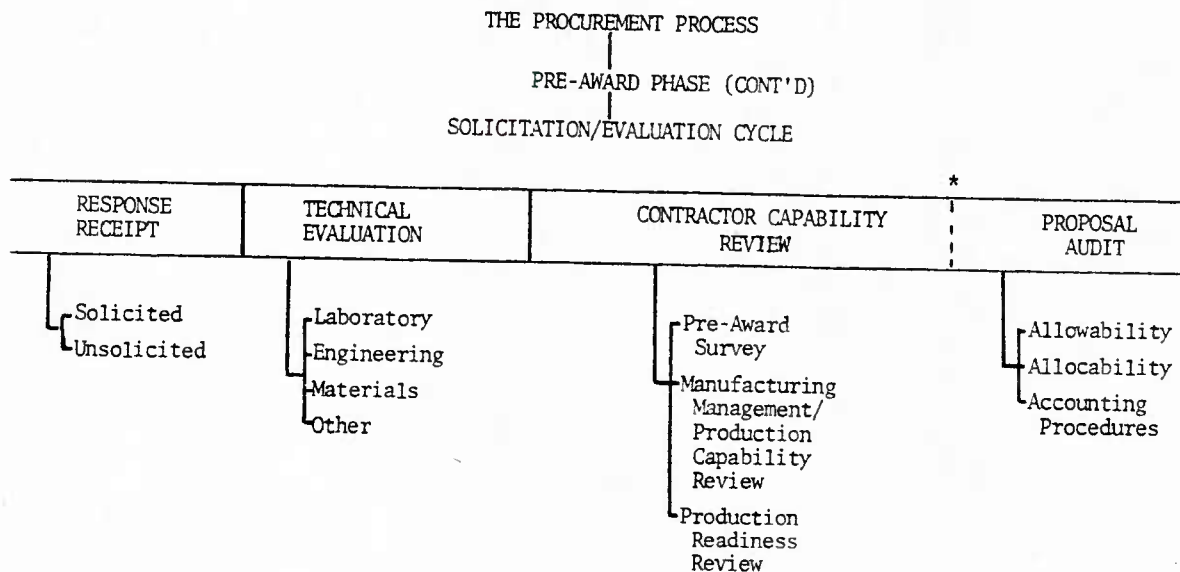


FIGURE 2. THE PROCUREMENT PROCESS (PHASES) (9)





*Broken line denotes possible overlapping events or that another sequence may be possible

FIGURE 4 (Cont'd) A PROCUREMENT TAXONOMY

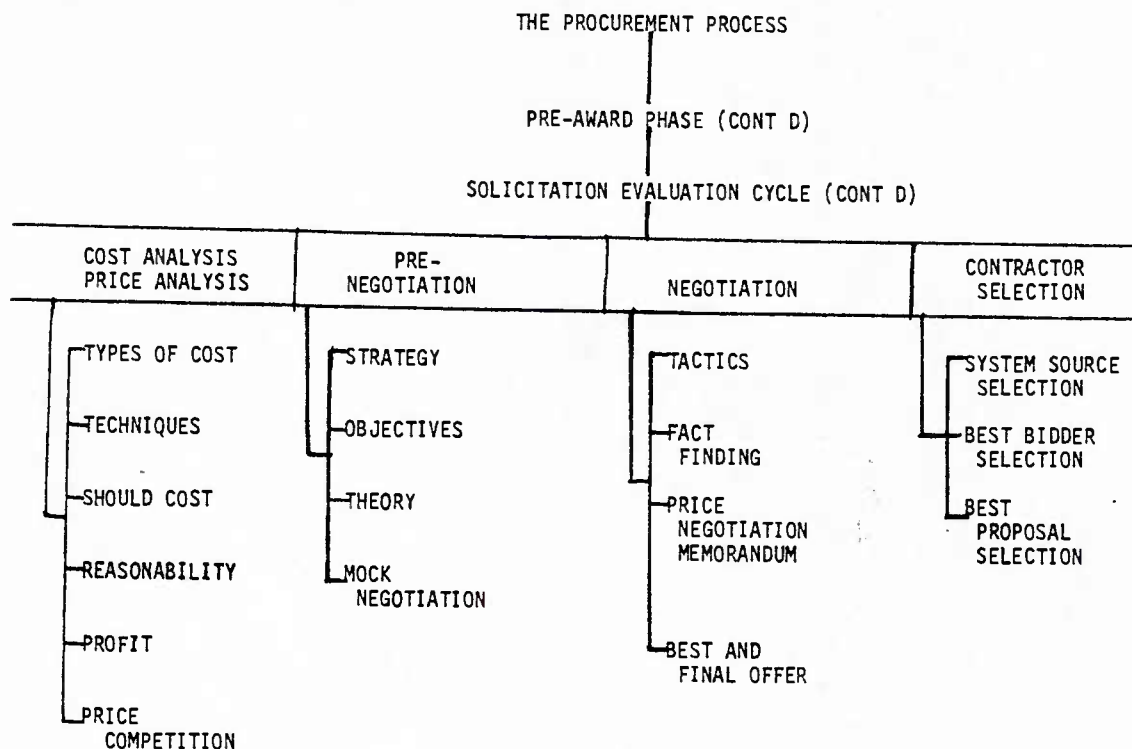


FIGURE 4 (CONT D) A PROCUREMENT TAXONOMY

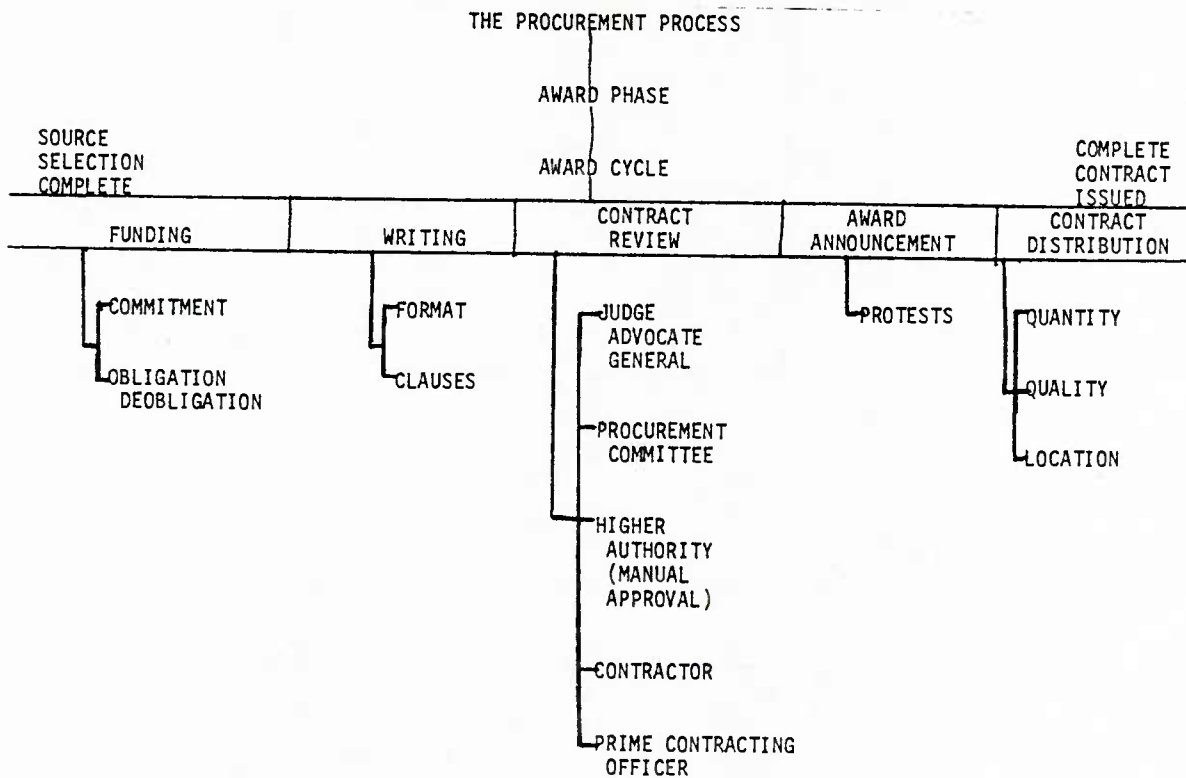


FIGURE 4 (CONT O) A PROCUREMENT TAXONOMY

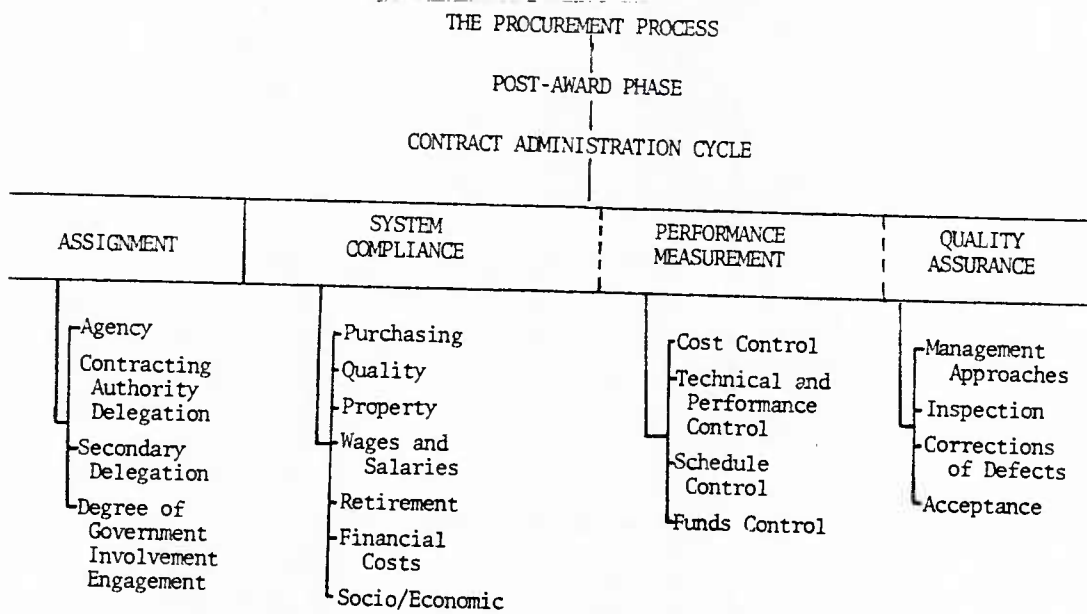


FIGURE 4 (cont'd) A PROCUREMENT TAXONOMY

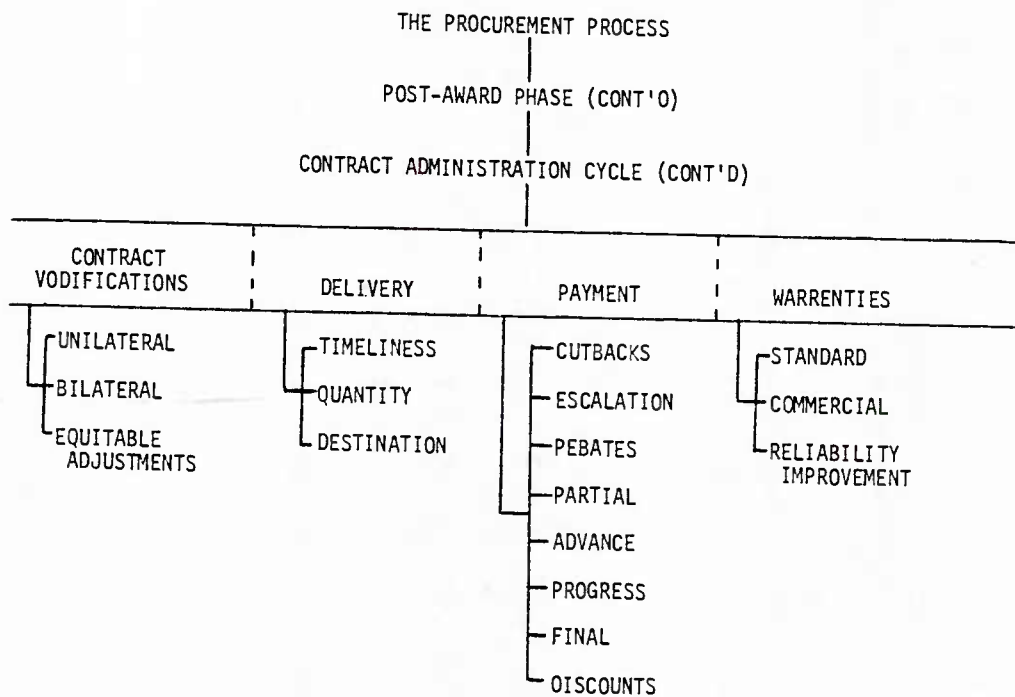


FIGURE 4(CONT'O) A PROCUREMENT TAXONOMY

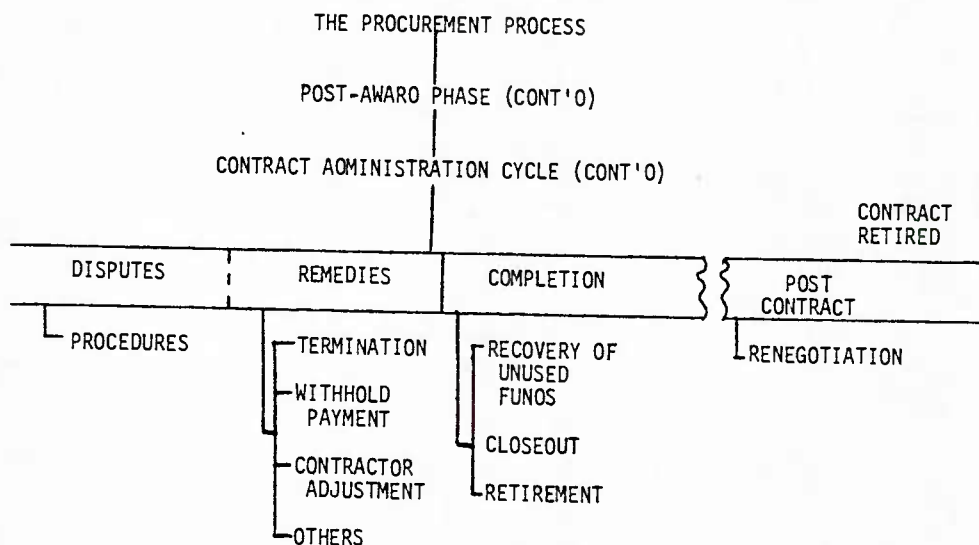


FIGURE 4 (CONT'D) A PROCUREMENT TAXONOMY

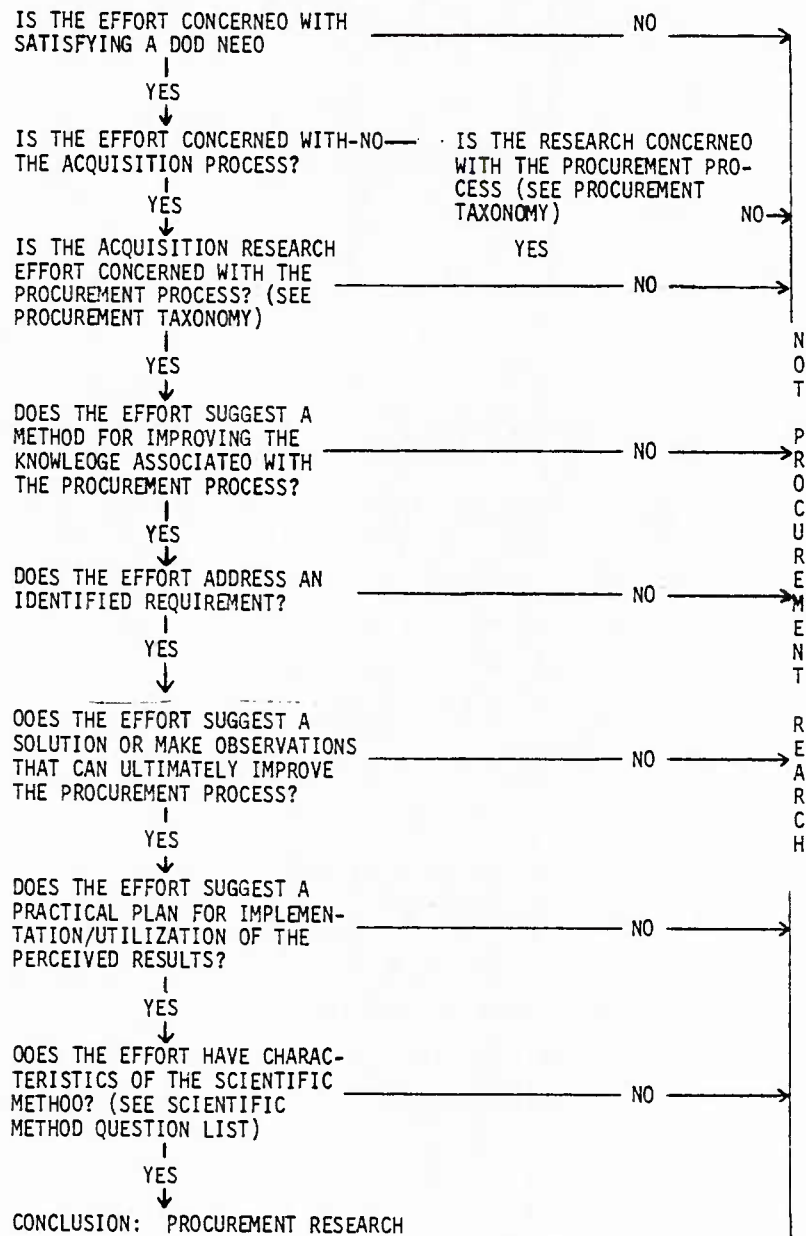


FIGURE 5. PROCUREMENT RESEARCH ALGORITHM

TABLE 3

CRITERIA FOR DETERMINING WHETHER A RESEARCH
EFFORT IS PROCUREMENT RELATED

1. IS IT CONCERNED WITH ISSUES PERVASIVE TO THE PROCUREMENT PROCESS (PROCUREMENT ETHICS, CONTRACT MANAGEMENT, TRAINING, ORGANIZATION)?
2. IS IT RELATED TO REQUIREMENTS DETERMINATION?
3. IS IT CONCERNED WITH REQUIREMENTS SPECIFICATION?
4. IS IT CONCERNED WITH PR ISSUANCE?
5. IS IT CONCERNED WITH OTHER ASPECTS OF THE REQUIREMENTS CYCLE?
6. IS IT RELATED TO THE RECEIPT OF A PR?
7. IS IT CONCERNED WITH PRE-SOLICITATION REVIEW?
8. IS IT CONCERNED WITH FORMAL SOLICITATION ISSUANCE?
9. IS IT CONCERNED WITH OTHER ASPECTS OF THE PR/MIPR CYCLE?
10. IS IT CONCERNED WITH THE RECEIPT OF RESPONSES TO SOLICITATION?
11. IS IT RELATED TO THE TECHNICAL EVALUATION OF RESPONSES?
12. IS IT CONCERNED WITH PROPOSAL AUDITS?
13. IS IT CONCERNED WITH COST ANALYSIS/PRICE ANALYSIS?
14. IS IT CONCERNED WITH PRE-NEGOTIATION ISSUES?
15. IS IT CONCERNED WITH CONTRACT NEGOTIATION?
16. IS IT CONCERNED WITH CONTRACTOR SELECTION?
17. IS IT CONCERNED WITH OTHER ASPECTS OF THE SOLICITATION/EVALUATION CYCLE?
18. IS IT CONCERNED WITH SOME ASPECT OF THE PRE-AWARD PHASE?
19. IS IT CONCERNED WITH CONTRACT FUNDING?
20. IS IT CONCERNED WITH CONTRACT WRITING?
21. IS IT CONCERNED WITH THE REVIEW OF A CONTRACT PRIOR TO ANNOUNCEMENT AND FINAL SIGNATURE?
22. IS IT CONCERNED WITH AWARD ANNOUNCEMENT PROCEDURES?
23. IS IT CONCERNED WITH CONTRACT DISTRIBUTION PROCEDURES?

24. IS IT CONCERNED WITH OTHER ISSUES OF THE AWARD CYCLE OR AWARD PHASE?
25. IS IT CONCERNED WITH THE ASSIGNMENT OF THE CONTRACT FOR ADMINISTRATION?
26. IS IT CONCERNED WITH CONTRACT SYSTEM COMPLIANCE?
27. IS IT CONCERNED WITH PERFORMANCE MEASUREMENT OF THE CONTRACTOR?
28. IS IT CONCERNED WITH QUALITY ASSURANCE/PRODUCT ACCEPTANCE?
29. IS IT CONCERNED WITH CONTRACT MODIFICATIONS?
30. IS IT CONCERNED WITH PRODUCT DELIVERY?
31. IS IT CONCERNED WITH CONTRACTOR PAYMENT?
32. IS IT CONCERNED WITH CONTRACT WARRANTIES?
33. IS IT CONCERNED WITH CONTRACT DISPUTES?
34. IS IT CONCERNED WITH REMEDIES RESULTING FROM CONTRACT DISPUTES?
35. IS IT CONCERNED WITH CONTRACT COMPLETION AND CLOSE-OUT?
36. IS IT CONCERNED WITH ANY OTHER ISSUES OF THE CONTRACT ADMINISTRATION CYCLE OR THE POST-AWARD PHASE?
37. IS IT CONCERNED WITH POST CONTRACT ISSUES SUCH AS RENEGOTIATION?

IF THE ANSWER TO ANY OF THE ABOVE QUESTIONS IS "YES", THEN THE EFFORT IS RELATED TO PROCUREMENT.

of the symposia "Proceedings" have been classified into various categories and sub-categories of characteristics. These scientific and research characteristics have been correlated with areas of the procurement and acquisition process.

To satisfy the first and second objectives, the methodological approach of semantic content analysis was adopted. From the universe of research, the population called procurement research was chosen. This population was further narrowed to the sub-population of procurement research as reported in the "Proceedings" of the five DOD Procurement Research Symposia.³ The analysis consisted of a census of the total sub-population of articles in these "Proceedings".

To validate the coding, a pilot study was accomplished. To enhance the reliability of the research effort, a "target" reliability percentage of 90% was achieved during the pilot study. Additionally, during the analysis, random samples of articles coded by one researcher were recoded by a second researcher to insure consistent and standard results.

After coding the data for each "Proceedings", a relative frequency count of occurrences under each digit code was tabulated. Each digit in the seven-digit code represented a category of science, research, the acquisition process, or the procurement process. The first digit was coded to show the division of science used in the research. The second digit was coded to show the breadth of application of the research techniques used. The third digit was coded to identify the amount of control used by the researcher and where the research was conducted. The fourth digit was coded to determine the level of outcome of the research effort, what could be said about the area studied, did it describe a situation, or could a model be developed to predict future events? The fifth digit was coded to indicate the level of effort used in the research, i.e., the amount of time and depth of effort necessary to accomplish the research. The sixth and seventh digits were coded to indicate the phases of the acquisition and procurement processes with which the research was concerned.

In the second design area, the results of the content analysis were combined into relative frequency distributions. Each sub-category was analyzed to determine those areas of procurement research which were most frequently investigated and which

were most prevalent in the population.

The third research design area, defining procurement research in terms of characteristics evidenced in the study, was addressed using the tabulated data. The characteristics of research and science derived from content analysis were combined with information obtained from literature reviews and personal interviews to develop a tentative conceptual definition of procurement research.

The fourth area of research design was planned to classify procurement research efforts into various areas, as stated in the second objective, and to suggest a detailed procurement taxonomy. Information for this area was gathered from existing literature and personal interviews (7, 9, 12, and 13).

In the fifth research design area, the designing of a detailed algorithm was envisioned to meet the third objective. This algorithm could be employed in determining whether an effort within DOD is related to procurement and whether it is research. The algorithm was derived from information gained from the content analysis, literature reviews and personal interviews as noted in the aforementioned paragraph.

FINDINGS

Data from the content analysis of the "Proceedings" have been tabulated, and a taxonomy and algorithm have been developed. The results of the content analysis, which are listed in Table 1, showed the following primary areas of emphasis as related to the selected criteria.

(See page 91)

CONCLUSIONS

The results of the research suggested the following definition of procurement research:

Procurement research (and acquisition research) is an applied science using the characteristics of the social sciences in combination with mathematical sciences to solve procurement problems. It tends to rely heavily on the use of previously gathered data to seek solutions to problems, equally dividing its efforts between the acquisition process, emphasis is on the pre-award phase in an effort to identify cost-related problems.

TABLE 1 - SUMMARY OF FINDINGS

1. DIVISION OF SCIENCE: SOCIAL (46%)
ABSTRACT/SOCIAL COMBINED (47%)
2. BREADTH OF APPLICATION: APPLIED (62%)
3. DEGREE OF CONTROL: LIBRARY (54%)
4. LEVEL OF OUTCOME: DESCRIPTIVE (55%)
5. LEVEL OF EFFORT: PROFESSIONAL PAPER/RESEARCH MONOGRAPH (68%)
6. PHASE OF THE ACQUISITION PROCESS:
MORE THAN ONE PHASE (68%)
NOT CONCERNED WITH THE ACQUISITION PROCESS (47%)
7. PHASE OF THE PROCUREMENT PROCESS
PRE-AWARD (47%)
MORE THAN ONE PHASE (33%)

As corollary information to the content analysis, the researchers noted the source of each article. Of the one hundred fourteen (114) articles, the source distribution is recorded in Table 2.

TABLE 2 - ARTICLE SOURCE DISTRIBUTION

AGENCY	NUMBER	PERCENTAGE
DOD	9	8%
ARMY	19	17%
NAVY	14	12%
AIR FORCE	39	34%
NON DOD		
Federal Agencies	11	10%
Private Business/		
Universities	22	19%

The initial taxonomy was divided into five levels of procurement research. Each level subdivided the previous level into more specific areas where procurement research can be identified.

a. Does it increase the uncertainty of the procurement process?

b. Will the suggested results of the research effort provide more knowledge of the procurement process, knowledge of an area that has not been investigated before?

c. Does the effort clarify events, areas, or issues in the process?

5. Does the effort address an identified requirement? Before passing judgement on the effort, a review by relevant procurement personnel should be obtained to establish the validity of the undertaking. If judged negatively, the effort should be discarded or held for later evaluation. If judged affirmatively, the effort passes on to the next algorithm question.

6. Does the effort suggest a solution or make observations that can ultimately improve the procurement process? An effort that is classified as procurement research should be directed toward the improvement of the procurement process.

The key to this decision point in the algorithm is that the research effort contributes to the improvement of the procurement process either through a solution to an existing problem or through observations that may lead to the understanding and solutions to future problems.

7. Does the effort suggest a practical plan for implementation or utilization of the perceived results? An effort may be directed at the ultimate improvement of the procurement process. It may suggest a solution to an existing problem or it may be used as a "stepping stone" to solutions of future problems. However, if the effort suggests using implementation/utilization procedures and/or techniques that would be impractical, the effort is suspect.

Application of this decision point requires a word of caution. Implementation/utilization plans suggested by some research efforts may be deemed impractical now, only to be proven practical at some future point in time. This fact may require that the final determination of whether some research efforts are procurement research needs to be deferred to a later date.

8. Does the effort have characteristics of the scientific method? Determination of whether the effort follows the scientific method is made by either the research analyst and/or the procurement manager subjecting the effort to the series of questions listed in Table 4. (If the effort is proposed, questions (1-10) would be applicable

but if the effort was completed research, all questions would be applicable.) If negative answers were obtained, the effort should be discarded, or returned to the researcher for clarification and rework and then returned for further analysis by the research approving agency.

This algorithm suggests that a certain level of effort be undertaken by the researchers who proposes the study prior to its submission to the approving agency for acceptance. Resources available to the procurement research community are necessarily limited and need to be applied only to pertinent research proposals. Time and funds cannot be ill-spent on poorly defined research proposals that return marginal results or have no applicability to the procurement process.

WHAT PROCUREMENT RESEARCH SHOULD BE . .

The previously discussed research efforts concentrated on what procurement research is and has been during the past few years. From exposure to the information that was reviewed in this effort, the research team gained an insight into procurement research and herein suggest what procurement research should be:

1. It should concern the acquisition or procurement processes. Research accomplished by procurement researchers that

(See page 93)

does not involve the procurement or acquisition processes makes an inefficient use of limited resources.

2. Procurement research should seek solutions to procurement problems. Procurement research should be applied research; it should be concerned with seeking solutions to problems faced by procurement managers and personnel.

3. Procurement research should be cost effective. Procurement researchers should concern themselves with a cost analysis of their own work. If the research can be performed at a lower cost external to the originating research agency, then the effort should be accomplished externally.

4. Procurement research should follow the scientific method. The "Proceedings" indicated that procurement research did follow the scientific method in its approach to problem solving. Future research should use the same procedures/techniques.

SCIENTIFIC METHOD QUESTIONS LIST

1. Does it define the problem?
2. Does the effort survey existing pertinent literature?
3. Has the researcher evaluated past studies for applicability to his effort?
4. Does the effort build on previously developed knowledge?
5. Is the scope defined and specified? And are the specified objectives to be met listed?
6. Does the effort suggest the testing of a hypothesis or the answering of a research question?
7. Is there a specified plan?
8. Does the effort list assumptions/limitations?
9. Is the methodology logical and appropriate for the objectives specified?
10. Does the effort gather data and/or facts?
11. Are the data valid and reliable?
12. Does the effort report describe predict or explain?
13. Do conclusions logically flow from the data?
14. Can the effort be replicated to achieve consistent results?

5. Procurement research should be unbiased. Procurement research should report true findings, not "channel" results to suit the researchers. The researchers should apply rigorous subjectivity to his research and remain unbiased in his analysis.

6. Procurement research should make use of the best analytical methods. Poor research techniques waste resources and provide weak solutions to problems that may require strong remedies. A careful, thorough evaluation of a procurement research problem can suggest the best analytical method to use in the effort.

7. Procurement research should be original and not redundant. Prior to doing research, procurement people should review previous studies and ascertain whether a new research effort is justified or whether the findings of a previous study are sufficient.

8. Procurement research should be shared. Central procurement information storage facilities should be accessible to all procurement research organizations, internal and external to the Government. Results should be publicized, such as those found in the "Proceedings". Only through the sharing of information can the redundancy be reduced and resources saved.

9. Procurement research should be simple, yet accomplish the task. Procurement research should accomplish its specific task in the most direct method possible. It should not confuse the problem-solving methodology with techniques designed to impress the requester while hiding the path the researcher used to seek his solution. The approach used by the researcher should be "fair and reasonable" to all parties.

COROLLARY OBSERVATIONS ON PROCUREMENT RESEARCH

Experience gained during the course of this research may prove enlightening to subsequent researchers. These observations are summarized as follows:

1. An increasing level of interest in procurement was noted as a definite trend during the past few years.

2. The annual DOD Procurement Research Symposium offers an excellent means for sharing procurement research information; however, often other research efforts and results are not shared.

3. Procurement researchers generally do not share their current progress or projects.

4. Often the method or technique that resulted from the research effort could be applied to other problem situations, but the research itself was done strictly in response to one problem. General research to improve the overall acquisition and procurement processes was lacking.

5. The present information retrieval systems do not provide a totally accessible system to the researcher.

These corollary observations would be incomplete without some suggestions or recommendations for improvement. Indication of a deficient area implies that better methods are perceived for getting the task done; the next section offers recommendations for improving procurement research.

RECOMMENDATIONS

Further studies must be made and current methods must be changed in order for procurement research to be improved. The results and conclusions from this study suggest starting for further studies and alternatives courses of action for current methods in procurement research. Eight recommendations for further study and procurement research improvement follow:

1. Add research studies with a longer range perspective to present problem/response type studies. The addition of some longer range research in procurement may identify influential factors that are not evident in the short-range, reactive approach.

2. Areas of procurement research effort, significant research progress, and research results should be shared with the procurement community. The area of sharing information on procurement research is essential to the DOD procurement community. Further research should be done: (1) to research the extent of the problem of how many completed procurement research studies do not get into the DOD information retrieval systems and to correct this deficiency in information flow, and (2) to find a means to identify current DOD procurement efforts in progress and to publicize this information on a regular basis.

3. The DOD should adopt the taxonomy developed in this research effort as a common taxonomy of procurement research for use by its agencies. A standardized taxonomy of procurement research would allow researchers from all DOD agencies to establish a common

framework for communication. Not only would researchers be on a common base, but procurement people could understand research results from other agencies and possibly apply new and better techniques to their own work. The procurement research taxonomy presented in this study could be a logical starting place from which a common DOD taxonomy could be expanded. Finally, a common taxonomy could be used as a data base for assigning descriptors to procurement research in a computerized information system.

4. The procurement research taxonomy that is suggested in this study should be critically analyzed and expanded. The taxonomy is an attempt at categorizing the procurement process and the field of procurement research. Through further study, this taxonomy could be validated and expanded to include requirement definition and use as they impact upon procurement.

5. Further algorithms for conducting procurement research and for deciding whether to research procurement problems should be constructed and used. During the construction of the algorithm, the researchers had much difficulty in establishing a perspective from which to construct the algorithm. Procurement research can be viewed in terms of a given output or ongoing process, a method for conducting the research, or a method for deciding whether a procurement problem should be researched by an organization/individual. Future efforts should research these two areas to provide guidelines for conducting the procurement research process and for making the important decision of whether or not to undertake a research effort.

6. A model for DLSIE (Defense Logistics Systems Information Exchange) abstracts should be developed so that key words would provide ready relevant information. Research should be done to develop a model for writing DLSIE abstracts so that a content analysis of an abstract would determine key words, words similar to the phases, cycles, events, and issues of the taxonomy presented in Figure 4. Procurement researchers could then identify those studies relevant to their areas of specific research from this content analysis of the abstracts.

7. A sequential analysis of procurement research efforts should be performed. Hood and Strayer (5) suggested that procurement research, as a developing discipline, can be portrayed as transitioning six development phases in a sequential evolutionary process from a new discipline to full maturation. The significance of this evolutionary process and its developmental phases is that each phase differs in terms of the kinds of questions or issues addressed and types of research activity conducted within each phase.

8. Research should be done to prioritize those "issues" of the procurement research taxonomy that offer the greatest opportunity for cost savings and improvement. An analysis at the "issue" level of the procurement research taxonomy could identify those areas that are costly to implement, difficult to administer, and subject to frequent delay, as well as those areas that offer the greatest benefits to the DOD, the public, and industry. A priority system of procurement research issues would identify those areas that should receive the most research emphasis. Limited resources could be applied to "issues" from the top down so that the most important areas are researched first.

SUMMARY

The result of this effort is only the first step toward defining and structuring procurement research. It will be up to the procurement community as to whether this initial effort is accepted and used. This definition and taxonomy offer a basis which researchers can use to more closely define procurement research and its relationship to the procurement process, while the algorithm provides the researcher or procurement manager with a logical process to evaluate the research effort as to its applicability to procurement.

Lastly, observations on "What Procurement Research Should Be..." and recommendations for further research were offered to the procurement community as a means of accelerating the evolutionary process of procurement research.

FOOTNOTES

¹A sequential decision making process or model.

²These categories were adopted from the Strayer-Lockwood taxonomy. See reference 3 and 14 for further discussion.

³The research for this study was conducted prior to the publication of the Sixth DOD Procurement Research Symposium.

REFERENCES

- (1) Babione, Dale R., "Procurement Research Solutions to Problems Through Innovation and Communication," Defense Management Journal, July, 1975, pp. 2-3.
- (2) Bennett, Dr. John J., "Comment," Defense Management Journal, July, 1975, p. 1.
- (3) Helmstadter, G.C., Research Concepts in Human Behavior. New York: Meredith Corporation, 1970.

- (4) Heuer, Major Gerald R. J., USAF, Captain John C. Kingston, USAF, and Captain Eddie L. Williams, USAF, "A Proposed Definition and Taxonomy for Procurement Research in the Department of Defense." Unpublished Master's thesis, LSSR 12 77B, AFIT/LGSR, Wright-Patterson AFB, OH, 1977.
- (5) Hood, Joseph L. and Lieutenant Colonel Daniel E. Strayer, "Sequential Research Needs in the Evolving Discipline of Procurement" (Draft Copy). Paper presented to the Department of Defense Sixth Annual Procurement Research Symposium, "Translating Procurement Research into Action", held at West Point, N.Y., U.S. Military Academy, 22-24 June 1977.
- (6) Judson, Robert, "Defining Procurement Research," Address to the Second DOD Procurement Symposium, as reprinted in Proceedings, Second DOD for Procurement Research Symposium: Procurement Problems. A Challenge for Procurement Research, Monterey, CA, Naval Postgraduate School, 1, 2, and 3 May 1973, pp. 90-99.
- (7) Lockwood, Major Lyle W., USAF, Deputy Director, Air Force Business Research Management Center, Wright-Patterson AFB, OH, Personal interviews conducted intermittently from 11 October 1976 through 2 August 1977.
- (8) Malloy, John M., "DOD Progress and Research," Address to the First DOD Procurement Symposium, as reprinted in Proceedings, DOD Procurement Symposium: Progress and Research in the Seventies. Wright-Patterson AFB, OH, Air Force Institute of Technology, School of Systems and Logistics, 23-24 February 1972, pp. 207-21.
- (9) Martin, Lieutenant Colonel Martin D. USAF, Chief, Department of Functional Management, AFIT/LGSM, Wright-Patterson AFB, OH, Personal interviews conducted intermittently from 4 October 1976 through 15 August 1977.
- (10) Price, Melvin, Chairman, House Committee on Armed Services, and Senator John C. Stennis, Chairman, Senate Committee on Armed Services, Joint Letter, concerning 4th Annual DOD Procurement Research Symposium, to James Schlesinger, Secretary of Defense, 8 October 1975.
- (11) Roback, Herbert, "Towards More and Better Procurement Research," Defense Management Journal, July 1975, pp. 4-6.
- (12) Smith, Lieutenant Colonel Larry L, USAF, OH, AFIT Course FM 5.23, "Procurement and Acquisition Management," Class 1977B. Lectures and intermittent personal interviews, 4 October 1976 through 15 August 1977.
- (13) Strayer, Lieutenant Colonel Daniel E., USAF, Executive Director, Air Force Business Research Management Center, Wright-Patterson AFB, OH, Personal interviews conducted intermittently 25 October 1976 through 28 July 1977.
- (14) Strayer, Lieutenant Colonel Daniel E., USAF, and Major Lyle W. Lockwood, USAF, "Evaluating Research Needs and Validating Research Results." Paper presented to the Fifth DOD Procurement Symposium, as reprinted in The Fifth Annual Department of Defense Procurement Research Symposium Monterey, CA, Naval Postgraduate School, 17-19 November 1976, pp. 11-33.
- (15) Trimble, Robert F., Assistant Administrator, Office of Federal Procurement Policy for Contract Administration, Washington, D.C., Personal interview 29 December 1976.

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ABSTRACT

The application of risk analysis by the Directorate of Pricing under the Deputy for Procurement and Manufacturing in the Aeronautical Systems Division is discussed in this paper. A method of analyzing FPIF contracts is presented along with guidelines for choosing share ratios and ceilings. Problems and pitfalls encountered during the implementation are discussed with several suggestions for future modifications.

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INTRODUCTION

During the development and procurement phases of acquiring a major defense weapon system, many decisions must be made concerning its performance, cost and scheduling. An important aspect of this decision making process is the analysis of uncertainty which exists. Common approaches to analyzing uncertainty have in the past focused on the decision maker's intuition, on sensitivity analysis and on risk analysis. The focus of this paper is the analysis of risk inherent in the projection of cost involved in a contract. The cost of a specific contract and not the cost of the entire system acquisition is discussed here.

When the term risk analysis is used, three types of risk are generally implied. These types are technical risk, cost risk, and schedule risk. In the study of a large weapon system, all of these risks should be analyzed to determine which alternatives should be chosen in order to maximize the probability of having a successful program. When a specific contract for a program is being negotiated, the primary variable of interest is the cost risk. Important to note, however, is that the cost is not independent of the amount of technical and schedule risk. The technical and schedule risks are important factors in the estimation of the cost risk and hence the cost which should be negotiated.

A price analyst in the Aeronautical Systems Division (ASD) has the responsibility of determining and negotiating a fair and reasonable cost and profit for a contract. Many of the cost elements may be estimated with some degree

of certainty and will be referred to as non-random. Examples of non-random cost include negotiated overhead rates, wage rates and certain routine labor costs. Other cost elements will not be known or identifiable with certainty and will be referred to as random. The randomness in the cost elements may be caused by some factor affecting cost or may be totally unexplainable. Causes of randomness in cost elements include design, labor and material uncertainties concerning costs and amounts. The price analyst must still estimate the cost and negotiate a price for the contract. The purpose of this paper is to explain how risk analysis is being used to reflect the extent to which randomness affects total cost.

Random factors affecting cost are events which the contractor cannot control and which are known (or suspected) to impact one or more elements of a cost of the contract. Risk analysis is a procedure for analyzing how randomness affects the total cost. An analyst must identify the random, uncontrollable factors and assess the probability of different events occurring. Then using risk analysis, the distribution of the total cost is obtained. Results of a risk analysis may be useful to a price analyst in several ways. First, it will help to show possible actual costs which might occur and the probability that they will occur. Second, it may help in determining the type of contract to offer. Third, expected cost to the government can be determined. And fourth, actual cost can be bounded or given a range over which it will most likely occur.

The remainder of this paper will discuss an implementation of risk analysis by the Directorate of Pricing under the Deputy for Procurement and Manufacturing in the Aeronautical Systems Division at Wright-Patterson AFB. First, the objectives of the risk analysis study will be given with a brief description of the methods being used before this undertaking. Second, a description of the system implemented will be given. Finally, some of the pitfalls and problems encountered will be discussed along with planned modifications that can be added to alleviate these problems.

OBJECTIVE FOR RISK ANALYSIS

As in any risk analysis, the primary goal is to determine the distribution of the total cost of a contract. In order to do this it is necessary to combine information from numerous

sources including the contractor's proposal, the PCO, DCAA, DCAS and (or) AFPRO. The risk analysis discussed here was developed for the price analyst whose responsibility it is to analyze all of the above sources of information and to negotiate a fair and reasonable price. Before the negotiations start, an initial position and objective must be established by the analyst summarizing all of the cost subcomponents and the total price. Historically, target costs were established by summing the most likely costs for each of the cost subcomponents. The risk analyses performed by the price analyst were achieved by summing the extreme costs for each of the cost subcomponent. These procedures give bad estimates of both the most likely total cost (the cost with the highest probability of occurring) and the extreme value of total cost. This is because the sum of most likely values of subcomponents generally is not the most likely value of the total cost and the sum of extreme values to estimate the extreme value of total cost assumes uncertainty among subcomponents is perfectly correlated.

The constraints invoked for the development of the risk analysis to be used by price analysts were as given below.

1. The procedure must be simple and easily performed.
2. The information needed should be readily available to the price analyst.
3. The output should be easily understood.
4. The procedure should be adaptable to most of the contracts under negotiation.
5. Computations should be quick and easily made.

In order to make the procedure adaptable to the contracts under negotiations a common cost breakdown was needed. It was found that the one common breakdown was that given by Form DD633 to provide a standard format which contractors submit to the government summarizing incurred and estimated costs. This total cost breakdown was into the categories or subcomponents:

- a) Material (MAT)
- b) Material Overhead (MATOH)
- c) Interdivision Transfer (IT)
- d) Direct Engineering Labor (DEL)
- e) Engineering Overhead (EOH)
- f) Direct Manufacturing Labor (DML)
- g) Manufacturing Overhead (MOH)
- h) Other Costs (OC), and
- i) General and Administrative Expenses (GAE).

In evaluation of a contract, each of these subcomponents are usually broken down further and are commonly interrelated as shown below, where P1 through P4 are specific percentage figures, and R1 and R2 are specific wage rates. The * is used to denote multiplication.

MAT = Estimated Material Cost

MATOH = P1 * MAT + Estimated Independent Material Overhead

IT = Estimated IT Cost

DEL = (Estimated Engineering Hours) * R1

EOH = P2 * DEL + Estimated Independent Engineering Overhead

DML = (Estimated Manufacturing Hours) * R2

MOH = P3 * DML + Estimated Independent Manufacturing Overhead

OC = Estimated Other Cost

SUBTOTAL = ST = MAT + MATOH + IT + DEL + EOH + DML + MOH + OC

GAE = P4 * ST

TOTAL COST = TC = ST + GAE

The relationships above define a general cost model for which eight estimates are needed to determine the total cost. A form for organizing the collection of data required for the risk analysis is given in Form I. The estimates requiring minimum, most likely, and maximum values must be supplied by the analyst. For each of the cost categories, either the cost (\$) or hours must be estimated. The overhead categories are divided into two parts, the independent overhead cost and the overhead rate. The independent overhead cost is a cost which does not change when the direct cost changes. Usually, the uncertainty in the independent overhead cost is due to future business conditions. The independent overhead cost is commonly allocated to the direct cost and then lumped with the overhead rate. However, it should be kept separate for a risk analysis. The overhead rate should reflect those costs which are directly proportional to the direct cost. It is assumed here that this rate is known with certainty. Using the Beta distribution implicitly assumes that the possible outcomes can be bounded in some finite range. For mature systems, this is not an unreasonable assumption.

The formula for the mean (expected) and variance are theoretically based on the properties of the Beta distribution and have been widely used in statistics, risk analysis and scheduling (PERT). The formulas for estimating the Mean and Variance for a Beta distribution are:

$$\text{Mean} = \frac{L + 4ML + H}{6}$$

$$\text{and}$$

$$\text{Variance} = \left(\frac{H-L}{6} \right)^2$$

where H = maximum, L = minimum and ML = most likely. These calculations are actually approximations and are very good if the distribution is not too severely skewed.

FORM I

ESTIMATES FOR RISK ANALYSIS

ESTIMATES

SUBCOMPONENTS		MOST		
		MINIMUM	LIKELY	MAXIMUM
MATERIAL	COST			
MATERIAL OVERHEAD	INDEPENDENT			
RATE FOR MATERIAL	P1			
INTERDIV RNSERS	COST			
DIRECT ENGRG LABOR	HOURS			
WAGE RATE	R1			
NEGRG OVERHEAD	INDEPENDENT			
RATE FOR ENGRG	P2			
DIRECT MFG LABOR	HOURS			
WAGE RATE	R2			
MFG OVERHEAD	INDEPENDENT			
RATE FOR MFG	P3			
OTHER COSTS	COST			
CSA EXPENSES				
PERCENT OF SUBTOTAL	P4			

The risk analysis was the application of some well known statistical analysis to the cost model described above. The statistical analysis approach is useful in the handling of continuous distribution problems.

The statistical concept used in this paper is one which states that the sum of independent random variables will be approximately normally distributed with a mean equal to the sum of the individual means and variance equal to the sum of the individual variances.

If we rewrite our total cost model, we can get it into the form needed. That is:

$$TC = \{(1+P1)*V1 + V2 + V4*(R1 + R1*P2) + V6*(R2 + R2*P3) + V5 + V3 + V7 + V8\}*(1+P4)$$

where V1 = Material Cost
V2 = Independent Material Overhead
V3 = IT Cost
V4 = Engineering Hours
V5 = Independent Engineering Overhead
V6 = Manufacturing Hours
V7 = Independent Manufacturing Overhead
V8 = Other Costs

Using the notation E(V1) to represent the mean of variable V1 and Var (V1) to denote the variance of V1, the mean E(TC), and variance, Var (TC), of the total cost are:

$$E(TC) = \{(1+P1)*E(V1) + E(V2) + E(V4)*(R1+R1*P2) + E(V6)*(R2+R2*P3) + E(V5) + E(V7) + E(V8)\}*(1+P4)$$

$$Var(TC) = \{(1+P1)^2*V(V1) + Var(V2) + Var(V4)*(R1+R1*P2)^2 + Var(V6)*(R2+R2*P3)^2 + Var(V5) + Var(V3) + Var(V7) + Var(V8)\}*(1+P4)^2$$

The distribution of the total cost would thus be normal with mean, E(TC) and variance, Var (TC).

The normal distribution has the property that probability statements can be made using only the mean and variance. For instance, there is a 68% chance that the total cost will be between E(TC) $\pm$ Var(TC) and a 95% chance that the total cost will be between E(TC) $\pm$ 2 * Var (TC).

Once the mean and variance of the total cost have been determined, the distribution of the total cost is completely described since the total cost is normally distributed. The functional form of the normal distribution is:

$$f(c) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(c-\mu)^2}{2\sigma^2}}$$

Where $\mu = E(TC)$ and $\sigma^2 = \text{Var}(TC)$. This distribution is then the completion of the risk analysis.

Let us now investigate the effect of risk on a Fixed Price Incentive Firm (FPIF) contract which is commonly used for contracts which have some risk but not enough to resort to a cost plus type contract. In particular, the expected profit and the expected cost to the government will be expressed in terms of the following variables:

TC = Target Cost

TP = Target Profit

PC = Ceiling Price

a = Contractor's share of underruns

b = Contractor's share of overruns

CC = Point of total assumption =

$$\frac{PC - (TC + TP)}{1-b} + TC$$

and

$f(c)$ = distribution of total cost

A profit-cost graph for a Fixed Price Incentive Firm contract is presented in Figure I. The line segments to the left of TC, between TC and CC and to the right of CC are given in terms of the cost (C) as

$$L1 = TP + a(TC - C)$$

$$L2 = TP - b(C - TC) \text{ and}$$

$$L3 = PC - C$$

Thus, the expected profit is given by:

$$E(\text{Profit}) = \int_{TC}^{CC} L1 f(c) dc + \int_{CC}^{TC+3\sigma} L2 f(c) dc + \int_{TC+3\sigma}^{\infty} L3 f(c) dc$$

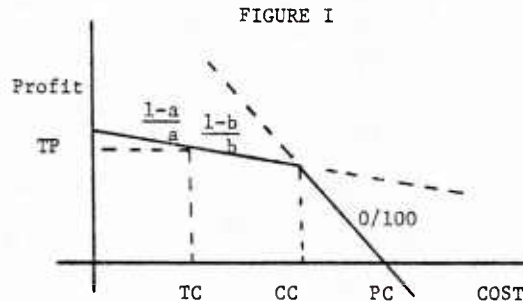
Of course if CC is greater than $TC + 3\sigma$, then the last term is dropped.

The expected cost to the government is then

$$E(TC) + E(\text{Profit}).$$

Notice that the Normal distribution has been truncated at plus or minus 3σ since it is extremely unlikely that the cost will be outside

of that range.

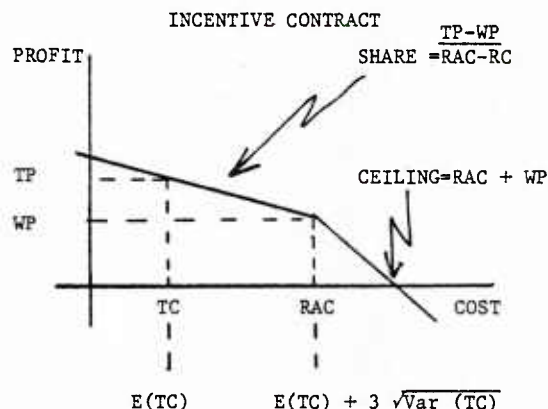


Fixed Price Incentive Firm, Cost-Profit Graph

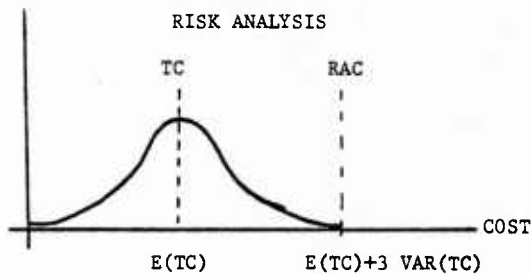
A computer program was provided to the price analyst for the calculations necessary for comparing different incentive plans. This program accepts as input TC, TP, σ , a, b, and PC, and prints the expected profit and cost to the government. Also the high and low profits and cost to the government are printed. The computer program uses Gaussian Quadrature as a numerical integration technique for calculation of the expected profit.

If, rather than evaluating different incentive plans, one wishes to use the risk analysis to establish targets, ceilings and share ratios, Figure II demonstrates how this might be done for a FPIF type contract. The two points TP (target profit) and WP (warrented profit) must be supplied by the price analyst. In Figure II, TC is the target cost and RAC is the risk analysis cost. With this type of incentive contract the government shares in overruns and underruns due to the randomness involved.

FIGURE II



(See next page)



A computer program is currently being used by price analysts for performing the arithmetic needed. The output of this program is illustrated in Exhibit I.

OBSERVATIONS, PITFALLS, AND FUTURE MODIFICATIONS

In the implementation of the risk analysis described above, the author found several problems which were difficult to overcome and may still exist. Each of these problems are discussed below.

1. The price analyst had preconceived definitions of terms which had different statistical definitions. For instant, expected cost in statistics is a technical term with a different meaning than the most likely cost or mode. The definition of these terms is different than a laymen's interpretation and therefore created a great deal of confusion.

EXHIBIT I

ELEMENTS		MINIMUM	MOST LIKELY	MAXIMUM
MATERIAL	COST	8400.00	9000.00	12000.00
MGT OVERHEAD	INDEPENDENT	0.00	0.00	0.00
RATE FOR MATERIAL	0.050			
INTERDIV TRSFERS	COST	1700.00	1800.00	2300.00
DIRECT ENGRG LABOR	HOURS	85.00	95.00	115.00
WAGE RATE	11.500			
ENGRG OVERHEAD	INDEPENDENT	0.00	0.00	0.00
RATE FOR ENGRG	0.700			
DIRECT MFG LABOR	HOURS	200.00	230.00	290.00
WAGE RATE	11.000			
MFG OVERHEAD	INDEPENDENT	0.00	0.00	0.00
RATE FOR MFT	1.700			
OTHER COST	COST	400.00	450.00	500.00
G&A EXPENSE	0.1000			

SUMMARY, CEILING/SHARE COMPUTATION

SUMMARY, MINIMUM COST	20373.93
SUMMARY, MOST LIKELY COST	22427.07
SUMMARY, MAXIMUM COST	28887.37
EXPECTED TOTAL COST, E(TC)	23161.60 EXCEEDED W/PROB OF 50%
RISK ANALYSIS COST, RAC	25149.55 EXCEEDED W/PROB OF 1% OR LESS
WARRANTED PROFIT	1802.47
TARGET PROFIT	2779.39
CEILING PRICE	27535.58
PERCENT DIFFERENCE BETWEEN RAC AND OBJECTIVE	11.77%
SHARING COMPUTATION:	
WGM PROFIT LESS WARRANTED PROFIT	993.37
RISK ANALYSIS COST LESS OBJECTIVE COST	2588.34
CONTRACTORS SHARE	38.36%

2. Since subjective estimates of the costs were the basis of the risk analysis, biased positions were often taken. These biases were often due to personal feeling towards what would happen in the future.
3. There tended to be an unconscious attempt to estimate costs which could be negotiated and not actual cost. This is very understandable since the primary job of the price analyst is to negotiate the contract.
4. Once positions and objectives had been established and the negotiations began, adjustments to the inputs to the risk analysis will most likely not be made because of the general procedures followed.
5. Target profit was often determined using profit weighted guidelines which add a percentage factor because of risk.
6. Future changes to the contract and other contractor or government actions tended to make it difficult to define exactly what total cost was being estimated.
7. The price analyst received point estimates of most of the cost subcomponents. The extent of the randomness was subjectively evaluated. Now that a risk analysis is being performed, hopefully more than point estimates can be requested and obtained from persons furnishing the information to the price analyst.

Using the current method of risk analysis, three major assumptions are made which may cause errors in the prediction intervals if violated. Each of these are discussed below with the method by which they are to be avoided in the future.

1. A major concern in this analysis is an assumption that the cost subcomponents are independent. In order to avoid this assumption a different cost breakdown is needed where all of the costs are independent or an estimate of the covariance is needed. The latter is not possible because of the bulk of information. A different cost breakdown might be possible for a specific contract, however, this would mean that each contract would require a different cost model and would require a great deal of statistical and mathematical sophistication on the part of the price analyst. The analyst has supplied upper limits for each cost subcomponents and the sum of the maximums is printed on the output as summary maximum cost. This would be the upper limit on total cost if there is perfect correlation between the cost subcomponents. At the other extreme of no correlation is the risk analysis cost also printed on the output. In order to

compensate for the dependence of the cost subcomponents, these two extremes of perfectly correlated deviations and independent random cost subcomponents can be analyzed and adjustments made.

2. In order to have a normal distribution of the total cost, the cost subcomponents can not be dominated by a single cost element. In the event that this is the case the sum of the maximum of each cost subcomponent is again better than the risk analysis cost.
3. The current system assumes that overhead rates and wage rates are fixed constants. The only way to avoid this in the current system is to run the risk analysis with different values and compare the results.

Currently, plans are being made to change the procedure being used to one which will assume that the total cost is Beta distributed and allow for randomness in the overhead and wage rates. Note that this will eliminate the last two assumptions completely. It is the opinion of the author that neither the information needed nor the sophistication required will be available to the price analyst for handling the interdependence of cost subcomponents in the near future. These dependencies should be recognized by the price analyst and adjusted for.

SUMMARY

The application of risk analysis at ASD pricing has been very successful. The author feels that an indicator of this success is the fact that the price analyst is now starting to think in a manner which does not solely focus on point estimates but allows for a consideration of the risk involved. This must be the first step and then more sophisticated procedures can be implemented. With this interest will come a request for information in a different format than previously requested allowing for more accuracy in the risk analysis. Also recommended is the coordination of efforts of ASD pricing with those who are considering the risk associated with other elements of the program.

BIBLIOGRAPHY

1. Black, R., "Beta Distribution from Moments," Grumman Aerospace Corporation, PDM-OP-79-115, June, 1979
2. Dienemann, P.F., "Estimating Cost Uncertainty Using Monte Carlo Techniques," RM-4854-PR, The Rand Corporation. January
3. Fisher, G.H., Cost Considerations in Systems Analysis, American Elsevier Publishing Company, New York
4. Klein, Michael R., Treating Uncertainty in Cost Analysis: The Beta Distribution, U.S. Navy CNO Resource Analysis Group
5. Murphy, E.L., Jr., "Statistical Methods of Measuring the Uncertainty of Cost Estimates," AD 718862, February, 1970
6. Quade, E.S. and Boucher, W.I., System Analysis and Policy Planning--Application in Defense, American Elsevier Publishing Company, New York
7. Schaefer, D. F., Husic, F.J. and Gutowski M.F., "A Monte Carlo Simulation Approach to Cost--Uncertainty Analysis," AD 850054, March, 1969
8. Wilder, J.J. An Analytical Method of Cost Risk Analysis, Gruman Aerospace Corporation, PDR-OP-T77-12, June, 1977
9. Worm, George H., "Application of Risk Analysis in the Acquisition of Major Weapon Systems" AF Business Research Management Center, Wright-Patterson AFB, Ohio, 1980

THE EVOLUTION OF RISK AND UNCERTAINTY
ANALYSIS FOR APRO

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ABSTRACT

Uncertainty analysis is being applied to an increasingly larger number of DOD projects. The starting point for the Army Procurement Research Office (APRO) has been to develop the concepts and factors which are important in its uncertainty analysis. Present work is concerned with locating appropriate techniques and automated procedures to implement some of the original procurement research. The purpose of this article is to present some of the historical work leading to the use of uncertainty analysis at APRO and to cite specific references which will be used on future applications.

A STARTING POINT: APRO MISSION

The mission of the Army Procurement Research Office (APRO) is to conduct procurement research studies leading to the improvement of Army procurement management, to develop new procurement concepts and techniques, and to provide consultation services on procurement and procurement related functions. The nature of procurement research has often led researchers to use qualitative approaches in their studies. The application of rigorous analytical tools has only recently been used by the procurement researchers.

THE TRANSITION: THE RECENT STORY

Much of the past work of the APRO has laid a conceptual groundwork for future uncertainty analysis. This work has been concerned with establishing relevant criteria and the analysis of individual programs (Should Cost Analysis, evaluation of competitive strategies, to name a few). This has led to a greater understanding of the important factors which will be included in future uncertainty analyses. By understanding the interrelationships amongst various factors, the procurement community has begun to more effectively articulate the problems and desires of uncertainty analysis. However, past efforts have centered more on establishing a cause/effect relationship with the goal of finding relationships and methods which reduce or eliminate the uncertainty. Whereas these studies have recognized that complex trade-offs had to be made, little effort was expended in developing methodologies for this trade-off analysis.

More recently, the procurement community is becoming more receptive to the concept of uncertainty analysis. For example, the APRO Study 806-1, Relating Acquisition and Contract Planning, completed in June, 1979 (10)*, illustrates a conceptual framework which would be amenable to uncertainty analysis using Monte Carlo simulation to determine uncertainty in various procurement alternatives. In November 1979, A Summary and Analysis of Army Project Manager Responses to a Questionnaire for the Army Acquisition Task Force (ASA-RDA), (3) was written. This publication contains a decision-tree model which could be automated and supplemented with utility assessment capability, resulting in a model for evaluating uncertainty in acquisition strategy planning. This publication indicated that the model contained therein would be utilized for a current APRO study project 904, Acquisition Strategy Development.

The above information is in no way exhaustive of all the APRO literature involved in the transition towards the use of uncertainty analysis. However, it does show the evolution of the interest of the procurement research community from the historical quantitative study to the current conditional studies, and eventually to the uncertainty analysis itself. However, research on the analytical tools is one current concern.

The research at APRO is now concerned with finding contemporary examples of uncertainty analysis which would help in the theoretical validation of any model which APRO may develop. A March 1976 article by the Aerospace Industries Association (AIA), titled Risk Elements in Government Contracting, (13) provides a good discussion on risk elements in procurement alternatives. Additionally, Decisions and Designs, Inc. has developed an extensive capability in Decision Analysis and Utility Theory as evidenced by studies of the Multi-Attribute Analysis of Alternative Naval Aviation Plans (7), An Analysis of Alternative Mideastern Oil Agreements, (1) and many studies using Multi-Attribute Utility Theory, (2, 4, 15) to name only a very few. Through similar studies, the use of the Multi-Attribute Utility Model (MAUM), trade-off analysis, and computer aided analysis has become more acceptable by reducing the manual manipulation and technical expertise needed to apply the models (14). This is in sharp contrast to former studies which needed simple relationships which all could understand before it was considered acceptable.

In mentioning studies which have contributed to

*Numbers in parentheses denote the number referenced in the list of references.

the acceptability and use of uncertainty analysis, consideration should be given to the work done by the Social Science Research Institute, University of Southern California (5, 9, 12). This work has helped APRO to gain a better understanding on topics such as group utility assessing and evaluation methodology.

It also appears that the past effort was hampered by a reluctance to accept uncertainty analysis coupled with the complexity and manual manipulation of data requirements. Much of the recent work has made significant progress in making the products more user oriented through computer assisted models. Perhaps by this very act of placing the manager in a role of model developer while also taking away the technical requirements of evaluation, we have gained more acceptability. It is particularly interesting to note that many of the models developed by DDI make extensive use of computer aids (see reference 4 for illustrations of computer aids).

It is anticipated that in early 1981, APRO will begin a study called "Uncertainty Analysis of Acquisition Alternatives." The study most likely will incorporate subjective and objective data and will utilize a Multi-attribute decision model. It is expected that this model will be automated to provide the user a computer assisted decision aiding model. APRO 80-10, Contractor Furnished Equipment v. Government Furnished Equipment - An Alternative Analysis, will address some of the subjective factors in the CFE vs. GFE analysis process. A decision aiding model will be developed to assist in the decision process of choosing the appropriate acquisition approach. Also, APRO is serving, on a consulting basis, on the Multiple Launch Rocket System (MLRS) Study. APRO was asked by the study team to recommend a probability distribution for recurring cost savings under competition. APRO analyzed the data assembled and reported by the Analytic Sciences Corporation in their report titled, "Predicting the Costs and Benefits of Competitive Production Sources" (31 Dec 79).

APRO UNCERTAINTY ANALYSIS: FUTURE STUDIES

APRO 806-1 (10) provides a starting point for future APRO studies using uncertainty analysis. Figure 1 below illustrates the concept of decomposition which Rex Brown discusses in Research and the Credibility of Estimates (11). Whereas the individual may not be able to give an assessment of the uncertainty of an alternative course of action, the decomposition method provides the analyst with a systematic method of partitioning the problem into successively more specific sub-elements until a highly specific level of problem definition is reached. These sub-elements are then combined into increasingly aggregated measures based upon predicted system characteristics and finally aggregated to the estimate of an alternative's utility. The approach which has been discussed above is commonly called the multi-attribute utility approach (2).

The structure of the model makes clear all of the elements and their relationships with each other. If any disagreement on the structure is found, it is fairly easy to enter the consideration into the model, change values, or remove elements as required. Thus, the model is not only the analytical structure, it also serves the important role of facilitating communication amongst those involved in the decision making process.

The specific structural principle of this model is the hierarchical decomposition. Each element of an alternative is partitioned into its sub-elements, each of which are partitioned into its sub-elements, etc. This decomposition continues until the final parameters affecting the alternative are reached. When thus isolated, uncertainties of these parameters can be assessed by groups of experts and recomposition (aggregation) takes place in the inverse order (6).

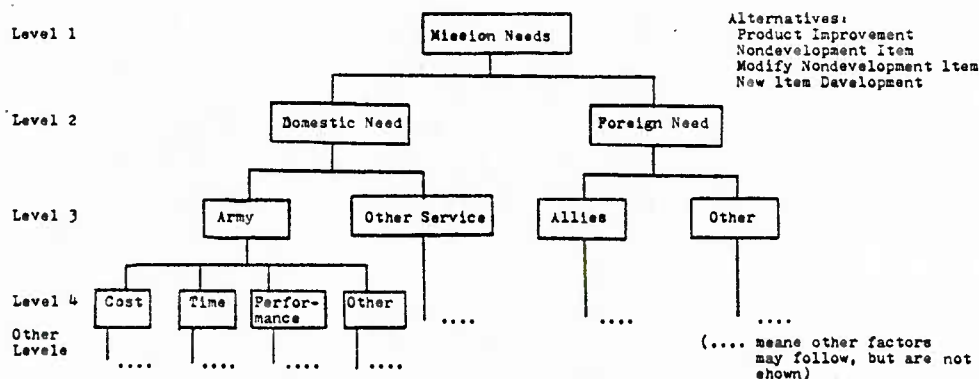


Figure 1

The first level of the hierarchical structure of figure 1 corresponds to the single value representing the utility of each of the alternatives to be analyzed. The second level represents the first of the major elements of concern: Domestic or Foreign. Under domestic, the area of concern is performance by the Army or other service. Successive levels involve cost, time, performance, and other considerations (political, social, etc.). These considerations are decomposed into layers considering marketplace, program resources, etc. When the final level of decomposition has been achieved, assessments of the outcomes of the final layers can be made. This decomposition should continue until, when an individual is asked to estimate the uncertainty, a reply such as "it depends" cannot be given. The "it depends" answer really signifies the need to further decompose the problem into still smaller sub-elements. These types of questions require the use of conditioning variables. For example, an alternative course of action frequently depends upon the dollar amount, a conditional variable.

The Decision Analysis Handbook (6) illustrates the decomposition process. It discusses rules of recombination (multiplicative and additive) and the steps in developing, analyzing, and validating the model. When the APRO uncertainty model is fully developed, it will allow users to interact with a computer assisted decision aiding tool. However, to implement this tool, certain steps remain to be taken:

1. The sub-elements of each alternative have to be identified.
2. Means to gather subjective and objective data must be provided.
3. The computer model has to be developed.
4. Implementation and use of the model requires briefings and training.

However, as DDI report 76-10 (14) relates, numerous considerations will impact upon the form which the model takes. This report gives the decision analysis users a way to identify appropriate analytic approaches for any given decision situation. It addresses the decision situation, the analytic options available, and various performance measures. It would be beneficial to use existing computer programs and methodology.

In addition to the programs addressed therein, consideration should also be given to the use of RISCA and VERT, available through the Systems and Cost Analysis Department (SCAD), Army Logistics Management Center (ALMC), Fort Lee, Virginia.

Another possible decision model for APRO studies would involve the use of a decision diagram. The Acquisition Strategies report (3) suggested a model which would form the basis of a decision diagram for acquisition strategy planning. The model in Figure 2 below is an altered form of the model presented in the APRO report.

This type of model distinguishes actions from events. Following a specific action, one or several events may occur. When the system is developed, the final objective is to assess the likelihoods of the occurrences of each event. Thus, this model requires a considerable amount of judgmental assessments. Many computer aided analysis programs are available to help with the final evaluation of the alternatives (8). As in the hierarchical decomposition process, this method attempts to decompose the problem into smaller sub-elements. However, this process also requires assessment of likelihoods of outcomes (events). The hierarchical decomposition model, on the other hand, requires the assessments of weights or measurements of importance for the various sub-elements. Both methods require subjective assessments (probabilities of outcomes or events or assessment of individual parameters). This type of model

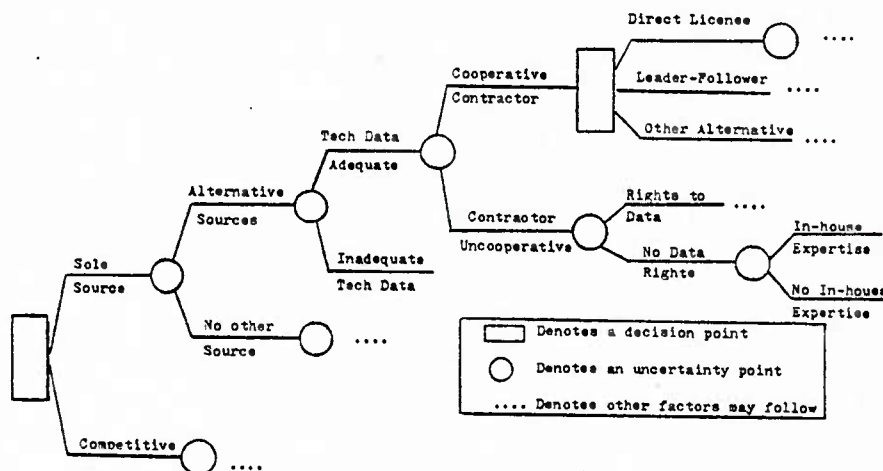


Figure 2.

was used in the Design-to-Cost evaluation for the Navy's Electronic Warfare System (2). The Decision Analysis Handbook (6) provides an excellent discussion on this decomposition process and the methodology for recomposition (the average out and fold back methodology).

The automation of the process facilitates the testing of certain "what if" questions or uncertainty analysis. For example, one may desire to see what events in the Acquisition Strategy Planning Process are more important than others. The analysis may indicate that under most reasonable circumstances, certain events will have little to no effect in the planning. This will help management to put those areas of lesser interest into proper perspective, leaving more time for evaluating those aspects of most importance. This model development will require input of opinions from many individuals. This very aspect appears to some to mean that the model is not to be used since it is just a matter of opinion. The virtue of the model is that it is systematically derived and logically constructed, making use of as much information as is available. When new information is available, it should be incorporated where possible or used to judge the analytic ability of the model.

To be successful, the application of decision analysis to major DOD projects will require several elements to be present:

1. A problem to be solved.
2. Viable and achievable alternative sources of action.
3. Information
4. A decision maker
5. A decision strategy

While reviewing several DDI decision analysis projects, the above elements were always present. The analyst usually has immediate access to the first three elements with lesser access to the last two elements. However, the DDI studies take great efforts to assure that all of these elements are present. The implication for in-house studies is apparent: success of the project is dependent upon gaining access to the Decision Maker at the start of the project.

Another concept employed by DDI projects is the team approach. Each of the three or more team members plays a specific role. One will be a recorder of rationale, another will play the role of facilitator, while another will be the model builder. The team elicits responses from the assembled experts with each team member having separate, distinct, and well defined roles in the process. Research into the applications does not indicate that

esoteric analytical methods are being employed. Rather, the circumstances of the problem definition/analysis are being controlled. This could have significant effect of in-house decision analyses: success or failure of the project is dependent upon the mechanics of application (team concept, elements present, etc.). This is not to say that sound, rigorous logic and analysis is not important. Rather, the implication is that these other factors are as important as the analytical method.

SUMMARY

It is important, in summary, to reiterate that APRO studies have not completely addressed all of the aspects of uncertainty analysis. Past efforts have laid the conceptual ground work which future efforts will use. This article has presented several approaches to uncertainty analysis: heirarchical decomposition and decision diagrams (also called trees). The selection of the technique depends upon the specific circumstance being analyzed. Many examples of analysis are available. This article has attempted to list several which will be useful to future APRO studies. Finally, it appears certain that uncertainty analysis on other than simple problems requires the use of automated analysis procedures. Many of the references selected for inclusion in this article incorporate or address computer aided analysis.

REFERENCES

1. An Agreement of Alternative Mideastern Oil Agreements, Decisions and Designs, Inc., Rex V. Brown, Cameron R. Peterson, Jacob W. Ulvila, December, 1975.
2. An Application of Multi-Attribute Utility Theory: Design-To-Cost Evaluation of the US Navy's Electronic Warfare System, Decisions and Designs, Inc., Michael L. Hays, Michael F. O'Connor, Cameron R. Peterson, October 1975.
3. "Acquisition Strategies in Army Programs", A Summary and Analysis of Army Project Manager Responses to a Questionnaire for the Army Acquisition Task Force (ASA-RDA), an APRO report dated 21 November 1979.
4. Decision Analysis as an Element in an Operational Decision Aiding System, Phase II, Technical Report 75-13, prepared for Operation Decision Aids Project (Code 455) by Decisions and Designs, Inc., R.V. Brown, C.R. Peterson, W.H. Shawcross, and J.W. Ulvila, authors. Report prepared in November 1975 (DLSIE LD 35297A)*.

*Defense Logistics Studies Information Exchange (DLSIE), US Army Logistics Management Center, Fort Lee, VA 23801

5. Experimental Tests and Independence Assumptions for Risky Multi-Attribute References, Detlof Von Winterfeldt, Social Science Research Institute, University of Southern California, October 1976, (SSRI Research Report 76-8).
6. Handbook for Decision Analysis, Decisions and Designs, Inc., Scott Barclay, Rex Brown, Clinton W. Kelly, Cameron R. Peterson, Lawrence D. Phillips, Judith Selvidge, September, 1977. (Defense Advanced Research Projects Agency, ARPA Order 3052).
7. A Multi-Attribute Utility Approach for Evaluating Alternative Naval Aviation Plans, Decisions and Designs, Inc., Michael F. O'Connor, Thomas R. Rhees, James J. Allen, September, 1976. (ARPA Order No. 3052).
8. A Pilot Survey of Computer Programs for Decision Analysis, Decisions and Designs, Inc., J.W. Ulvila, January, 1975 (DLSIE LD No. 34581A).
9. Rank Weighting in Multi-Attribute Utility Decision Making: Avoiding the Pitfalls of Equal Weights, William G. Stillwell and Ward Edwards, Social Science Research Institute, University of Southern California, September, 1979, (SSRI Research Report 79-2).
10. Relating Acquisition and Contract Planning, Army Procurement Research Office, Robert F. Williams and Wayne V. Zabel, June 1979 (APRO 806-1).
11. Research and the Credibility of Estimates, Rex V. Brown, Division of Research, Graduate School of Business Administration, Harvard University, 1969 (SBN 87584-079-5).
12. Research on the Technology of Inference and Decision, Ward Edwards, Richard S. John, and William Stillwell, Social Science Research Institute, University of Southern California (SSRI Research Report 79-1), January, 1979.
13. Risk Elements in Government Contracting, Aerospace Industries Association, March, 1976.
14. Selecting Analytic Approaches for Decision Situations. A Matching of Taxonomies, Rex V. Brown and Jacob W. Ulvila, Decisions and Designs, Inc., October, 1976 (DLSIE LD No. 38616A).
15. On Using Scenarios in the Evaluation of Complex Alternatives, Michael F. O'Connor and Ward Edwards, Decisions and Designs, Inc., December, 1976.

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INTRODUCTION

This paper is based upon studies of construction operations in the 1970's, as well as studies currently under way in the 1980's. Most of these studies have concerned firms with annual sales that range between one and twenty million dollars per year. The problems, to be discussed in detail, will concern the setting of a price when submitting competitive bids for the performance of construction work.

The author has not made extensive studies of specific DOD problems; however, based on briefings from government agencies and construction firms, as well as studies of large-scale problems on both buyer and seller sides, the author has concluded that lessons learned from studies of construction operations to all segments of the construction industry, to buyers as well as sellers, and of course, to the Department of Defense's problem of improving decision making in major acquisition activities.

Taking these conclusions even further, it is the author's belief that the Department of Defense has no unique problems with respect to risk and uncertainty. The problems encountered by DOD are similar to those encountered by other federal agencies, state governments, foreign governments, large buyers of construction services, and large contractors. The only essential differences are the specifics of the application and the values of the parameters, as we transfer technologies that have been useful in other areas to the problems of DOD.

The three major objectives of this paper are:

1. To report some methods that have been applied successfully in case studies of construction operations;
2. To report the results of these studies and comment upon causes of major problems that have been encountered; and,
3. To offer some recommendations for improving decision making on large future DOD projects.

The body of this paper is divided into five major steps for improving decision making in construction: (1) Starting; (2) Baselineing; (3) Modeling; (4) Applying; and (5) Evaluating.

Within each of these five divisions, the author discusses some of the methods used, results

obtained, and major problems encountered. Following these discussions, the author offers some final recommendations relative to the improvement of decision making on large DOD projects.

Finally, the author has included a number of appendices to facilitate the transfer of our approach at Ohio State to other participants in this workshop. Appendix A outlines the RS distribution which we use to approximate unimodal random variables. Appendix B describes what we call the M-Star Methodology for finding an optimum bid in a construction market. The methodology described in this appendix is the fundamental beginning point for modeling markets that behave in a simplistic and well-behaved manner. The final appendix, Appendix C, lists lambda parameters that are needed for the implementation and use of the RS distribution.

STEP 1: STARTING

When beginning a study of competitive bidding for any construction program, we must be certain that we are laying a solid foundation for acceptance and application of the models developed. The four most critical elements at this stage are: the identification of the firm's real objectives; the securing of approval and support for the study from the chief executive officer; the establishment of an agreed-upon method for evaluating results; and the identification of all significant constraints.

The author has found that many companies claim to have one objective while, in fact, the real objective goes unmentioned. In the general case of competitive bidding, we suggest that the primary objective of a construction company should be to maximize net profits in dollars. Yet we find in many companies that this is not the true objective; for example, a company might wish to maintain a maximum level of employment for nephews, sons, cousins, and other members of the owner's family. The true objective of the company must be determined before one proceeds with the studies, or else the policies developed will not achieve the real objectives of the firm.

In working with some government agencies, the author has found that the true objective of responsible persons may not be that of maximizing the use of taxpayer dollars. For example, the true objective of one government agency with

which the author has worked is to avoid embarrassment. The most serious embarrassment, from this agency's point of view, is having to go back to Congress and ask for more money. Its second most serious embarrassment is being guilty of not spending all the funds that were allocated for a given project.

The important point to remember is that we will develop the wrong solution if we fail to recognize the true objective of the agency we are trying to serve. True objectives must be hammered out at the onset. This is hard work, and can take several weeks to accomplish.

The need to secure the approval and full support of the chief executive officer of the company prior to beginning any study cannot be overemphasized. We have learned this the hard way. As one example, in a study that was fully approved by the president of a company, a one-year investigation resulting in recommendations for considerable capital investments was scuttled at 9:00 am on the day on which it was scheduled to be presented to the Board of Directors. The cost engineer preparing the study was, in fact, fired at that time, thus preventing the presentation of recommendations to the Board later on that day. The individual in question was fired by the Chairman of the Board, who had never been included in the problem being solved since he was approaching retirement. The Chairman of the Board had a buy-sell agreement and, as it turned out, the amount of money he would take with him when he left the company would be severely reduced if long-term investments were entered into prior to his retirement. Had the Chairman of the Board been brought in earlier and had we insisted upon his support of our studies relative to long-term capital investments, it would have been apparent that he was not supportive and the study would not and should not have proceeded.

The third major element in this stage is to have all parties agree upon a method of evaluating the results of any study. Our experience has been that contractors will buy any model we give them if they win the first two or three jobs after we give them a mathematical model, and they will reject any model if they do not win the first two or three jobs after we give them a new pricing policy -- that is, if we have not previously agreed that a sample size of twenty or thirty projects, or perhaps more, would be collected before final judgment is passed.

The last major concern in starting any study is the identification of all major constraints. This may sometimes become a sensitive matter because contractors do not want to disclose the fact that they really don't have all the money in the world, that they are approaching bankruptcy, that their lines of credit are not what they are claimed to be, or other factors that would seriously impact decision making. It is necessary to explore sensitive areas before

proceeding. The usual constraints in competitive bidding include such factors as the contractor's bonding limit, a limit on his ability to prepare and submit more than a given number of bids in a given time period, and the firm's inability to execute or perform more than a given volume of construction work in a given time period.

There are many other factors that should be and are considered before beginning a study. We never proceed with any study involving risk or uncertainty in a construction operation without attending to the four major items: identification of real objectives, securing the support of the chief executive officer, establishment of an agreed-upon method for evaluating results, and the identification of major constraints.

STEP 2: BASELINING

The second step in our studies is to establish a baseline against which we can measure future results. In the process of establishing this baseline, we become familiar with the major variables that are impacting the company and the decisions that must be made. In the case of competitive bidding, we make a retrospective study, often going back two or three years, to determine how well the company might have done in its market had it had perfect knowledge of that market. By this we mean, how many dollars could the company have made if it had known exactly the bid of each competitor prior to bidding. The major problem in establishing this baseline is that many companies, although they've been in business for many years, have no records at all of previous cost estimates, bids submitted by competitors, or other facts of importance. It is sometimes necessary to halt the study at this time and wait for six months or a year while the required data is collected.

Based upon studies of a large number of operations, we have acquired some idea of the level of achievement of construction firms using their existing methods. As a general rule, the typical firm will yield no more than 12 to 25 percent of the so-called "dollars in the market." That is, the typical firm is able to earn from one-eighth to one-fourth the the dollars the firm could earn if it knew the exact price of every competitor prior to submitting a bid.

When firms claim higher success rates, we consistently find that they are either omitting those embarrassing cases in which they were so far out of line, or they are not reporting to us those cases in which they were engaging in collusion or other price-fixing methods. Great tact and care are necessary at this point. It is important to make the contractor understand that we do not want those cases

which are not truly competitive bidding situations, but we do want those cases that are truly competitive bidding situations, regardless of how foolish the contractor might have been at the time of bidding. Thus, we not only establish a baseline for reference at a future data, after changing methods of bidding, but we also use baseline data to help us determine whether or not the dataset we are working with is actually the dataset we think we are working with.

STEP 3: MODELING

At least six sub-steps are necessary in modeling competitive bidding problems: (1) identify controllable variables; (2) identify uncontrollable variables; (3) develop a long-term mathematical model; (4) find a decision rule to achieve the objectives; (5) modify the rule as is necessary to fit temporary or permanent constraints; and (6) modify, if necessary, to better achieve short-term objectives.

The controllable variables are identified through our own knowledge of construction operations and interviews with concerned parties. Examples of controllable variables are crew composition in the case of studies of productivity, rate of hire in the case of studies of job completion rates, and level of detail in cost estimates in the case of competitive bidding strategies.

Identification of uncontrollable variables also depends primarily upon prior experience in the area, and interviews with persons intimately involved in the construction operation. Some of the uncontrollable variables include the number and types of competitors who will be submitting bids, the size of the project, short-term cyclic effects, seasonal variations of the market, and long-term (say, five or six year) cyclic effects in the marketplace.

By identifying the major variables, we develop mathematical models involving both parametric and random variable terms. We find that it is necessary to explain to the client the importance of the form of each parametric term as well as the method of estimating parameters in the model. We have found the thesis by Ludolph (10) to be useful in explaining our approach to contractors. We have also found that write-ups, such as those in Appendix B to this paper which was taken from the thesis by Li (8), are also useful in explaining to a contractor how we find an optimum pricing policy.

Part of the modeling problem is to find an approximation for random variable terms, including especially the unexplained variability. In the case of competitive bidding, this so-called unexplained variability is the prediction error as perceived by a subject contractor. In other words, it is the subject's perception of the market varying around his estimate of the cost to construct a project. We generally use the RS distribution to represent unimodal random variables. Appendix A from Li (8), which is a rewrite of sections from previous theses by Fantozzi (2) and Grieve (5), explains how to use the first four sample moments to estimate parameters.

After modeling the problem at hand, we find optimum solutions. In the case of competitive bidding, this means that we find a markup policy that will best achieve the contractor's objectives. It is important to note that the decision rules developed are long-term rules; that is, they are the rules that, in the long run, will best achieve management's objectives.

After developing long-term rules for standard unconstrained conditions, we examine the operation to determine if there are constraints that would cause us to modify the rule. If necessary, rules are modified to fit existing constraints. In the competitive bidding environment, the problem is that many companies are constrained either by the number of bids they may submit in a given time period, or by the number of jobs they may submit in a given time period.

This is illustrated in Figure 1, taken from Li (8). This figure shows equal profits contour lines for a construction company. Profits are maximized if the firm is able to complete j^{**} projects in a time period, and is able to bid b^{**} projects in a time period. However, if the firm is unable to bid or complete the required number of jobs to maximize profits, then another bidding policy must be adopted, depending upon the constraints that exist at the time of bidding.

It is noted that it is sometimes not possible to analytically model complex bidding environments. We often turn to computer simulation. An example of such a study of constraints is a thesis by Rhye (13) and his research concerning the influence of the backlog of work on construction operations. (Workshop participants who may be interested in the simulation approach to examination of risk under constrained conditions might wish to contact Captain Rhye, an Air Force officer currently stationed at the Air Force Academy).

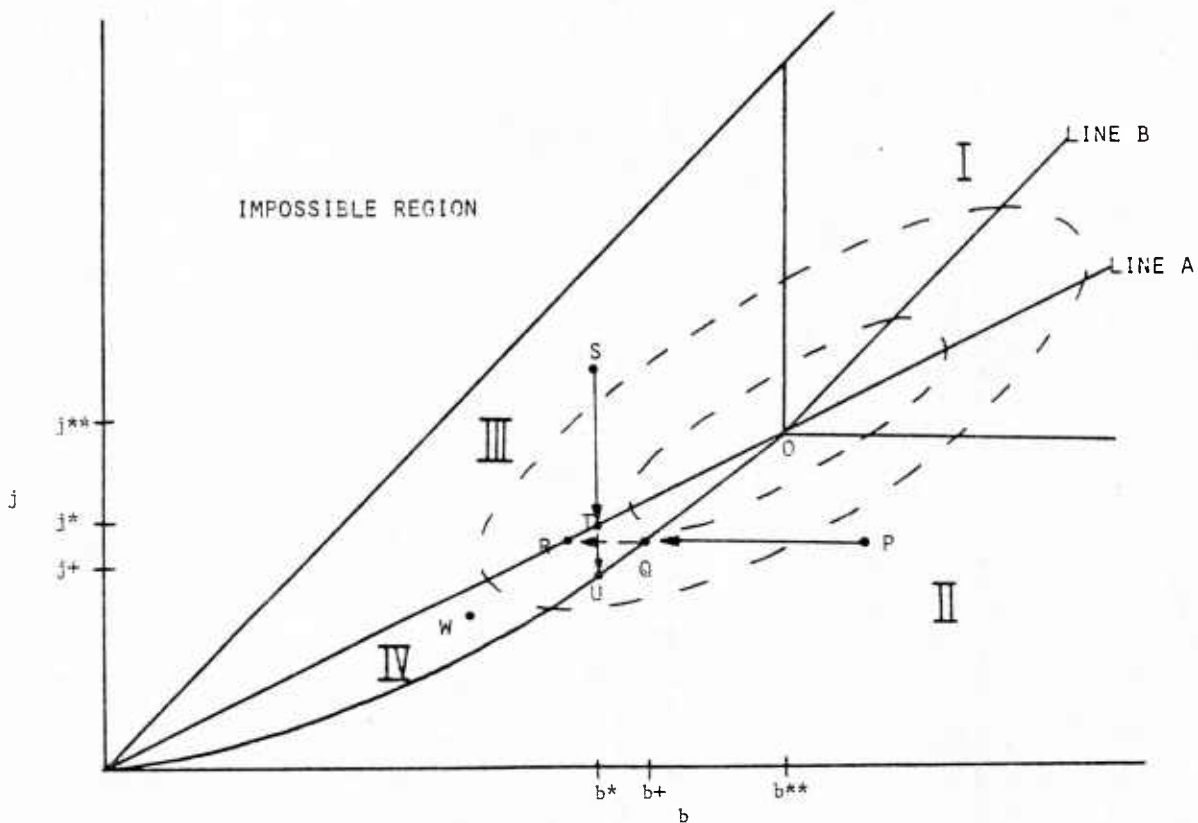


Figure 1. The Four Domains (From Reference 8)

Finally, after developing a long-term policy and modifying that policy as necessary when constraints do exist, we test the policy to insure that in striving to achieve long-term

we are also doing are best in the short run. An example from Li (8) is shown in Figure 2. This study involved the use of the binomial distribution to transform long-term bidding

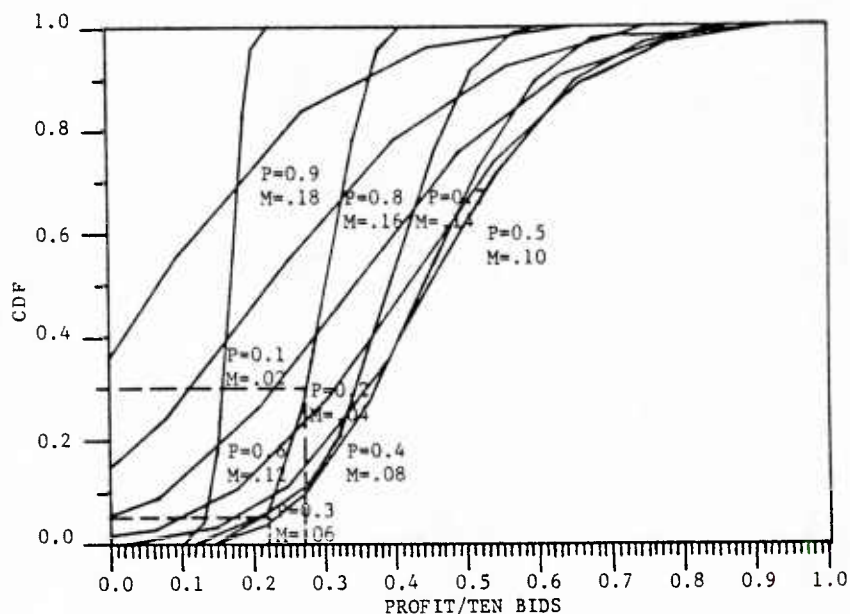


Figure 2. Short Term Profits for Ten Levels of $\bar{P}$ (From Reference 8)

probabilities into short-term bidding probabilities, and to evaluate the profits that might be realized when only a small number of projects are being bid in a time interval. From the study illustrated in Figure 2, it was found that by striving to achieve long-term objectives, the contractor does indeed achieve short-term objectives as well. That is, long-term pricing policies that are best in the long run are also best in the short run.

It has been our experience that on first glance, nearly all problems encountered in the construction industry are "bizarre" in the sense that they are poorly behaved, multimodal distributions. In all cases studied to date, when a relatively few number of independent variables (quantitative and/or qualitative) are properly included in our mathematical models, the unexplained variability is greatly reduced and it becomes unimodal, and falls within the range of skewness and kurtosis tables (which are included in Appendix C to this paper). Distributions outside the range of the tabled values have invariably been found to be reducible by the introduction of an additional explanatory variable.

It should also be noted that in our experience, the unexplained variability (that is, the prediction error) is usually significantly skewed and more peaked than a normal distribution. We seldom find any justification for the use of uniform, triangular, trapezoidal, Weibull or PERT-type distributions. All of these distributions are typically much too symmetrical and too flat to represent real life data. The only justification we have found for using such distributions is that they are convenient for simplistic practitioner applications. Given the fact that we have complex problems with significant impacts both in government and industry, clearly the time has come to use appropriate distributions that best represent reality, as distinguished from those that are convenient for the analyst.

We have also found, by experience, that the RS distribution is by far superior to all other percentile-type distributions for approximating unimodal random variables. We insist upon a percentile form of distribution since we must often turn to simulation, and this form is best suited for simulation applications. The RS distribution, its use in our pricing studies, and values of its lambda parameters are attached to this paper. The lambda values from Ricer's thesis (14), Appendix C, are found after calculating the sample moments. However, data is often unavailable for many types of studies and we therefore often use nonlinear regression to fit conceptual estimates of the distribution function of the RS distribution. Alternately, when we are working in areas in which we have considerable prior knowledge of the density functions being encountered, we may directly estimate the first two moments and the shape (skewness, kurtosis) of the random variable at

hand. Our choice of the method of estimating parameters depends entirely upon the data available and our experience in studying similar types of random variables.

Four major problem areas are sometimes encountered in our studies:

1. Nonlinear regression programs, such as BMDP-3R, are unable to handle models containing two or more nonlinear independent variables. To overcome this problem, we often work with successive generations of residuals.
2. Practical continuous simulation programs are not able to handle correlated distributions. We have developed some of our own programs to overcome this barrier. The first such program was developed by Frost (3) for studies of competitive bidding. This program has, however, been used to study all types of problems when random variables are correlated with one another. A very clever algorithm was recently developed by Lin (9) while developing a general model that links together all known theories of the probability of winning in a competitive bidding environment.
3. Missing data in regression studies is another major problem we often encounter. To understand this problem, suppose one has 1000 projects and wishes to estimate the parameters for 200 variables that are encountered in these projects. Assume that a linear multivariate model is appropriate. Also suppose that any one project includes only 30 to 50% of the variables. Under such conditions, when we attempt to run a simple linear regression program, all projects with missing data are thrown out. In fact, we end up with no projects remaining in our dataset, and we are unable to estimate the values of the parameters.
4. Network representation of projects has also posed problems. Based on a number of attempts to predict the time to complete projects using either arrow or precedence-type diagrams, the author has concluded that while these are excellent tools for planning projects and communicating interrelationships, networks are totally unacceptable for predicting and evaluating the time required for completing projects. The work by Graf (2) explains in some detail why these models are inappropriate for time predictions. He suggested that we must find and use other methods for modeling if our objective is to predict time required on a project. We are currently attempting to develop some new approaches in this area.

Another problem of growing concern is the need to develop a test for Lack of Fit. Ludolph (10) has addressed this problem using the WSSD statistic. However, we're not yet satisfied with our approach to the Lack of Fit problem. In

construction, our major problem is that the assumption of independence among all observations is, of course, false. This means that any time we attempt to run a Lack of Fit test on a selected model, it fails for lack of fit. Since all models fail due to this problem, we're not inclined to perform Lack of Fit tests. While this is not presently a top priority problem for us, it is one that the author feels should be addressed in the very near future. (Note: we have no problem handling missing data in typical time series problems. Our problem is in other domains, such as size, quantity and cost, when large proportions ranging from 10 to 80% of the cases are missing in each of these domains.

STEP 4: APPLYING

Before applying new decision-making rules in any operation, we suggest that:

1. A cum sum control chart should be developed so that sudden changes in the enterprise or environment will be promptly detected (we call this a change in modus operandi).
2. The expected results should be reviewed one more time before the model is put into use.
3. A number of cases or an elapsed time period before passing any judgments or evaluating the results should be re-approved by the chief executive officer.

The greatest problem, in the author's experience, when applying any new approach is that persons working on one project want to judge new decision-making rules by the outcome of the next one in which he has an interest. As a general rule, in the case of competitive bidding, if we happen to win the first three jobs using the new policy, management will immediately fully endorse the policy even if we only expected to win 1 in 20. Conversely, if we don't win the first 4 or 5 jobs using a new bidding policy, the entire project is likely to be rejected even though the bidding policy might be designed to win 80% of the jobs in the long run. For these reasons, it is absolutely essential that there be a pre-agreement on the number of projects to be bid before any judgments are passed.

STEP 5: EVALUATING

We have found that new pricing policies will double the profits of most companies. As a general rule, contractors are able to secure 50% of the so-called "dollars in the market" using analytical methods. Comparing these figures to those cited in the Baselining Section (Step 2), it is noted that this means that profits are typically doubled by turning from present methods to new analytical approaches in competitive bidding.

We have also found another rule of thumb: In any six-month period of time, the profits actually obtained by an analytical approach would be about 90% of those that were predicted, i.e., there is a shrinkage of about 10% in realization of profits as compared to the predicted amounts. This is due to a combination of sampling errors, changing markets, estimating errors, and other factors. Despite this shrinkage, the average firm can increase its profits by about 1% on sales.

When evaluating the results of competitive bidding policies, we often find that the client did not consistently use the proposed model throughout the trial period. However, as should be the case, it is found that in the long run, his attempts to beat the analytical model are to no avail. However, we carefully review those instances in which the subject contractor did feel that a special condition was being encountered and we consider this condition in future modeling to determine whether it does indeed impact the bidding model.

GENERAL RECOMMENDATIONS TO DOD

Based on the author's experiences in studies of competitive bidding and other risk and uncertainty problems in the construction industry, he offers five suggestions to DOD for improving its studies of risk and uncertainty in large projects:

1. There is a need for a trained core of specialists who are regularly engaged in the analysis of data from several sources. Diagnostic techniques and modeling skills cannot be maintained by persons working on one project or within one agency when they are looking at very few datasets. To maintain the necessary skills, one must continue to view and explore a wide variety of data. We find that it takes between 15 and 18 months for a Master of Science graduate student to become competent and comfortable in the application of modern techniques for modeling and assessing management and uncertainty.
2. Individuals responsible for performing major risk and uncertainty problems should serve as consultants to the responsible agency and should not be subordinates of the responsible manager. Time and again, we've seen competent study results altered to yield policies that best fit the self-interests of superiors. This is sometimes intentional, sometimes unintentional. In any event, it happens often enough to justify a consultancy relationship when performing major studies of risk and uncertainty.
3. DOD should cooperate with other federal agencies and the private sector to establish a national data bank for future studies of risk and uncertainty. The author has been

urging the creation of such a data bank for a number of years. The rationale behind this recommendation is that the data must be collected and stored as projects progress; otherwise, much data that will be needed in future analyses will never be collected and properly recorded. If such a data bank is not established, what little information that is collected which might be of use to us is eventually sent to the National Archives for aging ... anyone who has ever tried to recover information from the National Archives would agree that the time and cost of retrieval are prohibitive.

4. The Department of Defense should establish a large number of graduate student internships for M.S. and Ph.D. students, so that thesis and dissertation research may be directed toward DOD risk and uncertainly problems. However, research should not be limited to those attending military schools. The fact is, DOD's uncertainty and risk problems are not unique to that agency and graduate student research geared toward solving problems in other agencies and in the private sector will most assuredly benefit DOD as well.
5. The Department of Defense should use its influence to address the basic and critical issue of the need for significant financial support for software, hardware and additional faculty in universities and colleges where future managers are now being trained. Given the present trend, we are going to have very few DOMESTIC M.S. and Ph.D. graduates between now and the year 2000. National statistics indicate that nearly half of all graduate degrees are being awarded to international students, many of whom are fully supported financially by their governments and native businesses. These numbers are increasing every year. Given the current trend, we can fully expect that by the end of this century, the majority of real experts in the field of uncertainty and risk will be expatriots residing in their native countries, solving the problems of their governmental agencies and industries and establishing their own educational programs that will inevitably far surpass our own. If this trend continues unabated, we will be in the unenviable position of having to reimport our own technology because we will have become incapable of training experts of our own.

CONCLUSIONS

In this paper, the author has discussed some practical applications of risk and uncertainty analysis in construction operations. In particular, he has reported applications and discussed successes and failures relative to com-

petitive bidding strategies. The approach reported in this paper has been applied from the buyer's side as well as the seller's side in other studies. The approach has been applied in other areas, such as that of quality control. It has been applied in the design of labor-intensive crews and in capital-intensive spreads. It is the author's opinion that the methods reported are transferable to DOD large projects.

Perhaps the major problem in transferring these methods to DOD is the same in transferring the methods into the construction industry. Responsible persons seem, almost universally, to have little if any training in statistical methods, the use of computers, and basic concepts of risk and uncertainty. Persons responsible for analysis are not specifically trained in the methods required in modern-day studies. They think like engineers or they think like mathematicians. Unfortunately, they have great difficulty thinking in terms of random variables and thinking in terms of the interactions and transformations that occur among and through random variables. The author has offered no suggestion as to how this problem in thinking and understanding of responsible persons can or should be addressed.

However, the author has suggested that we need to begin to look ahead to the next 20 years, and to train a cadre of experts who can serve as consultants to responsible persons. The author has suggested that we need to implement internship programs, to increase support for those who are providing training for future managers of major acquisition activities, and the author has noted that unless changes are made, this nation will not only be dependent upon foreign governments for oil and other resources, but will be dependent upon foreign governments for its supply of persons expert in the field of uncertainty and risk.

BIBLIOGRAPHY

1. Dudewicz, E.J., Ramberg, J.S. and Tadi-kamalla, P.R., "A Distribution for Data Fitting and Simulation," Proceedings, Annual Technical Conference Transactions of the American Society for Quality Control, 38, 1974, pp. 407-418.
2. Fantozzi, Lawrence A., "Systems Approach for Research in Construction Estimating and Pricing," M.S. Thesis, The Ohio State University, Columbus, 1979.
3. Frost, Robert S., "Simulation of Competitive Bidding in Construction," M.S. Thesis, The Ohio State University, 1979.
4. Graf, Joseph G., "The Future of Simulation Methodology in the Construction Industry," M.S. Thesis, The Ohio State University, 1980.

5. Grieve, Marvin L., "M-Star Expectancy Pricing for Net Profit," M.S. Thesis, The Ohio State University, 1980.
6. Johnson, M.E. and Lowe, V.W., Jr., "Bounds on the Sample Skewness and Kurtosis," *Technometrics*, Vol. 21, No. 3, August 1979, pp. 377-378.
7. Larew, R.E. Cost Estimating and Pricing in a Construction Company, Vol. 2: Initial Stochastic Studies. Department of Civil Engineering, The Ohio State University, Columbus, 1976.
8. Li, Kirk "Pricing for Profit," M.S. Thesis, The Ohio State University, 1980.
9. Lin, Chia-Huang, "Analysis of Competitive Bidding Strategies," M.S. Thesis, The Ohio State University, 1980.
10. Ludolph, Douglas E., "Unit Cost Estimating," M.S. Thesis, The Ohio State University, 1979.
11. Ramberg, J.S., Dudewicz, E.J., Tadikamalla, P.R. and Mykytka, E.F., "A Probability Distribution and Its Uses in Fitting Data," *Technometrics*, Vol. 21, No. 2, May 1979.
12. Ramberg, J.S. and Schmeiser, B.W., "An Approximate Method for Generating Random Variables," *Communications of the ACM*, Vol. 17, 1974, pp. 78-82.
13. Rhye, Ralph C., "The Influence of the Backlog of Work on Construction Operations," M.S. Thesis, The Ohio State University, 1980.
14. Ricer, Terry L., "Accounting for Non-Normality and Sampling Error in Analysis of Variance of Construction Data," M.S. Thesis, The Ohio State University, 1979.
15. Tadikamalla, P.R., Ramberg, J.S., Dudewicz, E.J. and Mykytka, E.F., "A Probability Distribution and Its Uses in Fitting Data," *Technometrics*, Vol. 21, No. 2, May 1979, pp. 201-209.

APPENDIX A -- THE R-S DISTRIBUTION*

The residuals associated with the predicted equation represent the unexplained variation corresponding to the predicted equation's inability to properly describe the observed mark-ups. One can account for this variability by describing the distribution of the residuals. The R-S distribution is useful for the representation of data when the underlying model is unknown, since a wide variety of curve shapes is available with this distribution.

The R-S distribution is a generalization of Tukey's lambda (percentile) distribution. A percentile distribution characterizes a random variable as a function of its cumulative probability (from 0 to 1). This works well in pricing studies since X (markup) is a function of P (probability of winning). The standard form of the function is:

$$X = R(P) = \lambda_1 + (P^{\lambda_3} - (1-P)^{\lambda_4})/\lambda_2, \quad (A.1)$$

$$(0 \leq P \leq 1)$$

where X = the standardized value of the random variable;

P = the 100-pth percentile at which the function is being evaluated;

λ_1 = the location parameter;

λ_2 = the scaling parameter; and,

λ_3, λ_4 = the shape parameters.

The expected value of X will be:

$$E(X) = \int_{p=0}^1 R(P) dP = \lambda_1 + \left(\frac{1}{\lambda_3+1} - \frac{1}{\lambda_4+1} \right) / \lambda_2 \quad (A.2)$$

The density function of any percentile distribution is the inverse of the derivative of the distribution function:

$$f(X) = f(R(P)) = \frac{d}{dP} R(P)^{-1} \quad (A.3)$$

$$= \lambda_2 / (\lambda_3 P^{\lambda_3-1} + \lambda_4 (1-P)^{\lambda_4-1}) \quad (A.4)$$

The term R(P) in Equations A.1 and A.2 designates the standardized R-S Distribution whose mean (μ) is zero and variance (σ^2) is one.

*Taken From Li (8), which was derived from Fantozzi (2), Grieve (5), Larew (7), and Dudewicz (1).

Tables of 1 through 4 can be found in works by Dudewicz (1), Ramberg (11, 12), Tadikamalla (15), Larew (7), and Ricer (14), and are included as Appendix C to this paper.

The R-S distribution can also be used to approximate actual data. In this case, the fitted form of the equation becomes necessary:

$$\hat{X} = \hat{R}(P) = \mu + \sigma \hat{R}(P) \quad (A.5)$$

$$E(\hat{X}) = \mu + \sigma E(\hat{R}(P)) \quad (A.6)$$

$$f(\hat{X}) = f(R(P))/\sigma \quad (A.7)$$

where μ is the population mean and σ is the population variance.

The mean and variance can be estimated by the first (m_1) and second (m_2) sample moments.

The fitted values of the distribution function, the expected value and the density function will become:

$$\hat{X} = \hat{R}(P) = m_1 + \sqrt{m_2} (\lambda_1 + P^{\lambda_3} - (1-P)^{\lambda_4})/\lambda_2 \quad (A.8)$$

$$E(\hat{X}) = m_1 + \sqrt{m_2} (\lambda_1 + ((\lambda_3+1)^{-1} - (\lambda_4+1)^{-1})/\lambda_2) \quad (A.9)$$

$$f(\hat{X}) = \lambda_2 / (\sqrt{m_2} (\lambda_3 P^{\lambda_3-1} + \lambda_4 (1-P)^{\lambda_4-1})) \quad (A.10)$$

To choose the four lambda parameters, the skewness (the third standardized moment which is a measure of the symmetry of the probability density function) and kurtosis (the fourth standardized moment which is a measure of the peakedness of the probability density function) of the random variable must be estimated. This is accomplished by the following procedure:

1. Calculate the first, second, third and fourth sample moments:

$$m_1 = \bar{X} = \sum_{i=1}^n X_i / n \quad (A.11)$$

$$m_2 = \sum_{i=1}^n (X_i - \bar{X})^2 / n \quad (A.12)$$

$$m_3 = \sum_{i=1}^n (X_i - \bar{X})^3 / n \quad (A.13)$$

$$m_4 = \sum_{i=1}^n (X_i - \bar{X})^4 / n \quad (A.14)$$

2. Calculate the standardized (dimensionless) third and fourth moments of the sample:

$$\gamma_3 = m_3 / m_2^{3/2} \quad (A.15)$$

$$\gamma_4 = m_4 / m_2^2 \quad (A.16)$$

3. Match the values of $|\gamma_3|$ and $|\gamma_4|$ with the nearest table values of α_3 and α_4 , and record the values of λ_1 , λ_2 , λ_3 and λ_4 .
4. If γ_3 is negative, interchange the values of α_3 and α_4 , and change the sign of λ_1 .

The R-S distribution can also be used to approximate many of the widely used families of continuous unimodal distributions. Figure 3 shows some common unimodal distributions and their locations on the skewness-kurtosis plane. Studies at The Ohio State University have shown that the R-S distribution gives an excellent approximation of the random variables commonly found in construction costing and pricing studies.

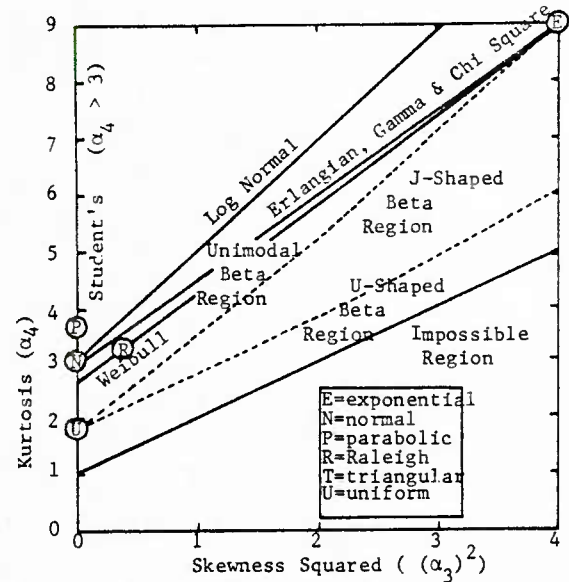


Figure 3. $(\alpha_3)^2$ versus α_4 for Various Distributions (5).

APPENDIX B -- M-STAR METHODOLOGY*

Pricing studies performed by Larew (7) indicate that: (1) markups of competitors may be expressed as a function of project size; (2) markups may or may not be independent of project size; and (3) economies or diseconomies of scale may exist in a competitively bid market. Based on these findings, Larew developed an equation for predicting the response variable, markup, as a function of the independent variable, estimated cost (or estimated project size). The equation is:

$$M = A + CX^k \quad (B.1)$$

where

M = the markup as a percentage or proportion of the estimated cost;

X = the estimated cost;

A = an estimate of the constant percentage added to any project irrespective of project size;

C = an estimate of the constant of proportionality; and,

k = an estimate of the economy of scale coefficient.

Larew found that markups tend to decrease as project size increases, with the economy of scale coefficient generally ranging from 0 to -1. These preliminary findings motivated the development of the M* bidding strategy

Using the above relationship, one begins to formulate a bidding policy by fitting the observed perceived markups of the low bidder as a function of estimated project cost for all past projects in a given market or class of work. (Obviously, the contractor with no information of past competitively bid projects need not consider this analytical procedure and must continue conceptual pricing practices until a data base is established). The perceived markup is found by the relationship:

$$\text{Perceived Markup} = \frac{\text{Low Bid} - \text{Subject Cost Estimate}}{\text{Subject Cost Estimate}} \quad (B.2)$$

All projects, won or lost, should be included in the data base. For projects won by the

*This appendix is taken from Li (8). The format and some comments in this section were taken from Fantozzi (2) and reproduced in Appendix A of Rhye's thesis (21).

contractor, the perceived markup represents the actual markup applied to the cost estimate. For projects won by a competitor, the perceived markup is a perception of the competitor's pricing policy with respect to the contractor's estimated cost. Figure 4 shows a plot of perceived markups versus estimated project costs and the fitted line, $M = A + CX^k$. The relationship between the two variables, M and X, is statistical and residuals (or errors) may be associated with each observation with respect to the fitted line. Residual is defined as the observed markup minus the predicted markup; thus,

$$\text{Residual} = (\text{Observed } M) - (A + CX^k) \quad (B.3)$$

The residuals represent some unexplained variability in the observations and may be approximated by the R-S distribution if homoscedasticity of the residuals is obtained. Homoscedasticity exists if the mean of the residuals is zero and the variance around the fitted equation is constant over the entire range of the independent variable. Figure 5 shows a residual plot where the residuals may be considered homoscedastic. The zero residual line in this plot represents the value of the markup found by the fitted equation, $M = A + CX^k$. It is often difficult to visually test for homoscedasticity since datasets are relatively small; however, one must look for trends in the residual plot to make the assumption that homoscedasticity does or does not exist. Figure 6 shows a residual plot where homoscedasticity does not exist. The absence of homoscedasticity requires further refinement of data and/or additional analysis to remove some unexplained quantitative or qualitative factor.

Assuming homoscedasticity exists, the prediction equation is improved by including a description of the residuals, R(P), approximated using the R-S distribution, and the equation becomes:

$$M = A + CX^k + R(P) \quad (B.4)$$

The R-S distribution is a percentile distribution that characterizes a random variable as a function of its cumulative probability. As explained in Appendix A, to use the R-S distribution, one must first determine the first, second, third and fourth sample moments of the residuals around the fitted line, $A + CX^k$, and then standardize (i.e., make dimensionless) the third and fourth moments which are measures of the symmetry (skewness) and peakedness (kurtosis), respectively, of the residuals around the fitted line. The

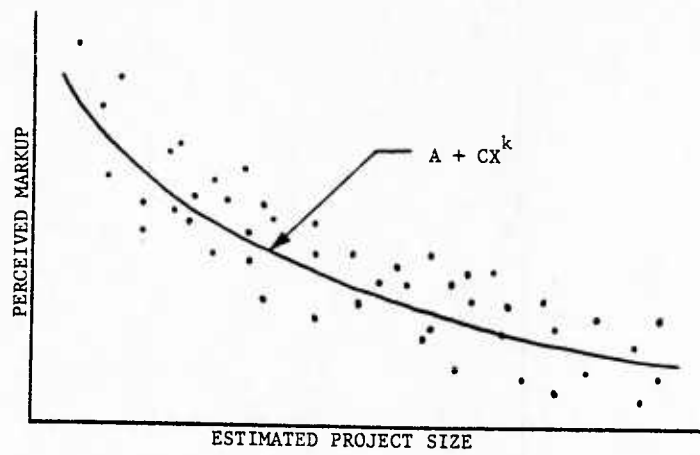


Figure 4. Perceived Markup versus Estimated Project Size (After Rhye (13))

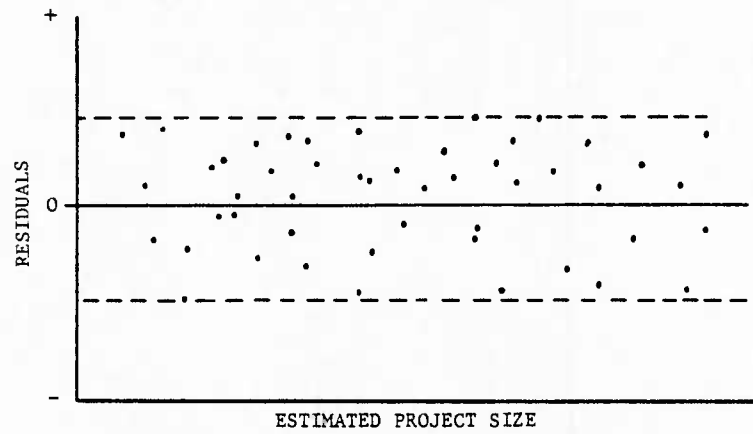


Figure 5. Homoscedastic Residuals (After Rhye (13))

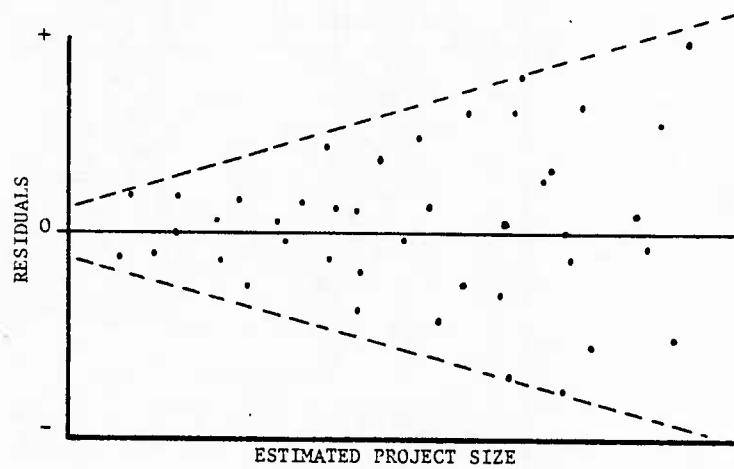


Figure 6. Non-Homoscedastic Residuals (After Rhye (13))

impact of these calculations may be understood by examining the probability distribution function (pdf) of the residuals. Construction of the pdf may be visualized by rotating the residual plot, such as that shown in Figure 5, 90 degrees clockwise and mapping the residuals down to the residual axis. One may visualize the construction of a histogram for the residuals, shown in Figure 7, such that each residual is mapped into the appropriate interval. The dotted line in Figure 7 represents the pdf of the residuals. This distribution appears to be negatively skewed; thus, the third standardized moment will be some value less than zero (the skewness of a symmetrical distribution, such as the normal distribution, is zero). It

is very difficult to visually estimate the peakedness of a distribution; however, this distribution appears to be more peaked (a higher kurtosis value) than, for example, a normal distribution.

While the pdf may be constructed with the R-S distribution by taking the inverse of the derivative of $R(P)$, the cumulative distribution function is developed using the R-S distribution and the above calculated moments, since markup is a function of the probability of winning. The cdf is constructed by iteratively determining the expected value of the residual (markup) for various probabilities of occurrence (from 0 to 1), as shown in Figure 8.

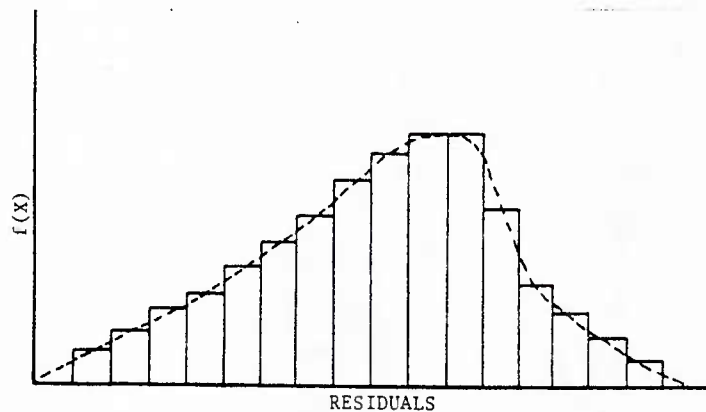


Figure 7. Histogram of Residuals (After Li (8)).

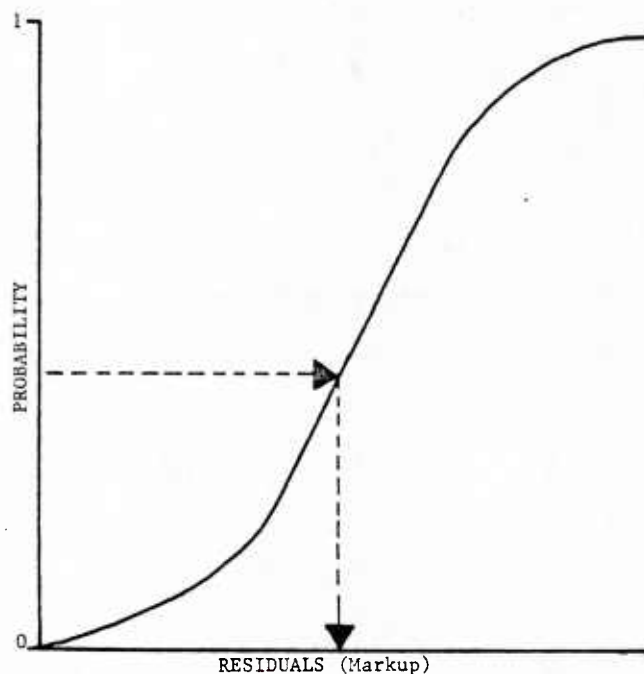


Figure 8. Cumulative Density Function: Markup as a Function of P (After Li (8)).

The probability, P , may be interpreted as the probability of not winning a contract at the corresponding markup; therefore, the probability of winning is $(1 - P)$.

The above information may now be used to develop a bidding strategy aimed at maximizing expected net profits. Net profits for a project may be considered to equal the markup minus the costs of overhead and estimating, and expectancy theory states that the expected net profits for a project are:

$$E(\Pi) = (A + CX^k + R(P))(1-P) - C_0(1-P) - C_{est} \quad (B.5)$$

where

$$\begin{aligned} E(\Pi) &= \text{estimated net profits;} \\ A + CX^k + R(P) &= \text{markup;} \\ (1 - P) &= \text{probability of winning at the above markup;} \\ C_0 &= \text{cost of overhead function;} \\ &\text{and,} \\ C_{est} &= \text{cost of estimating function.} \end{aligned}$$

The expected net profits are maximum for the above relationship when $\frac{d}{dP} E(\Pi) = 0$. Taking the derivative of the above equation and setting it equal to zero gives:

$$(1-P) \frac{d}{dP} (R(P)) = A + CX^k + R(P) - C_0 \quad (B.6)$$

The above equation may be solved by iterating P for any given project size, and the P that satisfies the relationship is termed P^* . The P^* associated with the residuals is also the P^* for the total markup for any given project size since $A + CX^k$ is constant. The optimum markup to bid for a given project size is therefore:

$$M^* = A + CX^k + R(P^*) \quad (B.7)$$

One may obtain a general bidding policy over a range of project sizes by calculating M^* at, say, 20 levels of project size, and then fitting these M^* observations as a function of project size by the equation:

$$M^* = A^* + C^*X^{k^*} \quad (B.8)$$

This equation represents the M-Star Methodology.

The following tables are taken from Appendix H of Ricer (14). Values are those currently used at The Ohio State University. They have been selected from tables previously published by Tadikamalla, Ramberg, Schmeiser, Dudewicz and Mykvtka (1, 11, 12, 15).

ALPHA3 = 0.0					ALPHA3 = 0.05				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
1.8	0.0	0.57740000	1.00000000	1.00000000	1.8	0.039	0.57810000	2.08200000	1.88280000
2.0	0.0	0.53120000	2.82470000	2.82470000	2.0	0.041	0.53160000	2.97490000	2.61150000
2.2	0.0	0.41970000	0.40921000	0.40921000	2.2	0.220	0.41430000	0.50056000	0.32017000
2.4	0.0	0.35330000	0.30321000	0.30321000	2.4	-0.375	0.33280000	0.18762000	0.39407000
2.6	0.0	0.29500000	0.23035000	0.23035000	2.6	-0.143	0.29240000	0.19733000	0.26047000
2.8	0.0	0.24340000	0.17655000	0.17655000	2.8	-0.083	0.24290000	0.16252000	0.19026000
3.0	0.0	0.19750000	0.13491000	0.13491000	3.0	-0.058	0.19750000	0.12760000	0.14247000
3.2	0.0	0.15630000	0.10157000	0.10157000	3.2	-0.046	0.15650000	0.09744800	0.10611000
3.4	0.0	0.11910000	0.07418000	0.07418000	3.4	-0.038	0.11940000	0.07181800	0.07699900
3.6	0.0	0.08530000	0.05122000	0.05122000	3.6	-0.032	0.08560000	0.04992600	0.05297000
3.8	0.0	0.05440000	0.03165600	0.03165600	3.8	-0.028	0.05480000	0.03105400	0.03269900
4.0	0.0	0.02610000	0.01476000	0.01476000	4.0	-0.025	0.02650000	0.01462600	0.01531300
4.1	0.0	0.01280000	0.00714000	0.00714000	4.1	-0.024	0.01320000	0.00718400	0.00750400
4.2	0.0	-0.00070000	-0.00036300	-0.00036300	4.2	-0.023	-0.00070000	-0.00037700	-0.00039300
4.3	0.0	-0.01230000	-0.00670600	-0.00670600	4.3	-0.022	-0.01200000	-0.00638600	-0.00644300
4.4	0.0	-0.02420000	-0.01301900	-0.01301900	4.4	-0.021	-0.02380000	-0.01259000	-0.01307600
4.6	0.0	-0.04660000	-0.02460000	-0.02460000	4.6	-0.019	-0.04630000	-0.02399800	-0.02485000
4.8	0.0	-0.06750000	-0.03497700	-0.03497700	4.8	-0.018	-0.06720000	-0.03424700	-0.03537600
5.0	0.0	-0.08710000	-0.04433700	-0.04433700	5.0	-0.017	-0.08670000	-0.04351000	-0.04485000
5.2	0.0	-0.10540000	-0.05282600	-0.05282600	5.2	-0.016	-0.10510000	-0.05192600	-0.05342900
5.4	0.0	-0.12260000	-0.06056700	-0.06056700	5.4	-0.015	-0.12230000	-0.05961100	-0.06124000
5.6	0.0	-0.13880000	-0.06765700	-0.06765700	5.6	-0.014	-0.13850000	-0.06665900	-0.06838600
5.8	0.0	-0.15410000	-0.07417800	-0.07417800	5.8	-0.014	-0.15380000	-0.07314800	-0.07495200
6.0	0.0	-0.16860000	-0.08019900	-0.08019900	6.0	-0.013	-0.16830000	-0.07914500	-0.08100900
6.2	0.0	-0.18230000	-0.08577800	-0.08577800	6.2	-0.013	-0.18200000	-0.08470500	-0.08661700
6.4	0.0	-0.19530000	-0.09096400	-0.09096400	6.4	-0.012	-0.19500000	-0.08987700	-0.09182500
6.6	0.0	-0.20770000	-0.09579700	-0.09579700	6.6	-0.012	-0.20740000	-0.09470100	-0.09667700
6.8	0.0	-0.21950000	-0.10032000	-0.10032000	6.8	-0.011	-0.21920000	-0.09921300	-0.10121000
7.0	0.0	-0.23060000	-0.10450000	-0.10450000	7.0	-0.011	-0.23050000	-0.10344000	-0.10545000
7.2	0.0	-0.24140000	-0.10850000	-0.10850000	7.2	-0.011	-0.24120000	-0.10742000	-0.10944000
7.4	0.0	-0.25180000	-0.11230000	-0.11230000	7.4	-0.010	-0.25150000	-0.11116000	-0.11319000
7.6	0.0	-0.26150000	-0.11580000	-0.11580000	7.6	-0.010	-0.26130000	-0.11469000	-0.11672000
7.8	0.0	-0.27090000	-0.11910000	-0.11910000	7.8	-0.010	-0.27070000	-0.11803000	-0.12006000
8.0	0.0	-0.28000000	-0.12230000	-0.12230000	8.0	-0.009	-0.27980000	-0.12119000	-0.12322000
8.2	0.0	-0.28870000	-0.12530000	-0.12530000	8.2	-0.009	-0.28850000	-0.12418000	-0.12622000
8.4	0.0	-0.29690000	-0.12810000	-0.12810000	8.4	-0.009	-0.29680000	-0.12700000	-0.12910000
8.6	0.0	-0.30500000	-0.13080000	-0.13080000	8.6	-0.009	-0.30480000	-0.12970000	-0.13180000
8.8	0.0	-0.31280000	-0.13340000	-0.13340000	8.8	-0.009	-0.31250000	-0.13230000	-0.13430000
9.0	0.0	-0.32030000	-0.13590000	-0.13590000	9.0	-0.008	-0.32010000	-0.13480000	-0.13680000

Table C.1 Lambda Parameters

ALPHA3 = 0.10				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
1.8	0.097	0.58080000	1.18000000	0.94210000
2.0	1.174	0.33870000	0.87245000	0.07325100
2.2	0.089	0.50010000	3.80780000	2.96290000
2.4	-0.515	0.31640000	0.14770000	0.41158000
2.6	-0.269	0.28630000	0.16783000	0.28310000
2.8	-0.164	0.24170000	0.14856000	0.20333000
3.0	-0.117	0.19770000	0.12048000	0.15033000
3.2	-0.092	0.15720000	0.09364500	0.11114000
3.4	-0.076	0.12030000	0.06983600	0.08034600
3.6	-0.065	0.08670000	0.04903200	0.05523200
3.8	-0.057	0.05590000	0.03084900	0.03422400
4.0	-0.051	0.02750000	0.01487800	0.01431600
4.1	-0.048	0.01420000	0.00760600	0.00830200
4.2	-0.046	-0.00090000	-0.00048500	-0.00052700
4.3	-0.044	-0.01090000	-0.00570300	-0.00617400
4.4	-0.042	-0.02270000	-0.01180700	-0.01274000
4.6	-0.039	-0.04520000	-0.02306000	-0.02473400
4.8	-0.036	-0.06620000	-0.03319800	-0.03543000
5.0	-0.034	-0.08570000	-0.04237900	-0.04503900
5.2	-0.032	-0.10410000	-0.05073700	-0.05372600
5.4	-0.030	-0.12130000	-0.05837900	-0.06162400
5.6	-0.029	-0.13760000	-0.06539700	-0.06884100
5.8	-0.027	-0.15290000	-0.07186500	-0.07546500
6.0	-0.026	-0.16740000	-0.07784800	-0.08157000
6.2	-0.025	-0.18120000	-0.08340000	-0.08721800
6.4	-0.024	-0.19420000	-0.08856700	-0.09245900
6.6	-0.023	-0.20660000	-0.09339000	-0.09733900
6.8	-0.023	-0.21840000	-0.09790300	-0.10189000
7.0	-0.022	-0.22970000	-0.10214000	-0.10616000
7.2	-0.021	-0.24040000	-0.10611000	-0.11016000
7.4	-0.021	-0.25070000	-0.10986000	-0.11392000
7.6	-0.020	-0.26060000	-0.11340000	-0.11747000
7.8	-0.019	-0.27000000	-0.11675000	-0.12082000
8.0	-0.019	-0.27910000	-0.11991000	-0.12398000
8.2	-0.019	-0.28780000	-0.12290000	-0.12700000
8.4	-0.018	-0.29610000	-0.12580000	-0.12980000
8.6	-0.017	-0.30410000	-0.12850000	-0.13250000
8.8	-0.017	-0.31190000	-0.13110000	-0.13510000
9.0	-0.017	-0.31930000	-0.13350000	-0.13760000

ALPHA3 = 0.15				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
1.8	0.118	0.58430000	2.07940000	1.54010000
2.0	0.120	0.53530000	3.21160000	2.31260000
2.2	0.132	0.50180000	3.98810000	2.75070000
2.4	-0.617	0.30310000	0.12148000	0.41942000
2.6	-0.376	0.27910000	0.14350000	0.29943000
2.8	-0.244	0.23980000	0.13502000	0.21565000
3.0	-0.177	0.19800000	0.11347000	0.15854000
3.2	-0.138	0.15840000	0.09006000	0.11675000
3.4	-0.114	0.12190000	0.06815200	0.08428800
3.6	-0.098	0.08840000	0.04847600	0.05805900
3.8	-0.086	0.05760000	0.03099700	0.03627300
4.0	-0.076	0.02930000	0.01548200	0.01780200
4.1	-0.073	0.01600000	0.00837800	0.00956400
4.2	-0.068	-0.00050000	-0.00027300	-0.00030900
4.3	-0.066	-0.00911300	-0.00468000	-0.00527800
4.4	-0.063	-0.02100000	-0.01069100	-0.01199300
4.6	-0.059	-0.04350000	-0.02180100	-0.02423500
4.8	-0.055	-0.06450000	-0.03183900	-0.03512800
5.0	-0.051	-0.08410000	-0.04095300	-0.04489400
5.2	-0.048	-0.10250000	-0.04926500	-0.05371000
5.4	-0.046	-0.11980000	-0.05687700	-0.06171300
5.6	-0.043	-0.13610000	-0.06387500	-0.06901700
5.8	-0.041	-0.15140000	-0.07033300	-0.07571300
6.0	-0.040	-0.16600000	-0.07631200	-0.08187900
6.2	-0.038	-0.17980000	-0.08186400	-0.08757800
6.4	-0.036	-0.19280000	-0.08703600	-0.09286300
6.6	-0.035	-0.20530000	-0.09186500	-0.09778000
6.8	-0.034	-0.21710000	-0.09638700	-0.10237000
7.0	-0.033	-0.22840000	-0.10063000	-0.10666000
7.2	-0.032	-0.23920000	-0.10462000	-0.11068000
7.4	-0.031	-0.24950000	-0.10838000	-0.11447000
7.6	-0.030	-0.25940000	-0.11193000	-0.11803000
7.8	-0.029	-0.26880000	-0.11529000	-0.12139000
8.0	-0.028	-0.27790000	-0.11847000	-0.12457000
8.2	-0.028	-0.28660000	-0.12149000	-0.12759000
8.4	-0.027	-0.29500000	-0.12433000	-0.13045000
8.6	-0.027	-0.30310000	-0.12710000	-0.13320000
8.8	-0.026	-0.31080000	-0.12970000	-0.13570000
9.0	-0.025	-0.31830000	-0.13220000	-0.13820000

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 0.20					ALPHA3 = 0.25				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
1.8	0.153	0.58050000	2.24900000	1.52070000	2.0	0.197	0.54300000	3.31000000	1.94780000
2.0	0.159	0.53860000	3.28280000	2.13200000	2.2	0.214	0.50740000	4.25540000	2.34650000
2.2	0.174	0.50420000	4.14030000	2.54490000	2.4	-0.789	0.28200000	0.08435700	0.42936000
2.4	-0.706	0.29190000	0.10126000	0.42460000	2.6	-0.558	0.26490000	0.10617000	0.32259000
2.6	-0.471	0.27180000	0.12334000	0.31197000	2.8	-0.398	0.23490000	0.10988000	0.23852000
2.8	-0.322	0.23740000	0.12211000	0.22731000	3.0	-0.299	0.19870000	0.09955600	0.17631000
3.0	-0.237	0.19830000	0.10652000	0.16720000	3.2	-0.236	0.16190000	0.08312400	0.12997000
3.2	-0.187	0.15990000	0.08658800	0.12301000	3.4	-0.196	0.12660000	0.06531900	0.09420100
3.4	-0.154	0.12400000	0.06667800	0.08888700	3.6	-0.167	0.09370000	0.04810100	0.06560600
3.6	-0.132	0.09080000	0.04819000	0.06150100	3.8	-0.146	0.06330000	0.03214500	0.04210500
3.8	-0.115	0.06010000	0.03144700	0.03888600	4.0	-0.130	0.03500000	0.01759700	0.02235400
4.0	-0.103	0.03190000	0.01640200	0.01980300	4.1	-0.126	0.02170000	0.01080000	0.01360000
4.1	-0.097	0.01850000	0.00946700	0.01130000	4.2	-0.118	0.00890000	0.00440800	0.00546700
4.2	-0.093	0.00570000	0.00289400	0.00342900	4.3	-0.113	-0.00347600	-0.00171300	-0.00210300
4.3	-0.089	-0.00664100	-0.00334200	-0.00392900	4.4	-0.108	-0.01540000	-0.00754000	-0.00917500
4.4	-0.085	-0.01850000	-0.00926100	-0.01081200	4.6	-0.100	-0.03800000	-0.01838200	-0.02201900
4.6	-0.079	-0.04110000	-0.02023600	-0.02333600	4.8	-0.093	-0.05910000	-0.02824800	-0.03339500
4.8	-0.073	-0.06210000	-0.03018500	-0.03445500	5.0	-0.087	-0.07890000	-0.03725300	-0.04355500
5.0	-0.069	-0.08180000	-0.03924100	-0.04440400	5.2	-0.082	-0.09740000	-0.04550100	-0.05269500
5.2	-0.065	-0.10030000	-0.04751700	-0.05337000	5.4	-0.077	-0.11480000	-0.05308100	-0.06096900
5.4	-0.061	-0.11760000	-0.05510900	-0.06149700	5.6	-0.073	-0.13120000	-0.06007000	-0.06850000
5.6	-0.058	-0.13390000	-0.06209800	-0.06890600	5.8	-0.070	-0.14670000	-0.06653400	-0.07539000
5.8	-0.055	-0.14940000	-0.06855500	-0.07569000	6.0	-0.067	-0.16140000	-0.07253100	-0.08172000
6.0	-0.053	-0.16400000	-0.07453900	-0.08193100	6.2	-0.064	-0.17530000	-0.07810900	-0.08756000
6.2	-0.051	-0.17780000	-0.08010000	-0.08769400	6.4	-0.062	-0.18840000	-0.08331200	-0.09296400
6.4	-0.049	-0.19090000	-0.08528300	-0.09303300	6.6	-0.059	-0.20100000	-0.08817600	-0.09798900
6.6	-0.047	-0.20340000	-0.09012700	-0.09799800	6.8	-0.057	-0.21290000	-0.09273500	-0.10267000
6.8	-0.046	-0.21530000	-0.09466400	-0.10263000	7.0	-0.055	-0.22430000	-0.09701700	-0.10704000
7.0	-0.044	-0.22660000	-0.09892300	-0.10695000	7.2	-0.054	-0.23520000	-0.10105000	-0.11114000
7.2	-0.043	-0.23740000	-0.10293000	-0.11101000	7.4	-0.052	-0.24550000	-0.10485000	-0.11498000
7.4	-0.041	-0.24780000	-0.10671000	-0.11482000	7.6	-0.051	-0.25550000	-0.10844000	-0.11860000
7.6	-0.040	-0.25770000	-0.11028000	-0.11841000	7.8	-0.049	-0.26500000	-0.11184000	-0.12201000
7.8	-0.039	-0.26720000	-0.11365000	-0.12179000	8.0	-0.048	-0.27420000	-0.11506000	-0.12524000
8.0	-0.038	-0.27630000	-0.11685000	-0.12499000	8.2	-0.047	-0.28290000	-0.11811000	-0.12829000
8.2	-0.037	-0.28500000	-0.11988000	-0.12802000	8.4	-0.046	-0.29140000	-0.12102000	-0.13118000
8.4	-0.036	-0.29340000	-0.12277000	-0.13090000	8.6	-0.045	-0.29950000	-0.12379000	-0.13393000
8.6	-0.035	-0.30140000	-0.12550000	-0.13360000	8.8	-0.044	-0.30720000	-0.12640000	-0.13650000
8.8	-0.035	-0.30920000	-0.12810000	-0.13620000	9.0	-0.043	-0.31470000	-0.12890000	-0.13900000
9.0	-0.034	-0.31680000	-0.13060000	-0.13870000	9.2	-0.042	-0.32200000	-0.13130000	-0.14140000
9.2	-0.034	-0.32410000	-0.13300000	-0.14110000					

Table C.1 Lambda Parameters
(continued)

----- ALPHA3 = 0.30 -----					----- ALPHA3 = 0.35 -----				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.0	0.235	0.54860000	3.28050000	1.75790000	2.0	0.273	0.55570000	3.17470000	1.55620000
2.2	0.252	0.51150000	4.32460000	2.15530000	2.2	0.289	0.51650000	4.33920000	1.96970000
2.4	-0.871	0.27320000	0.06949200	0.43477000	2.4	-0.955	0.26530000	0.05590100	0.44146000
2.6	-0.642	0.25860000	0.09108500	0.33243000	2.6	-0.725	0.25270000	0.07745400	0.34228000
2.8	-0.474	0.23230000	0.09830400	0.24952000	2.8	-0.550	0.22980000	0.08727100	0.26060000
3.0	-0.362	0.19920000	0.09254200	0.18593000	3.0	-0.427	0.19960000	0.08542600	0.19611000
3.2	-0.288	0.16410000	0.07956400	0.13768000	3.2	-0.343	0.16650000	0.07580900	0.14619000
3.4	-0.239	0.12980000	0.06397500	0.10028000	3.4	-0.285	0.13330000	0.06254100	0.10719000
3.6	-0.204	0.09730000	0.04813000	0.07043200	3.6	-0.243	0.10140000	0.04818900	0.07602100
3.8	-0.179	0.06710000	0.03303000	0.04597400	3.8	-0.213	0.07140000	0.03403400	0.05053600
4.0	-0.159	0.03890000	0.01902100	0.02549100	4.0	-0.189	0.04340000	0.02062400	0.02925100
4.2	-0.144	0.01280000	0.00617500	0.00803500	4.2	-0.171	0.01730000	0.00815800	0.01164400
4.3	-0.138	0.00078900	0.00038000	0.00048900	4.3	-0.163	0.00487000	0.00229300	0.00309000
4.4	-0.131	-0.01160000	-0.00555400	-0.00705700	4.4	-0.156	-0.00710000	-0.00333200	-0.00443100
4.5	-0.129	-0.02310000	-0.01100000	-0.01390000	4.5	-0.151	-0.01870000	-0.00872300	-0.01150000
4.6	-0.121	-0.03430000	-0.01625900	-0.02026200	4.6	-0.144	-0.02990000	-0.01388900	-0.01804200
4.8	-0.113	-0.05540000	-0.02604100	-0.03193100	4.8	-0.133	-0.05110000	-0.02358300	-0.03004400
5.0	-0.105	-0.07530000	-0.03500000	-0.04233300	5.0	-0.125	-0.07110000	-0.03249300	-0.04072100
5.2	-0.099	-0.09390000	-0.04322500	-0.05167400	5.2	-0.117	-0.08980000	-0.04069900	-0.05029200
5.4	-0.094	-0.11140000	-0.05080000	-0.06011700	5.4	-0.111	-0.10740000	-0.04827300	-0.05892900
5.6	-0.089	-0.12790000	-0.05779500	-0.06779100	5.6	-0.105	-0.12400000	-0.05528000	-0.06676900
5.8	-0.085	-0.14350000	-0.06427400	-0.07480300	5.8	-0.100	-0.13960000	-0.06177800	-0.07392300
6.0	-0.081	-0.15820000	-0.07029000	-0.08123900	6.0	-0.096	-0.15450000	-0.06782100	-0.08048200
6.2	-0.078	-0.17220000	-0.07589200	-0.08717100	6.2	-0.092	-0.16850000	-0.07345200	-0.08652000
6.4	-0.075	-0.18540000	-0.08112100	-0.09245700	6.4	-0.088	-0.18180000	-0.07871300	-0.09209900
6.6	-0.072	-0.19800000	-0.08601300	-0.09774900	6.6	-0.085	-0.19450000	-0.08363900	-0.09727400
6.8	-0.069	-0.21000000	-0.09060100	-0.10249000	6.8	-0.082	-0.20660000	-0.08826100	-0.10209000
7.0	-0.067	-0.22150000	-0.09491200	-0.10692000	7.0	-0.079	-0.21810000	-0.09260600	-0.10658000
7.2	-0.065	-0.23240000	-0.09897100	-0.11106000	7.2	-0.077	-0.22910000	-0.09669900	-0.11078000
7.4	-0.063	-0.24280000	-0.10280000	-0.11495000	7.4	-0.074	-0.23960000	-0.10056000	-0.11472000
7.6	-0.061	-0.25280000	-0.10642000	-0.11861000	7.6	-0.072	-0.24970000	-0.10421000	-0.11842000
7.8	-0.060	-0.26240000	-0.10984000	-0.12205000	7.8	-0.070	-0.25930000	-0.10767000	-0.12191000
8.0	-0.058	-0.27160000	-0.11309000	-0.12531000	8.0	-0.068	-0.26860000	-0.11095000	-0.12520000
8.2	-0.057	-0.28040000	-0.11617000	-0.12839000	8.2	-0.067	-0.27740000	-0.11406000	-0.12832000
8.4	-0.055	-0.28890000	-0.11911000	-0.13131000	8.4	-0.065	-0.28600000	-0.11702000	-0.13127000
8.6	-0.054	-0.29710000	-0.12190000	-0.13408000	8.6	-0.063	-0.29420000	-0.11984000	-0.13407000
8.8	-0.053	-0.30500000	-0.12460000	-0.13670000	8.8	-0.062	-0.30200000	-0.12250000	-0.13670000
9.0	-0.052	-0.31250000	-0.12710000	-0.13920000	9.0	-0.060	-0.30960000	-0.12510000	-0.13920000
9.2	-0.051	-0.31970000	-0.12950000	-0.14160000	9.2	-0.059	-0.31720000	-0.12760000	-0.14170000

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 0.40					ALPHA3 = 0.45				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.0	0.313	0.56430000	2.94950000	1.32530000	2.0	0.381	0.57320000	2.23920000	0.89646000
2.2	0.325	0.52260000	4.29000000	1.78740000	2.2	0.359	0.52980000	4.16540000	1.60400000
2.4	-1.043	0.25800000	0.04305000	0.44996000	2.4	-1.138	0.25110000	0.03050600	0.46082000
2.6	-0.808	0.24730000	0.06480500	0.35268000	2.6	-0.895	0.24230000	0.05276800	0.36411000
2.8	-0.628	0.22730000	0.07665900	0.27200000	2.8	-0.707	0.22480000	0.06633100	0.28400000
3.0	-0.495	0.20000000	0.07816600	0.20691000	3.0	-0.565	0.20040000	0.07071900	0.21841000
3.2	-0.400	0.16900000	0.07177100	0.15552000	3.2	-0.461	0.17160000	0.06737000	0.16572000
3.4	-0.333	0.13710000	0.06091200	0.11495000	3.4	-0.385	0.14120000	0.05898100	0.12362000
3.6	-0.285	0.10600000	0.04818200	0.08242400	3.6	-0.329	0.11100000	0.04800700	0.08968900
3.8	-0.249	0.07640000	0.03508100	0.05583900	3.8	-0.287	0.08180000	0.03608300	0.06193000
4.0	-0.221	0.04850000	0.02234600	0.03367700	4.0	-0.255	0.05420000	0.02412000	0.03881200
4.2	-0.199	0.02240000	0.01031100	0.01489100	4.2	-0.229	0.02820000	0.01258200	0.01925400
4.3	-0.190	0.01000000	0.00459700	0.00652100	4.3	-0.221	0.01580000	0.00704500	0.01060000
4.4	-0.182	-0.00039700	-0.00018200	-0.00025400	4.4	-0.208	0.00410200	0.00183300	0.00269100
4.5	-0.174	-0.01360000	-0.00620400	-0.00853300	4.5	-0.200	-0.00786100	-0.00350500	-0.00506500
4.6	-0.167	-0.02480000	-0.01129600	-0.01533400	4.6	-0.192	-0.01910000	-0.00851100	-0.01210900
4.8	-0.155	-0.04620000	-0.02089100	-0.02771100	4.8	-0.178	-0.04060000	-0.01798900	-0.02490800
5.0	-0.145	-0.06620000	-0.02974900	-0.03870000	5.0	-0.166	-0.06070000	-0.02678400	-0.03625000
5.2	-0.136	-0.08500000	-0.03793400	-0.04853300	5.2	-0.156	-0.07970000	-0.03494200	-0.04637900
5.4	-0.129	-0.10270000	-0.04550700	-0.05739200	5.4	-0.147	-0.09750000	-0.04251400	-0.05548900
5.6	-0.122	-0.11940000	-0.05252900	-0.06542100	5.6	-0.139	-0.11430000	-0.04955000	-0.06373400
5.8	-0.116	-0.13520000	-0.05905200	-0.07273800	5.8	-0.133	-0.13020000	-0.05610000	-0.07123700
6.0	-0.111	-0.15010000	-0.06512500	-0.07943800	6.0	-0.127	-0.14530000	-0.06220700	-0.07809800
6.2	-0.106	-0.16430000	-0.07079100	-0.08559900	6.2	-0.121	-0.15950000	-0.06791200	-0.08440000
6.4	-0.102	-0.17770000	-0.07609000	-0.09128700	6.4	-0.116	-0.17310000	-0.07325300	-0.09021100
6.6	-0.098	-0.19050000	-0.08105500	-0.09655700	6.6	-0.112	-0.18590000	-0.07826100	-0.09559000
6.8	-0.095	-0.20270000	-0.08571600	-0.10145000	6.8	-0.108	-0.19820000	-0.08296600	-0.10059000
7.0	-0.091	-0.21430000	-0.09010100	-0.10602000	7.0	-0.104	-0.20990000	-0.08739500	-0.10524000
7.2	-0.088	-0.22530000	-0.09423300	-0.11029000	7.2	-0.101	-0.22110000	-0.09157100	-0.10958000
7.4	-0.086	-0.23590000	-0.09813400	-0.11429000	7.4	-0.098	-0.23170000	-0.09551600	-0.11365000
7.6	-0.083	-0.24610000	-0.10182000	-0.11805000	7.6	-0.095	-0.24190000	-0.09924700	-0.11747000
7.8	-0.081	-0.25580000	-0.10532000	-0.12158000	7.8	-0.092	-0.25170000	-0.10278000	-0.12107000
8.0	-0.079	-0.26510000	-0.10863000	-0.12492000	8.0	-0.090	-0.26110000	-0.10614000	-0.12446000
8.2	-0.077	-0.27400000	-0.11178000	-0.12808000	8.2	-0.087	-0.27010000	-0.10932000	-0.12766000
8.4	-0.075	-0.28260000	-0.11477000	-0.13106000	8.4	-0.085	-0.27880000	-0.11236000	-0.13069000
8.6	-0.073	-0.29090000	-0.11763000	-0.13389000	8.6	-0.083	-0.28710000	-0.11524000	-0.13356000
8.8	-0.072	-0.29880000	-0.12035000	-0.13658000	8.8	-0.081	-0.29510000	-0.11800000	-0.13628000
9.0	-0.070	-0.30640000	-0.12290000	-0.13910000	9.0	-0.080	-0.30290000	-0.12060000	-0.13890000
9.2	-0.069	-0.31390000	-0.12540000	-0.14160000	9.2	-0.078	-0.31020000	-0.12310000	-0.14130000
9.4	-0.067	-0.32100000	-0.12780000	-0.14390000	9.4	-0.076	-0.31760000	-0.12560000	-0.14370000

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 0.50				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.2	0.395	0.53840000	3.94680000	1.41230000
2.4	-1.245	0.24450000	0.01782800	0.47479000
2.6	-0.986	0.23760000	0.04102100	0.37702000
2.8	-0.790	0.22250000	0.05614100	0.29686000
3.0	-0.639	0.20070000	0.06304000	0.23071000
3.2	-0.525	0.17420000	0.06254100	0.17681000
3.4	-0.440	0.14550000	0.05665000	0.13323000
3.6	-0.376	0.11630000	0.04755900	0.09786300
3.8	-0.328	0.08770000	0.03694900	0.06885700
4.0	-0.291	0.06040000	0.02586700	0.04470300
4.2	-0.262	0.03450000	0.01491100	0.02429500
4.3	-0.248	0.02210000	0.00958200	0.01520000
4.4	-0.238	0.01010000	0.00438300	0.00681500
4.5	-0.228	-0.00161200	-0.00070000	-0.00106600
4.6	-0.219	-0.01280000	-0.00557000	-0.00833400
4.8	-0.202	-0.03440000	-0.01490400	-0.02160800
5.0	-0.189	-0.05460000	-0.02361900	-0.03334500
5.2	-0.177	-0.07370000	-0.03174000	-0.04380900
5.4	-0.167	-0.09170000	-0.03930500	-0.05320400
5.6	-0.158	-0.10860000	-0.04635400	-0.06169200
5.8	-0.150	-0.12470000	-0.05293000	-0.06940500
6.0	-0.143	-0.13980000	-0.05907200	-0.07644900
6.2	-0.137	-0.15420000	-0.06481900	-0.08291100
6.4	-0.131	-0.16790000	-0.07020400	-0.08886400
6.6	-0.126	-0.18090000	-0.07526000	-0.09436700
6.8	-0.122	-0.19320000	-0.08001400	-0.09947300
7.0	-0.117	-0.20500000	-0.08449100	-0.10422000
7.2	-0.114	-0.21630000	-0.08871500	-0.10866000
7.4	-0.110	-0.22710000	-0.09270700	-0.11281000
7.6	-0.107	-0.23740000	-0.09648400	-0.11670000
7.8	-0.104	-0.24720000	-0.10006000	-0.12036000
8.0	-0.101	-0.25670000	-0.10346000	-0.12381000
8.2	-0.098	-0.26580000	-0.10669000	-0.12706000
8.4	-0.096	-0.27450000	-0.10976000	-0.13014000
8.6	-0.094	-0.28290000	-0.11269000	-0.13306000
8.8	-0.091	-0.29100000	-0.11549000	-0.13582000
9.0	-0.089	-0.29860000	-0.11810000	-0.13840000
9.2	-0.088	-0.30640000	-0.12070000	-0.14100000
9.4	-0.086	-0.31340000	-0.12310000	-0.14330000
9.6	-0.084	-0.32060000	-0.12550000	-0.14560000

ALPHA3 = 0.55				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.2	0.433	0.54840000	3.59000000	1.19530000
2.4	-1.370	0.23790000	0.00446300	0.49307000
2.6	-1.086	0.23310000	0.02924300	0.39200900
2.8	-0.877	0.22030000	0.04592900	0.31090000
3.0	-0.716	0.20090000	0.05507400	0.24396000
3.2	-0.593	0.17670000	0.05722600	0.18887000
3.4	-0.499	0.14970000	0.05382400	0.14382000
3.6	-0.427	0.12170000	0.04672800	0.10699000
3.8	-0.373	0.09390000	0.03757400	0.07667100
4.0	-0.330	0.06700000	0.02750200	0.05139700
4.2	-0.296	0.04130000	0.01722600	0.03005900
4.4	-0.269	0.01700000	0.00714900	0.01181200
4.5	-0.257	0.00535500	0.00225800	0.00364400
4.6	-0.247	-0.00600000	-0.00251500	-0.00397500
4.7	-0.237	-0.01690000	-0.00716000	-0.01110000
4.8	-0.228	-0.02760000	-0.01167000	-0.01777900
5.0	-0.212	-0.04790000	-0.02028000	-0.02996000
5.2	-0.199	-0.06710000	-0.02834800	-0.04080000
5.4	-0.187	-0.08520000	-0.03589500	-0.05051400
5.6	-0.177	-0.10230000	-0.04295100	-0.05927800
5.8	-0.168	-0.11850000	-0.04955000	-0.06722800
6.0	-0.160	-0.13380000	-0.05572700	-0.07447900
6.2	-0.153	-0.14830000	-0.06151600	-0.08112200
6.4	-0.147	-0.16210000	-0.06694900	-0.08723300
6.6	-0.141	-0.17530000	-0.07205400	-0.09287800
6.8	-0.136	-0.18770000	-0.07685900	-0.09810900
7.0	-0.131	-0.19970000	-0.08138800	-0.10297000
7.2	-0.127	-0.21100000	-0.08566400	-0.10751000
7.4	-0.123	-0.22190000	-0.08970700	-0.11175000
7.6	-0.119	-0.23230000	-0.09353400	-0.11572000
7.8	-0.116	-0.24230000	-0.09716300	-0.11945000
8.0	-0.113	-0.25180000	-0.10061000	-0.12297000
8.2	-0.110	-0.26100000	-0.10388000	-0.12629000
8.4	-0.107	-0.26980000	-0.10700000	-0.12942000
8.6	-0.104	-0.27830000	-0.10997000	-0.13239000
8.8	-0.102	-0.28650000	-0.11281000	-0.13520000
9.0	-0.100	-0.29430000	-0.11550000	-0.13790000
9.2	-0.097	-0.30190000	-0.11810000	-0.14040000
9.4	-0.095	-0.30920000	-0.12060000	-0.14280000
9.6	-0.094	-0.31640000	-0.12300000	-0.14520000

Table C.1

Lambda Parameters
(continued)

ALPHA3 = 0.60				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.2	0.499	0.55820000	2.82520000	0.85244000
2.4	0.482	0.52030000	4.77890000	1.36010000
2.6	-1.198	0.22860000	0.01705500	0.40983000
2.8	-0.972	0.21800000	0.03551000	0.32653000
3.0	-0.799	0.20100000	0.04675000	0.25835000
3.2	-0.665	0.17910000	0.05137200	0.20197000
3.4	-0.562	0.15400000	0.05042100	0.15545000
3.6	-0.482	0.12740000	0.04541000	0.11713000
3.8	-0.420	0.10040000	0.03785100	0.08542200
4.0	-0.372	0.07400000	0.02892800	0.05894800
4.2	-0.334	0.04860000	0.01944900	0.03659600
4.4	-0.303	0.02440000	0.00991100	0.01750200
4.5	-0.289	0.01280000	0.00521500	0.00896500
4.6	-0.277	0.00150000	0.00061100	0.00102600
4.7	-0.266	-0.00953100	-0.00391600	-0.00642500
4.8	-0.256	-0.02020000	-0.00832600	-0.01338600
5.0	-0.238	-0.04070000	-0.01679800	-0.02606500
5.2	-0.223	-0.06000000	-0.02479000	-0.03732500
5.4	-0.209	-0.07820000	-0.03230300	-0.04739800
5.6	-0.198	-0.09550000	-0.03935500	-0.05647000
5.8	-0.188	-0.11180000	-0.04597200	-0.06468800
6.0	-0.179	-0.12730000	-0.05218100	-0.07217000
6.2	-0.171	-0.14190000	-0.05801100	-0.07901700
6.4	-0.163	-0.15590000	-0.06349000	-0.08530700
6.6	-0.157	-0.16910000	-0.06864700	-0.09111000
6.8	-0.151	-0.18170000	-0.07350500	-0.09648300
7.0	-0.146	-0.19380000	-0.07808900	-0.10147000
7.2	-0.141	-0.20530000	-0.08242000	-0.10612000
7.4	-0.136	-0.21630000	-0.08651700	-0.11046000
7.6	-0.132	-0.22680000	-0.09039800	-0.11453000
7.8	-0.128	-0.23680000	-0.09408000	-0.11835000
8.0	-0.125	-0.24650000	-0.09757600	-0.12194000
8.2	-0.121	-0.25580000	-0.10090000	-0.12532000
8.4	-0.118	-0.26470000	-0.10407000	-0.12852000
8.6	-0.115	-0.27320000	-0.10709000	-0.13155000
8.8	-0.113	-0.28150000	-0.10997000	-0.13441000
9.0	-0.110	-0.28940000	-0.11272000	-0.13714000
9.2	-0.108	-0.29700000	-0.11530000	-0.13970000
9.4	-0.105	-0.30450000	-0.11790000	-0.14220000
9.6	-0.103	-0.31160000	-0.12030000	-0.14450000

ALPHA3 = 0.65				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.4	0.516	0.53040000	4.36130000	1.17300000
2.6	-1.329	0.22400000	0.00390800	0.43182000
2.8	-1.076	0.21570000	0.02464100	0.34431000
3.0	-0.889	0.20100000	0.03796700	0.27416000
3.2	-0.744	0.18130000	0.04492400	0.21624000
3.4	-0.630	0.15810000	0.04636600	0.16819000
3.6	-0.542	0.13300000	0.04349900	0.12832000
3.8	-0.472	0.10710000	0.03766700	0.09516600
4.0	-0.418	0.08140000	0.03004000	0.06740900
4.2	-0.374	0.05630000	0.02148700	0.04395700
4.4	-0.339	0.03230000	0.01258900	0.02392700
4.5	-0.324	-0.02070000	0.00813700	0.01500000
4.6	-0.298	-0.00040000	-0.00016100	-0.00028200
4.7	-0.297	-0.00159300	-0.00063400	-0.00110600
4.8	-0.285	-0.01230000	-0.00492100	-0.00839100
5.0	-0.265	-0.03290000	-0.01321100	-0.02162400
5.2	-0.248	-0.05230000	-0.02109500	-0.03335400
5.4	-0.233	-0.07070000	-0.02855300	-0.04382900
5.6	-0.220	-0.08810000	-0.03558700	-0.05324600
5.8	-0.208	-0.10460000	-0.04221000	-0.06176300
6.0	-0.198	-0.12020000	-0.04844400	-0.06950600
6.2	-0.189	-0.13500000	-0.05431100	-0.07658100
6.4	-0.181	-0.14910000	-0.05983600	-0.08307200
6.6	-0.174	-0.16250000	-0.06504400	-0.08905300
6.8	-0.167	-0.17520000	-0.06995700	-0.09458400
7.0	-0.161	-0.18740000	-0.07459700	-0.09971500
7.2	-0.155	-0.19900000	-0.07898400	-0.10449000
7.4	-0.150	-0.21010000	-0.08313800	-0.10895000
7.6	-0.146	-0.22080000	-0.08707600	-0.11312000
7.8	-0.141	-0.23090000	-0.09081200	-0.11703000
8.0	-0.137	-0.24070000	-0.09436300	-0.12070000
8.2	-0.134	-0.25010000	-0.09774100	-0.12417000
8.4	-0.130	-0.25910000	-0.10096000	-0.12744000
8.6	-0.127	-0.26780000	-0.10403000	-0.13053000
8.8	-0.124	-0.27610000	-0.10695000	-0.13346000
9.0	-0.121	-0.28410000	-0.10975000	-0.13623000
9.2	-0.119	-0.29190000	-0.11243000	-0.13887000
9.4	-0.116	-0.29940000	-0.11500000	-0.14140000
9.6	-0.114	-0.30650000	-0.11740000	-0.14380000
9.8	-0.112	-0.31360000	-0.11980000	-0.14610000

Table C.1

Lambda Parameters
(continued)

ALPHA3 = 0.70					ALPHA3 = 0.75				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.4	0.563	0.54110000	3.71660000	0.93547000	2.6	0.601	0.51740000	4.95390000	1.08800000
2.6	0.569	0.50720000	5.48890000	1.25770000	2.8	0.631	0.48800000	6.60410000	1.27670000
2.8	-1.194	0.21320000	0.01296700	0.36513000	3.0	-1.097	0.20030000	0.01834200	0.31189000
3.0	-0.987	0.20080000	0.02857700	0.29179000	3.2	-0.921	0.18500000	0.02992700	0.24920000
3.2	-0.828	0.18330000	0.03781100	0.23188000	3.4	-0.785	0.16580000	0.03601400	0.19743000
3.4	-0.704	0.16210000	0.04158800	0.18212000	3.6	-0.677	0.14400000	0.03753100	0.15417000
3.6	-0.606	0.13860000	0.04090300	0.14063000	3.8	-0.590	0.12060000	0.03547700	0.11788000
3.8	-0.529	0.11390000	0.03691300	0.10596000	4.0	-0.522	0.09660000	0.03086700	0.08730500
4.0	-0.467	0.08890000	0.03072400	0.07684000	4.2	-0.466	0.07260000	0.02459600	0.06138300
4.2	-0.418	0.06430000	0.02324000	0.05219900	4.4	-0.421	0.04920000	0.01736200	0.03923900
4.4	-0.345	0.01780000	0.00676700	0.01302700	4.6	-0.383	0.02660000	0.00966300	0.02016200
4.7	-0.331	0.00679900	0.00260700	0.00487200	4.7	-0.367	0.01560000	0.00574900	0.01160000
4.8	-0.318	-0.00390000	-0.00151200	-0.00275000	4.8	-0.352	0.00490000	0.00183300	0.00358300
4.9	-0.305	-0.01440000	-0.00557400	-0.00989300	4.9	-0.339	-0.00550900	-0.00206100	-0.00391600
5.0	-0.294	-0.02450000	-0.00956500	-0.01659900	5.0	-0.326	-0.01570000	-0.00591500	-0.01094900
5.2	-0.275	-0.04410000	-0.01730000	-0.02885400	5.2	-0.304	-0.03530000	-0.01345000	-0.02378600
5.4	-0.258	-0.06260000	-0.02467300	-0.03977700	5.4	-0.285	-0.05400000	-0.02070000	-0.03521000
5.6	-0.243	-0.08010000	-0.03166700	-0.04958100	5.6	-0.268	-0.07160000	-0.02762500	-0.04544300
5.8	-0.230	-0.09680000	-0.03828200	-0.05843100	5.8	-0.253	-0.08840000	-0.03421100	-0.05466700
6.0	-0.219	-0.11250000	-0.04453000	-0.06646600	6.0	-0.241	-0.10440000	-0.04045900	-0.06302700
6.2	-0.208	-0.12750000	-0.05042800	-0.07379600	6.2	-0.229	-0.11950000	-0.04637600	-0.07064100
6.4	-0.199	-0.14170000	-0.05599500	-0.08051200	6.4	-0.219	-0.13390000	-0.05197700	-0.07760800
6.6	-0.191	-0.15530000	-0.06125100	-0.08669200	6.6	-0.210	-0.14760000	-0.05727700	-0.08401100
6.8	-0.184	-0.16820000	-0.06621700	-0.09240000	6.8	-0.201	-0.16070000	-0.06229500	-0.08991600
7.0	-0.177	-0.18050000	-0.07091400	-0.09768900	7.0	-0.194	-0.17320000	-0.06704700	-0.09538100
7.2	-0.171	-0.19230000	-0.07536000	-0.10261000	7.2	-0.187	-0.18510000	-0.07155000	-0.10046000
7.4	-0.165	-0.20350000	-0.07957200	-0.10719000	7.4	-0.181	-0.19650000	-0.07582200	-0.10518000
7.6	-0.160	-0.21430000	-0.08356800	-0.11148000	7.6	-0.175	-0.20730000	-0.07987800	-0.10940000
7.8	-0.155	-0.22460000	-0.08736300	-0.11549000	7.8	-0.170	-0.21780000	-0.08373200	-0.11373000
8.0	-0.151	-0.23450000	-0.09097100	-0.11926000	8.0	-0.165	-0.22780000	-0.08739900	-0.11761000
8.2	-0.147	-0.24400000	-0.09440400	-0.12281000	8.2	-0.160	-0.23740000	-0.09089000	-0.12126000
8.4	-0.143	-0.25310000	-0.09767600	-0.12616000	8.4	-0.156	-0.24660000	-0.09421900	-0.12470000
8.6	-0.139	-0.26180000	-0.10080000	-0.12933000	8.6	-0.152	-0.25550000	-0.09739400	-0.12794000
8.8	-0.136	-0.27030000	-0.10378000	-0.13232000	8.8	-0.148	-0.26400000	-0.10043000	-0.13101000
9.0	-0.133	-0.27840000	-0.10662000	-0.13516000	9.0	-0.145	-0.27230000	-0.10333000	-0.13392000
9.2	-0.130	-0.28620000	-0.10935000	-0.13766000	9.2	-0.141	-0.28020000	-0.10610000	-0.13668000
9.4	-0.127	-0.29380000	-0.11195000	-0.14043000	9.4	-0.138	-0.28780000	-0.10876000	-0.13931000
9.6	-0.125	-0.30110000	-0.11440000	-0.14290000	9.6	-0.135	-0.29520000	-0.11131000	-0.14181000
9.8	-0.122	-0.30810000	-0.11680000	-0.14520000	9.8	-0.133	-0.30240000	-0.11375000	-0.14419000
					10.0	-0.130	-0.30930000	-0.11610000	-0.14650000

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 0.80				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.6	0.647	0.52790000	4.20140000	0.87379000
2.8	0.655	0.49760000	6.04130000	1.13630000
3.0	-1.225	0.19950000	0.00684900	0.33555000
3.2	-1.025	0.18650000	0.02110300	0.24870000
3.4	-0.873	0.16930000	0.02954800	0.21434000
3.6	-0.754	0.14920000	0.03329400	0.16906000
3.8	-0.658	0.12720000	0.03325300	0.13102000
4.0	-0.581	0.10420000	0.03034800	0.09888000
4.2	-0.518	0.08100000	0.02543900	0.07157800
4.4	-0.467	0.05810000	0.01924400	0.04823400
4.6	-0.425	0.03570000	0.01231300	0.02812400
4.8	-0.390	0.01420000	0.00503500	0.01066000
4.9	-0.375	0.00377000	0.00135200	0.00277000
5.0	-0.361	-0.00630000	-0.00227800	-0.00453100
5.1	-0.349	-0.01640000	-0.00598100	-0.01160000
5.2	-0.335	-0.02610000	-0.00959800	-0.01811000
5.4	-0.314	-0.04480000	-0.01667500	-0.03008800
5.6	-0.295	-0.06260000	-0.02349500	-0.04080100
5.8	-0.279	-0.07960000	-0.03002500	-0.05044000
6.0	-0.264	-0.09570000	-0.03625200	-0.05916200
6.2	-0.251	-0.11100000	-0.04217400	-0.06709300
6.4	-0.240	-0.12560000	-0.04779800	-0.07434000
6.6	-0.230	-0.13940000	-0.05313500	-0.08099000
6.8	-0.220	-0.15270000	-0.05819800	-0.08711500
7.0	-0.212	-0.16530000	-0.06300200	-0.09277700
7.2	-0.204	-0.17740000	-0.06756200	-0.09802900
7.4	-0.197	-0.18890000	-0.07190000	-0.10290000
7.6	-0.191	-0.19990000	-0.07600800	-0.10747000
7.8	-0.185	-0.21050000	-0.07992300	-0.11173000
8.0	-0.179	-0.22070000	-0.08365000	-0.11573000
8.2	-0.174	-0.23040000	-0.08720100	-0.11949000
8.4	-0.170	-0.23970000	-0.09058800	-0.12302000
8.6	-0.165	-0.24870000	-0.09382100	-0.12636000
8.8	-0.161	-0.25740000	-0.09691000	-0.12952000
9.0	-0.157	-0.26570000	-0.09986400	-0.13250000
9.2	-0.154	-0.27380000	-0.10269000	-0.13534000
9.4	-0.150	-0.28150000	-0.10540000	-0.13803000
9.6	-0.147	-0.28900000	-0.10800000	-0.14059000
9.8	-0.144	-0.29620000	-0.11049000	-0.14302000
10.0	-0.141	-0.30330000	-0.11290000	-0.14540000
10.2	-0.139	-0.31000000	-0.11520000	-0.14760000

ALPHA3 = 0.85				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.8	0.686	0.50800000	5.35500000	0.97656000
3.0	0.715	0.48070000	7.11870000	1.14110000
3.2	-1.145	0.13750000	0.01103600	0.29118000
3.4	-0.972	0.17240000	0.02204800	0.23325000
3.6	-0.838	0.15410000	0.02809000	0.18552000
3.8	-0.732	0.13360000	0.03013800	0.14551000
4.0	-0.646	0.11180000	0.02905300	0.11166000
4.2	-0.576	0.08950000	0.02564700	0.08286400
4.4	-0.518	0.06710000	0.02064000	0.05821600
4.6	-0.471	0.04510000	0.01461000	0.03697200
4.8	-0.431	0.02380000	0.00800100	0.01853900
4.9	-0.413	0.03140000	0.00458100	0.01020000
5.0	-0.398	0.00350000	0.00121100	0.00261200
5.1	-0.383	-0.00670100	-0.00234500	-0.00489600
5.2	-0.370	-0.01640000	-0.00580800	-0.01177700
5.4	-0.345	-0.03520000	-0.01265200	-0.02437200
5.6	-0.324	-0.05320000	-0.01932000	-0.03561700
5.8	-0.306	-0.07020000	-0.02575800	-0.04571800
6.0	-0.289	-0.08650000	-0.03193700	-0.05484200
6.2	-0.275	-0.10200000	-0.03784400	-0.06312700
6.4	-0.262	-0.11670000	-0.04347600	-0.07068500
6.6	-0.251	-0.13080000	-0.04883900	-0.07760900
6.8	-0.240	-0.14420000	-0.05393900	-0.08397900
7.0	-0.231	-0.15700000	-0.05879000	-0.08985900
7.2	-0.223	-0.16920000	-0.06340200	-0.09530600
7.4	-0.215	-0.18090000	-0.06778900	-0.10037000
7.6	-0.208	-0.19210000	-0.07196400	-0.10508000
7.8	-0.201	-0.20280000	-0.07593900	-0.10949000
8.0	-0.195	-0.21310000	-0.07972700	-0.11362000
8.2	-0.189	-0.22300000	-0.08333900	-0.11750000
8.4	-0.184	-0.23240000	-0.08678600	-0.12114000
8.6	-0.179	-0.24160000	-0.09007800	-0.12458000
8.8	-0.175	-0.25030000	-0.09322500	-0.12783000
9.0	-0.171	-0.25880000	-0.09623600	-0.13090000
9.2	-0.167	-0.26690000	-0.09911800	-0.13381000
9.4	-0.163	-0.27480000	-0.10188000	-0.13657000
9.6	-0.159	-0.28240000	-0.10453000	-0.13920000
9.8	-0.156	-0.28970000	-0.10707000	-0.14170000
10.0	-0.153	-0.29680000	-0.10952000	-0.14409000
10.2	-0.150	-0.30360000	-0.11186000	-0.14636000
10.4	-0.147	-0.31020000	-0.11412000	-0.14854000

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 0.10					ALPHA3 = 0.15				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
2.8	0.739	0.51740000	4.41340000	0.76325000	3.0	0.773	0.50080000	5.52450000	0.85032000
3.0	0.739	0.49070000	6.39070000	1.00870000	3.2	0.796	0.47570000	7.40030000	1.00890000
3.2	0.778	0.46610000	8.21710000	1.12200000	3.8	-0.906	0.14550000	0.02074900	0.17941000
3.4	-1.085	0.17510000	0.01327300	0.25483000	4.0	-0.797	0.12640000	0.02364800	0.14140000
3.6	-0.933	0.15860000	0.02178400	0.20389000	4.2	-0.709	0.10620000	0.02365600	0.10913000
3.8	-0.814	0.13970000	0.02601600	0.16153000	4.4	-0.637	0.08530000	0.02146700	0.08147900
4.0	-0.718	0.11920000	0.02686100	0.12577000	4.6	-0.576	0.06440000	0.01768500	0.05765800
4.2	-0.639	0.09790000	0.02509600	0.09533700	4.8	-0.526	0.04370000	0.01281200	0.03698800
4.4	-0.575	0.07620000	0.02142400	0.06926600	5.0	-0.484	0.02350000	0.00722600	0.01888900
4.6	-0.521	0.05470000	0.01644400	0.04679100	5.2	-0.448	0.00400000	0.00127600	0.00307400
4.8	-0.477	0.03370000	0.01063300	0.02729300	5.4	-0.417	-0.01480000	-0.00487300	-0.01095800
5.0	-0.439	0.01320000	0.00432800	0.01020000	5.6	-0.390	-0.03290000	-0.01105400	-0.02344900
5.1	-0.422	0.00333900	0.00111100	0.00252600	5.8	-0.367	-0.05020000	-0.01716300	-0.03463200
5.2	-0.407	-0.00640000	-0.00215400	-0.00473500	6.0	-0.346	-0.06670000	-0.02313300	-0.04470100
5.3	-0.394	-0.01590000	-0.00542800	-0.01160000	6.2	-0.328	-0.08250000	-0.02892200	-0.05381400
5.4	-0.379	-0.02520000	-0.00869400	-0.01801300	6.4	-0.312	-0.09760000	-0.03450300	-0.06210100
5.6	-0.356	-0.04320000	-0.01515300	-0.02984800	6.6	-0.298	-0.11200000	-0.03986400	-0.06967000
5.8	-0.335	-0.06040000	-0.02145400	-0.04046200	6.8	-0.285	-0.12570000	-0.04500200	-0.07661200
6.0	-0.317	-0.07680000	-0.02755000	-0.05003400	7.0	-0.273	-0.13890000	-0.04991600	-0.08300400
6.2	-0.301	-0.09250000	-0.03341500	-0.05871100	7.2	-0.263	-0.15140000	-0.05461200	-0.08890800
6.4	-0.286	-0.10740000	-0.03903500	-0.06661500	7.4	-0.253	-0.16350000	-0.05909700	-0.09438100
6.6	-0.274	-0.12160000	-0.04440700	-0.07384500	7.6	-0.245	-0.17500000	-0.06338000	-0.09947000
6.8	-0.262	-0.13520000	-0.04953400	-0.08048600	7.8	-0.236	-0.18600000	-0.06747000	-0.10421000
7.0	-0.252	-0.14820000	-0.05442200	-0.08660900	8.0	-0.229	-0.19660000	-0.07137600	-0.10865000
7.2	-0.242	-0.16050000	-0.05908100	-0.09227300	8.2	-0.222	-0.20680000	-0.07510800	-0.11280000
7.4	-0.233	-0.17240000	-0.06352000	-0.09753000	8.4	-0.216	-0.21650000	-0.07867600	-0.11670000
7.6	-0.226	-0.18380000	-0.06775200	-0.10242000	8.6	-0.210	-0.22590000	-0.08208900	-0.12037000
7.8	-0.218	-0.19460000	-0.07178600	-0.10699000	8.8	-0.204	-0.23500000	-0.08535500	-0.12383000
8.0	-0.212	-0.20510000	-0.07563400	-0.11126000	9.0	-0.199	-0.24370000	-0.08848400	-0.12710000
8.2	-0.205	-0.21510000	-0.07930600	-0.11527000	9.2	-0.194	-0.25210000	-0.09148200	-0.13020000
8.4	-0.200	-0.22470000	-0.08281400	-0.11904000	9.4	-0.190	-0.26010000	-0.09435700	-0.13313000
8.6	-0.194	-0.23390000	-0.08616600	-0.12259000	9.6	-0.186	-0.26790000	-0.09711600	-0.13592000
8.8	-0.189	-0.24290000	-0.08937300	-0.12594000	9.8	-0.182	-0.27550000	-0.09976600	-0.13856000
9.0	-0.184	-0.25140000	-0.09244200	-0.12910000	10.0	-0.178	-0.28280000	-0.10231000	-0.14108000
9.2	-0.180	-0.25970000	-0.09538100	-0.13210000	10.2	-0.174	-0.28980000	-0.10476000	-0.14348000
9.4	-0.176	-0.26760000	-0.09819900	-0.13494000	10.4	-0.171	-0.29660000	-0.10712000	-0.14578000
9.6	-0.172	-0.27530000	-0.10090000	-0.13765000	10.6	-0.168	-0.30320000	-0.10939000	-0.14797000
9.8	-0.168	-0.28280000	-0.10350000	-0.14022000	10.8	-0.165	-0.30960000	-0.11157000	-0.15066000
10.0	-0.165	-0.28990000	-0.10599000	-0.14267000	11.0	-0.162	-0.31580000	-0.11368000	-0.15207000
10.2	-0.162	-0.29690000	-0.10839000	-0.14500000					
10.4	-0.159	-0.30360000	-0.11070000	-0.14723000					

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 1.00					ALPHA3 = 1.10				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
3.0	0.855	0.50600000	4.25260000	0.60467000	3.2	1.700	0.37720000	2.93560000	0.11710000
3.2	0.822	0.48570000	6.49730000	0.87809000	3.4	0.909	0.48140000	6.32360000	0.74100000
3.4	0.856	0.46250000	8.40460000	0.99148000	3.6	0.931	0.46040000	8.31040000	0.86594000
3.6	0.908	0.44150000	10.48700000	1.04910000	3.8	0.977	0.44030000	10.39100000	0.93066000
3.8	-1.010	0.15090000	0.01413100	0.19962000	4.0	-1.108	0.14580000	0.00603500	0.20127000
4.0	-0.887	0.13330000	0.01926500	0.15884000	4.2	-0.974	0.12940000	0.01250900	0.16073000
4.2	-0.787	0.11420000	0.02119300	0.12441000	4.4	-0.868	0.11170000	0.01574300	0.12675000
4.4	-0.705	0.09430000	0.02063600	0.09500500	4.6	-0.781	0.09320000	0.01649700	0.09774700
4.6	-0.638	0.07410000	0.01820300	0.06967500	4.8	-0.709	0.07430000	0.01535100	0.07271000
4.8	-0.581	0.05390000	0.01441600	0.04771300	5.0	-0.648	0.05520000	0.01275500	0.05078200
5.0	-0.533	0.03400000	0.00969500	0.02853900	5.2	-0.596	0.03650000	0.00916800	0.03183800
5.2	-0.493	0.01470000	0.00438300	0.01171900	5.4	-0.552	0.01810000	0.00483900	0.01501700
5.3	-0.474	0.00519200	0.00158400	0.00406100	5.5	-0.532	0.00903800	0.00248400	0.00734200
5.4	-0.445	-0.00031700	-0.00010100	-0.00024200	5.6	-0.517	0.00099700	0.00027900	0.00079500
5.5	-0.442	-0.01320000	-0.00417600	-0.00994600	5.7	-0.497	-0.00862900	-0.00247900	-0.00672600
5.6	-0.428	-0.02220000	-0.00709700	-0.01636500	5.8	-0.481	-0.01720000	-0.00504600	-0.01318600
5.8	-0.401	-0.03960000	-0.01294800	-0.02817900	6.0	-0.452	-0.03400000	-0.01027100	-0.02509700
6.0	-0.379	-0.05620000	-0.01873800	-0.03880000	6.2	-0.426	-0.05010000	-0.01553500	-0.03582500
6.2	-0.358	-0.07210000	-0.02440700	-0.04839600	6.4	-0.404	-0.06560000	-0.02076200	-0.04553400
6.4	-0.340	-0.08730000	-0.02991600	-0.05710900	6.6	-0.384	-0.08050000	-0.02590300	-0.05436000
6.6	-0.324	-0.10190000	-0.03524000	-0.06505400	6.8	-0.366	-0.09470000	-0.03092100	-0.06241700
6.8	-0.310	-0.11580000	-0.04036700	-0.07233100	7.0	-0.350	-0.10840000	-0.03579500	-0.06980200
7.0	-0.297	-0.12910000	-0.04529100	-0.07902000	7.2	-0.335	-0.12150000	-0.04051100	-0.07659500
7.2	-0.285	-0.14190000	-0.05001200	-0.08519100	7.4	-0.322	-0.13400000	-0.04506100	-0.08286600
7.4	-0.275	-0.15410000	-0.05453400	-0.09090400	7.6	-0.310	-0.14600000	-0.04944300	-0.08867300
7.6	-0.265	-0.16580000	-0.05886100	-0.09620800	7.8	-0.299	-0.15760000	-0.05365700	-0.09406600
7.8	-0.256	-0.17700000	-0.06300000	-0.10115000	8.0	-0.289	-0.16870000	-0.05770600	-0.09908800
8.0	-0.248	-0.18770000	-0.06696100	-0.10576000	8.2	-0.280	-0.17930000	-0.06159400	-0.10378000
8.2	-0.240	-0.19800000	-0.07075000	-0.11007000	8.4	-0.271	-0.18960000	-0.06532700	-0.10817000
8.4	-0.233	-0.20800000	-0.07437700	-0.11412000	8.6	-0.263	-0.19940000	-0.06891100	-0.11229000
8.6	-0.227	-0.21750000	-0.07785000	-0.11793000	8.8	-0.256	-0.20890000	-0.07235200	-0.11616000
8.8	-0.220	-0.22670000	-0.08117600	-0.12151000	9.0	-0.249	-0.21800000	-0.07565600	-0.11981000
9.0	-0.215	-0.23550000	-0.08436400	-0.12490000	9.2	-0.242	-0.22680000	-0.07883000	-0.12325000
9.2	-0.209	-0.24400000	-0.08742100	-0.12810000	9.4	-0.236	-0.23530000	-0.08188000	-0.12650000
9.4	-0.205	-0.25220000	-0.09035400	-0.13113000	9.6	-0.231	-0.24350000	-0.08481200	-0.12959000
9.6	-0.200	-0.26020000	-0.09317100	-0.13400000	9.8	-0.226	-0.25140000	-0.08763200	-0.13251000
9.8	-0.195	-0.26780000	-0.09587600	-0.13673000	10.0	-0.221	-0.25900000	-0.09034600	-0.13529000
10.0	-0.191	-0.27520000	-0.09847700	-0.13933000	10.2	-0.216	-0.26640000	-0.09295800	-0.13793000
10.2	-0.187	-0.28240000	-0.10098000	-0.14180000	10.4	-0.211	-0.27360000	-0.09547500	-0.14045000
10.4	-0.184	-0.28930000	-0.10339000	-0.14417000	10.6	-0.207	-0.28050000	-0.09790000	-0.14285000
10.6	-0.180	-0.29600000	-0.10571000	-0.14642000	10.8	-0.203	-0.28720000	-0.10024000	-0.14514000
10.8	-0.177	-0.30250000	-0.10794000	-0.14858000	11.0	-0.200	-0.29370000	-0.10249000	-0.14733000

Table C.1 Lambda Parameters
(continued)

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ALPHA3 = 1.20				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
3.2	2.314	0.31240000	3.08860000	0.03356800
3.4	2.116	0.33370000	3.26790000	0.06339800
3.6	1.019	0.47530000	5.79080000	0.58346000
3.8	1.009	0.45880000	7.93240000	0.73992000
4.0	1.044	0.44010000	9.99990000	0.81738000
4.2	-0.563	-0.00020000	-0.00004400	-0.00014200
4.4	-1.083	0.12780000	0.00509800	0.16750000
4.6	-0.965	0.11140000	0.00996800	0.13292000
4.8	-0.870	0.09410000	0.01220800	0.10364000
5.0	-0.791	0.07640000	0.01244600	0.07841500
5.2	-0.724	0.05860000	0.01115300	0.05645700
5.4	-0.668	0.04080000	0.00870500	0.03719000
5.6	-0.619	0.02330000	0.00541100	0.02017100
5.7	-0.597	0.04160000	0.00352500	0.01240000
5.8	-0.577	0.00610000	0.00151500	0.00505000
5.9	-0.558	-0.00231900	-0.00059400	-0.00188400
6.0	-0.562	-0.00096200	-0.00024500	-0.00078400
6.2	-0.508	-0.02680000	-0.00734300	-0.02058100
6.4	-0.480	-0.04240000	-0.01204000	-0.03151900
6.6	-0.455	-0.05750000	-0.01679100	-0.04142900
6.8	-0.432	-0.07200000	-0.02153300	-0.05044800
7.0	-0.412	-0.08600000	-0.02621900	-0.05868800
7.2	-0.394	-0.09940000	-0.03081800	-0.06624500
7.4	-0.377	-0.11230000	-0.03530600	-0.07319900
7.6	-0.363	-0.12470000	-0.03966900	-0.07962000
7.8	-0.349	-0.13660000	-0.04389900	-0.08556800
8.0	-0.337	-0.14800000	-0.04798900	-0.09109300
8.2	-0.325	-0.15900000	-0.05194000	-0.09623900
8.4	-0.315	-0.16960000	-0.05575100	-0.10104000
8.6	-0.305	-0.17970000	-0.05942400	-0.10554000
8.8	-0.296	-0.18950000	-0.06296200	-0.10976000
9.0	-0.288	-0.19900000	-0.06637000	-0.11373000
9.2	-0.280	-0.20810000	-0.06965200	-0.11746000
9.4	-0.273	-0.21680000	-0.07281200	-0.12099000
9.6	-0.266	-0.22530000	-0.07585600	-0.12432000
9.8	-0.259	-0.23350000	-0.07878900	-0.12748000
10.0	-0.253	-0.24140000	-0.08161500	-0.13047000
10.2	-0.248	-0.24900000	-0.08433900	-0.13331000
10.4	-0.243	-0.25640000	-0.08696500	-0.13602000
10.6	-0.237	-0.26360000	-0.08949900	-0.13859000
10.8	-0.233	-0.27050000	-0.09194400	-0.14105000
11.0	-0.228	-0.27720000	-0.09430500	-0.14339000
11.2	-0.224	-0.28370000	-0.09660000	-0.14560000
11.4	-0.220	-0.29010000	-0.09880000	-0.14780000

ALPHA3 = 1.30				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
3.8	1.311	0.44150000	4.39930000	0.30896000
4.0	1.102	0.45600000	7.24220000	0.60354000
4.2	1.114	0.44010000	9.33850000	0.70343000
4.4	1.155	0.42360000	11.51700000	0.75751000
4.6	1.210	0.40760000	13.96100000	0.78535000
4.8	-1.084	0.11290000	0.00317400	0.14353000
5.0	-0.975	0.09680000	0.00722500	0.11303000
5.2	-0.886	0.08020000	0.00903500	0.08702600
5.4	-0.812	0.06340000	0.00914800	0.06448100
5.6	-0.749	0.04660000	0.00795900	0.04471800
5.8	-0.695	0.02990000	0.00578300	0.02727800
6.0	-0.604	0.00028600	0.00006619	0.00023900
6.1	-0.617	0.00044600	0.00010000	0.00010000
6.2	-0.616	-0.00052600	-0.00011800	-0.00044200
6.3	-0.589	-0.01040000	-0.00245000	-0.00850400
6.4	-0.571	-0.01820000	-0.00439900	-0.01457400
6.6	-0.539	-0.03330000	-0.00846900	-0.02583000
6.8	-0.511	-0.04800000	-0.01268800	-0.03603800
7.0	-0.486	-0.06220000	-0.01698100	-0.04533200
7.2	-0.463	-0.07590000	-0.02129100	-0.05382900
7.4	-0.443	-0.08900000	-0.02557600	-0.06162400
7.6	-0.424	-0.10180000	-0.02980400	-0.06879900
7.8	-0.407	-0.11400000	-0.03395200	-0.07542600
8.0	-0.392	-0.12570000	-0.03800600	-0.08156400
8.2	-0.378	-0.13710000	-0.04195300	-0.08726500
8.4	-0.365	-0.14800000	-0.04578800	-0.09257600
8.6	-0.353	-0.15850000	-0.04950700	-0.09753400
8.8	-0.342	-0.16860000	-0.05310800	-0.10217000
9.0	-0.332	-0.17840000	-0.05659200	-0.10653000
9.2	-0.323	-0.18780000	-0.05995900	-0.11062000
9.4	-0.314	-0.19690000	-0.06321300	-0.11447000
9.6	-0.306	-0.20570000	-0.06635500	-0.11810000
9.8	-0.298	-0.21420000	-0.06939000	-0.12154000
10.0	-0.291	-0.22240000	-0.07232100	-0.12479000
10.2	-0.284	-0.23030000	-0.07515200	-0.12787000
10.4	-0.277	-0.23790000	-0.07788600	-0.13080000
10.6	-0.271	-0.24540000	-0.08052700	-0.13358000
10.8	-0.266	-0.25250000	-0.08307900	-0.13624000
11.0	-0.260	-0.25950000	-0.08554600	-0.13876000
11.2	-0.255	-0.26620000	-0.08793100	-0.14117000
11.4	-0.250	-0.27280000	-0.09023800	-0.14348000
11.6	-0.246	-0.27910000	-0.09247000	-0.14568000
11.8	-0.242	-0.28530000	-0.09463000	-0.14780000

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 1.40				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
4.2	1.255	0.44530000	6.10130000	0.42931000
4.4	1.200	0.43880000	8.40330000	0.58043000
4.6	1.219	0.42460000	10.53200000	0.65450000
4.8	1.262	0.40980000	12.79900000	0.69618000
5.0	1.318	0.39530000	15.34800000	0.71771000
5.2	-1.106	0.10110000	0.00078700	0.12683000
5.4	-1.001	0.08550000	0.00454600	0.09910100
5.6	-0.916	0.06970000	0.00629600	0.07537100
5.8	-0.844	0.05380000	0.00653000	0.05472000
6.0	-0.782	0.03790000	0.00560300	0.03654100
6.2	-0.729	0.02220000	0.00378500	0.02040500
6.3	-0.706	0.01450000	0.00261100	0.01300000
6.4	-0.683	0.00680000	0.00129200	0.00598700
6.5	-0.660	-0.00122600	-0.00024400	-0.00105200
6.6	-0.643	-0.00830000	-0.00170200	-0.00696800
6.8	-0.607	-0.02300000	-0.00506000	-0.01866600
7.0	-0.575	-0.03730000	-0.00867000	-0.02927700
7.2	-0.546	-0.05110000	-0.01244600	-0.03894100
7.4	-0.521	-0.06450000	-0.01631800	-0.04777600
7.6	-0.497	-0.07750000	-0.02023400	-0.05588200
7.8	-0.476	-0.09000000	-0.02415300	-0.06334400
8.0	-0.457	-0.10210000	-0.02804500	-0.07023400
8.2	-0.440	-0.11370000	-0.03188500	-0.07661600
8.4	-0.424	-0.12500000	-0.03565700	-0.08254300
8.6	-0.409	-0.13580000	-0.03934900	-0.08806300
8.8	-0.396	-0.14630000	-0.04295300	-0.09321400
9.0	-0.383	-0.15640000	-0.04646200	-0.09803400
9.2	-0.372	-0.16610000	-0.04987400	-0.10255000
9.4	-0.361	-0.17560000	-0.05318700	-0.10680000
9.6	-0.351	-0.18470000	-0.05640000	-0.11080000
9.8	-0.342	-0.19340000	-0.05951500	-0.11457000
10.0	-0.333	-0.20190000	-0.06253300	-0.11813000
10.2	-0.325	-0.21010000	-0.06545500	-0.12150000
10.4	-0.317	-0.21810000	-0.06828500	-0.12470000
10.6	-0.310	-0.22580000	-0.07102500	-0.12773000
10.8	-0.303	-0.23320000	-0.07367800	-0.13061000
11.0	-0.297	-0.24050000	-0.07624600	-0.13336000
11.2	-0.291	-0.24750000	-0.07873300	-0.13597000
11.4	-0.285	-0.25420000	-0.08114100	-0.13847000
11.6	-0.279	-0.26080000	-0.08347400	-0.14085000
11.8	-0.274	-0.26720000	-0.08573400	-0.14313000
12.0	-0.269	-0.27340000	-0.08790000	-0.14530000
12.2	-0.265	-0.27940000	-0.09000000	-0.14740000

ALPHA3 = 1.50				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
4.4	1.966	0.35820000	4.50420000	0.12876000
4.6	1.337	0.43110000	7.10470000	0.42910000
4.8	1.302	0.42390000	9.32070000	0.54132000
5.0	1.323	0.41140000	11.48100000	0.60187000
5.2	1.365	0.39810000	13.79600000	0.63706000
5.4	1.419	0.38500000	16.38600000	0.65586000
5.6	1.484	0.37210000	19.36300000	0.66279000
5.8	-1.042	0.07730000	0.00194900	0.08991400
6.0	-0.957	0.06220000	0.00390700	0.06770300
6.2	-0.885	0.04710000	0.00444100	0.04834600
6.4	-0.824	0.03210000	0.00388500	0.03126600
6.6	-0.688	0.00056600	0.00010400	0.00049400
6.7	-0.747	0.00996200	0.00153800	0.00905900
6.8	-0.714	-0.00029000	-0.00004897	-0.00025600
6.9	-0.704	-0.00444600	-0.00076800	-0.00388200
7.0	-0.684	-0.01150000	-0.00208800	-0.00987500
7.2	-0.647	-0.02540000	-0.00498900	-0.02101900
7.4	-0.615	-0.03900000	-0.00815600	-0.03116200
7.6	-0.585	-0.05210000	-0.01150900	-0.04043100
7.8	-0.559	-0.06480000	-0.01498300	-0.04893200
8.0	-0.535	-0.07720000	-0.01852800	-0.05675500
8.2	-0.513	-0.08910000	-0.02210500	-0.06397600
8.4	-0.494	-0.10070000	-0.02568100	-0.07066200
8.6	-0.475	-0.11180000	-0.02923300	-0.07686900
8.8	-0.459	-0.12260000	-0.03274300	-0.08264600
9.0	-0.443	-0.13300000	-0.03620000	-0.08800000
9.2	-0.429	-0.14310000	-0.03960000	-0.09310000
9.4	-0.416	-0.15280000	-0.04289900	-0.09780300
9.6	-0.404	-0.16220000	-0.04613400	-0.10224000
9.8	-0.392	-0.17140000	-0.04928800	-0.10642000
10.0	-0.382	-0.18020000	-0.05235900	-0.11035000
10.2	-0.372	-0.18870000	-0.05534500	-0.11407000
10.4	-0.363	-0.19690000	-0.05824700	-0.11759000
10.6	-0.354	-0.20490000	-0.06106700	-0.12092000
10.8	-0.346	-0.21270000	-0.06380400	-0.12408000
11.0	-0.338	-0.22010000	-0.06646000	-0.12708000
11.2	-0.331	-0.22740000	-0.06903900	-0.12994000
11.4	-0.324	-0.23450000	-0.07154100	-0.13266000
11.6	-0.317	-0.24130000	-0.07396800	-0.13526000
11.8	-0.311	-0.24790000	-0.07632400	-0.13774000
12.0	-0.305	-0.25440000	-0.07861100	-0.14011000
12.2	-0.300	-0.26070000	-0.08083000	-0.14238000
12.4	-0.294	-0.26670000	-0.08298400	-0.14455000
12.6	-0.289	-0.27270000	-0.08507600	-0.14663000
12.8	-0.284	-0.27840000	-0.08710700	-0.14863000

Table C.1 Lambda Parameters
(continued)

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ALPHA3 = 1.60				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
5.8	1.515	0.37620000	17.06300000	0.59931800
6.0	1.577	0.36440000	19.98300000	0.60731000
6.2	1.647	0.35280000	23.35600000	0.60746000
6.4	-1.011	0.05730000	0.00169900	0.86343300
6.6	-0.937	0.04300000	0.00268400	0.04486700
6.8	-0.875	0.02870000	0.00259700	0.02849800
7.0	-0.746	-0.00042200	-0.00006356	0.00037800
7.1	-0.796	0.00777300	0.00096900	0.08717700
7.2	-0.771	-0.00034100	-0.00004634	-0.08030900
7.3	-0.751	-0.00592400	-0.00085800	-0.80527900
7.4	-0.731	-0.01260000	-0.00194200	-0.81105900
7.6	-0.693	-0.02580000	-0.00438300	-0.02182400
7.8	-0.639	-0.03870000	-0.00711100	-0.03164700
8.0	-0.629	-0.05120000	-0.01004900	-0.84064600
8.2	-0.602	-0.06340000	-0.01313600	-0.84892000
8.4	-0.577	-0.07520000	-0.01632200	-0.85655100
8.6	-0.554	-0.08660000	-0.01956700	-0.86361100
8.8	-0.533	-0.09770000	-0.02283900	-0.87816000
9.0	-0.514	-0.10840000	-0.02611400	-0.07625300
9.2	-0.497	-0.11880000	-0.02937100	-0.88193400
9.4	-0.480	-0.12880000	-0.03259600	-0.08724400
9.6	-0.465	-0.13860000	-0.03577600	-0.09221700
9.8	-0.451	-0.14800000	-0.03890200	-0.09688500
10.0	-0.438	-0.15710000	-0.04196900	-0.10128000
10.2	-0.426	-0.16590000	-0.04497000	-0.10541000
10.4	-0.415	-0.17450000	-0.04790400	-0.10932000
10.6	-0.404	-0.18280000	-0.05076700	-0.11301000
10.8	-0.395	-0.19080000	-0.05355900	-0.11659000
11.0	-0.385	-0.19860000	-0.05627900	-0.11982000
11.2	-0.376	-0.20620000	-0.05892800	-0.12296000
11.4	-0.368	-0.21350000	-0.06150600	-0.12596000
11.6	-0.360	-0.22060000	-0.06401400	-0.12880000
11.8	-0.353	-0.22750000	-0.06645400	-0.13152000
12.0	-0.346	-0.23420000	-0.06882700	-0.13411000
12.2	-0.339	-0.24070000	-0.07113400	-0.13659000
12.4	-0.333	-0.24700000	-0.07337700	-0.13896000
12.6	-0.327	-0.25320000	-0.07555900	-0.14123000
12.8	-0.321	-0.25920000	-0.07768000	-0.14340000
13.0	-0.315	-0.26500000	-0.07974300	-0.14549000
13.2	-0.310	-0.27070000	-0.08175000	-0.14749000
13.4	-0.305	-0.27620000	-0.08370200	-0.14942000
13.6	-0.301	-0.28160000	-0.08560200	-0.15127000
13.8	-0.296	-0.28680000	-0.08745000	-0.15305000

ALPHA3 = 1.70				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
4.8	6.736	0.14100000	5.55430000	-0.09290800
5.0	2.792	0.28580000	5.16110000	0.04125300
5.2	1.919	0.36580000	5.86250000	0.17963000
5.4	1.562	0.40140000	8.24260000	0.36839000
5.6	1.516	0.39830000	10.42100000	0.44444000
5.8	1.526	0.38940000	12.58600000	0.49687000
6.0	1.560	0.37910000	14.88200000	0.52822000
6.2	1.607	0.36850000	17.39700000	0.54705800
6.4	1.664	0.35780000	20.21100000	0.55680000
6.6	1.729	0.34720000	23.40800000	0.55959080
6.8	1.802	0.33670000	27.08800000	0.55686080
7.0	-1.001	0.04110000	0.00102700	0.84405400
7.2	-0.935	0.02750000	0.00151300	0.02802300
7.4	-0.878	0.01420000	0.00114200	0.01375400
7.6	-0.852	0.00754600	0.00069600	0.08717900
7.8	-0.824	-0.00020000	-0.00002600	-0.08023200
8.0	-0.806	-0.00546900	-0.00061900	-0.08500000
8.2	-0.784	-0.01190000	-0.00146300	-0.01070800
8.4	-0.745	-0.02450000	-0.00342300	-0.02119900
8.6	-0.710	-0.03670000	-0.00570500	-0.03083300
8.8	-0.678	-0.04870000	-0.00822500	-0.03967300
9.0	-0.649	-0.06030000	-0.01092400	-0.04781400
9.2	-0.623	-0.07170000	-0.01375100	-0.05533500
9.4	-0.599	-0.08260000	-0.01666600	-0.06230400
9.6	-0.577	-0.09330000	-0.01963700	-0.06878800
9.8	-0.557	-0.10360000	-0.02263600	-0.07481300
10.0	-0.538	-0.11370000	-0.02564300	-0.08044600
10.2	-0.521	-0.12340000	-0.02864000	-0.08571800
10.4	-0.505	-0.13280000	-0.03161400	-0.09063000
10.6	-0.490	-0.14200000	-0.03455400	-0.09530900
10.8	-0.476	-0.15080000	-0.03745300	-0.09968400
11.0	-0.463	-0.15940000	-0.04030400	-0.10381000
11.2	-0.451	-0.16780000	-0.04310100	-0.10771800
11.4	-0.440	-0.17590000	-0.04584300	-0.11140800
11.6	-0.429	-0.18370000	-0.04852400	-0.11489000
11.8	-0.419	-0.19130000	-0.05114800	-0.11821000
12.0	-0.409	-0.19870000	-0.05371000	-0.12136000
12.2	-0.401	-0.20590000	-0.05621100	-0.12436000
12.4	-0.392	-0.21290000	-0.05865000	-0.12722000
12.6	-0.384	-0.21960000	-0.06102800	-0.12994000
12.8	-0.376	-0.22620000	-0.06334700	-0.13255000
13.0	-0.369	-0.23260000	-0.06560700	-0.13504000
13.2	-0.362	-0.23880000	-0.06780800	-0.13740000
13.4	-0.356	-0.24500000	-0.07000000	-0.13970800
13.6	-0.350	-0.25080000	-0.07200000	-0.14190800
13.8	-0.344	-0.25660000	-0.07410000	-0.14400800
14.0	-0.338	-0.26220000	-0.07610000	-0.14600800
14.2	-0.333	-0.26750000	-0.07800000	-0.14790800

Table C.1 Lambda Parameters
(continued)

ALPHA3 = 1.80					ALPHA3 = 1.90				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4	ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
5.4	2.891	0.27980000	5.60790000	0.04148800	5.8	3.084	0.26740000	6.05750000	0.03399200
5.6	2.090	0.34810000	6.26120000	0.15650000	6.0	2.333	0.32510000	6.59940000	0.12351000
5.8	1.702	0.38560000	6.44790000	0.31186000	6.2	1.876	0.36750000	8.44810000	0.25743000
6.0	1.632	0.38630000	10.60900000	0.39551000	6.4	1.761	0.37380000	10.57300000	0.34266000
6.2	1.631	0.37970000	12.75000000	0.44558000	6.6	1.741	0.36990000	12.67900000	0.39457000
6.4	1.656	0.37090000	14.99500000	0.47764080	6.8	1.755	0.36300000	14.86000000	0.42653000
6.6	1.697	0.36150000	17.42400000	0.49797000	7.0	1.787	0.35490000	17.18800000	0.45143000
6.8	1.748	0.35190000	20.10400000	0.58988000	7.2	1.831	0.34640000	19.72100000	0.46540800
7.0	1.807	0.34230000	23.10100000	0.51539008	7.4	1.883	0.33770000	22.51400000	0.47366000
7.2	1.874	0.33270000	26.49200000	0.51584808	8.0	-1.023	0.02200000	0.0	0.82300000
7.4	-1.039	0.03670000	0.0	0.03960800	8.2	-1.018	0.01750000	0.0	0.81810000
7.6	-1.007	0.02830000	0.00037800	0.02978700	8.4	-0.968	0.00644700	0.00015000	0.80443100
7.8	-0.946	0.01550000	0.00064600	0.01555000	8.5	-0.946	0.00123900	0.00004128	0.08121500
7.9	-0.918	0.00917700	0.00049800	0.00900400	8.6	-0.917	-0.00544400	-0.00025700	-0.00522000
8.0	-0.880	-0.00040000	-0.00002400	-0.00034000	8.7	-0.893	-0.01130000	-0.00065700	-0.01060800
8.1	-0.868	-0.00329100	-0.00025400	-0.00310200	8.8	-0.871	-0.01710000	-0.00116700	-0.01580900
8.2	-0.846	-0.00940000	-0.00082600	-0.00872100	9.0	-0.831	-0.02840000	-0.00247500	-0.02540000
8.4	-0.804	-0.02150000	-0.00228900	-0.01919300	9.2	-0.794	-0.03950000	-0.00410000	-0.03430800
8.6	-0.766	-0.03330000	-0.00410300	-0.02476500	9.4	-0.761	-0.05030000	-0.00597500	-0.04240000
8.8	-0.733	-0.04480000	-0.00619000	-0.03755200	9.6	-0.731	-0.06090000	-0.00804600	-0.05009000
9.0	-0.702	-0.05590000	-0.00868900	-0.04565000	9.8	-0.704	-0.07110000	-0.01026900	-0.05695200
9.2	-0.674	-0.06680000	-0.01094800	-0.05313900	10.0	-0.678	-0.08100000	-0.01260700	-0.06345900
9.4	-0.649	-0.07740000	-0.01352600	-0.06008500	10.2	-0.655	-0.09080000	-0.01503000	-0.06952900
9.6	-0.625	-0.08770000	-0.01618800	-0.06654600	10.4	-0.634	-0.10020000	-0.01751300	-0.07520600
9.8	-0.604	-0.09770000	-0.01890600	-0.07257200	10.6	-0.614	-0.10940000	-0.02003400	-0.08052800
10.0	-0.584	-0.10740000	-0.02165600	-0.07820400	10.8	-0.595	-0.11830000	-0.02257700	-0.08552600
10.2	-0.565	-0.11690000	-0.02442100	-0.08348000	11.0	-0.578	-0.12700000	-0.02512800	-0.09023000
10.4	-0.548	-0.12600000	-0.02716500	-0.08864300	11.2	-0.562	-0.13540000	-0.02767500	-0.09466500
10.6	-0.532	-0.13490000	-0.02993600	-0.09309100	11.4	-0.547	-0.14360000	-0.03020800	-0.09885300
10.8	-0.517	-0.14360000	-0.03266300	-0.09748000	11.6	-0.533	-0.15140000	-0.03272000	-0.10281000
11.0	-0.503	-0.15200000	-0.03535900	-0.10162000	11.8	-0.520	-0.15930000	-0.03520600	-0.10657000
11.2	-0.490	-0.16010000	-0.03801800	-0.10554800	12.0	-0.507	-0.16690000	-0.03765900	-0.11013000
11.4	-0.478	-0.16800000	-0.04063400	-0.10925000	12.2	-0.495	-0.17420000	-0.04007600	-0.11351000
11.6	-0.466	-0.17570000	-0.04320600	-0.11277000	12.4	-0.484	-0.18130000	-0.04245300	-0.11673000
11.8	-0.456	-0.18320000	-0.04572800	-0.11611000	12.6	-0.474	-0.18830000	-0.04479000	-0.11980000
12.0	-0.445	-0.19040000	-0.04820100	-0.11928000	12.8	-0.464	-0.19500000	-0.04708400	-0.12272000
12.2	-0.436	-0.19750000	-0.05062200	-0.12231000	13.0	-0.455	-0.20160000	-0.04933400	-0.12551000
12.4	-0.427	-0.20430000	-0.05299100	-0.12519000	13.2	-0.446	-0.20800000	-0.05153800	-0.12818000
12.6	-0.418	-0.21100000	-0.05530700	-0.12794000	13.4	-0.437	-0.21420000	-0.05369800	-0.13071000
12.8	-0.410	-0.21750000	-0.05757000	-0.13057000	13.6	-0.429	-0.22030000	-0.05581200	-0.13317000
13.0	-0.402	-0.22380000	-0.05978100	-0.13308000	13.8	-0.421	-0.22620000	-0.05788100	-0.13551000
13.2	-0.394	-0.22990000	-0.06194100	-0.13549000	14.0	-0.414	-0.23200000	-0.05990500	-0.13776000
13.4	-0.388	-0.23590000	-0.06400000	-0.13780000	14.2	-0.407	-0.23760000	-0.06188400	-0.13992000
13.6	-0.381	-0.24170000	-0.06610000	-0.14000000	14.4	-0.400	-0.24310000	-0.06382000	-0.14199000
13.8	-0.374	-0.24730000	-0.06810000	-0.14210000	14.6	-0.394	-0.24840000	-0.06571300	-0.14399000
14.0	-0.368	-0.25360000	-0.07010000	-0.14420000	14.8	-0.388	-0.25370000	-0.06756300	-0.14591000
14.2	-0.362	-0.25830000	-0.07200000	-0.14610000	15.0	-0.382	-0.25880000	-0.06937100	-0.14775000
14.4	-0.357	-0.26320000	-0.07370000	-0.14790000	15.2	-0.376	-0.26370000	-0.07113900	-0.14954000
					15.4	-0.371	-0.26860000	-0.07286700	-0.15126000

Table C.1 Lambda Parameters
(continued)

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ALPHA1 = 2.00				
ALPHA4	LAMBDA1	LAMBDA2	LAMBDA3	LAMBDA4
6.2	3.365	0.25130000	6.50470000	0.02153700
6.4	2.430	0.29980000	6.90190000	0.00987200
6.6	2.106	0.34500000	8.31150000	0.19884000
6.8	1.915	0.35950000	10.34000000	0.28726000
7.0	1.863	0.35950000	12.39800000	0.34295000
7.2	1.861	0.35490000	14.50800000	0.37995000
7.4	1.881	0.34830000	16.73100000	0.40523000
7.6	1.916	0.34100000	19.11700000	0.42235000
7.8	1.961	0.33330000	21.71200000	0.43341000
8.0	2.014	0.32550000	24.56200000	0.43177000
8.6	-1.009	0.00839700	0.0	0.00854100
8.8	-1.004	0.00414700	0.0	0.00418200
8.9	-1.002	0.00206100	0.00000001	0.00207000
9.0	-0.993	-0.00108100	-0.00000407	-0.00107100
9.1	-0.974	-0.00567500	-0.00007075	-0.00556700
9.2	-0.949	-0.01130000	-0.00027200	-0.01084500
9.4	-0.905	-0.02230000	-0.00101200	-0.02074000
9.6	-0.865	-0.03300000	-0.00212500	-0.02777400
9.8	-0.828	-0.04350000	-0.00353700	-0.03008200
10.0	-0.796	-0.05370000	-0.00518700	-0.04575600
10.2	-0.766	-0.06370000	-0.00702700	-0.05207000
10.4	-0.738	-0.07340000	-0.00901600	-0.05948700
10.6	-0.713	-0.08280000	-0.01112200	-0.06546000
10.8	-0.689	-0.09200000	-0.01331600	-0.07143300
11.0	-0.668	-0.10100000	-0.01557600	-0.07684400
11.2	-0.648	-0.10970000	-0.01788200	-0.08192700
11.4	-0.629	-0.11820000	-0.02021700	-0.08671200
11.6	-0.611	-0.12640000	-0.02257000	-0.09122400
11.8	-0.595	-0.13450000	-0.02492700	-0.09548600
12.0	-0.580	-0.14230000	-0.02728100	-0.09951900
12.2	-0.565	-0.14990000	-0.02962300	-0.10334000
12.4	-0.552	-0.15730000	-0.03194800	-0.10697000
12.6	-0.539	-0.16450000	-0.03425000	-0.11041900
12.8	-0.527	-0.17150000	-0.03652400	-0.11369000
13.0	-0.515	-0.17840000	-0.03876900	-0.11682000
13.2	-0.505	-0.18500000	-0.04098000	-0.11980000
13.4	-0.494	-0.19150000	-0.04315400	-0.12244000
13.6	-0.485	-0.19790000	-0.04529600	-0.12536000
13.8	-0.475	-0.20400000	-0.04739800	-0.12797000
14.0	-0.467	-0.21000000	-0.04946200	-0.13046000
14.2	-0.458	-0.21590000	-0.05148700	-0.13285000
14.4	-0.450	-0.22160000	-0.05347200	-0.13514000
14.6	-0.443	-0.22720000	-0.05541800	-0.13735000
14.8	-0.435	-0.23260000	-0.05732600	-0.13946000
15.0	-0.428	-0.23800000	-0.05920000	-0.14158000
15.2	-0.422	-0.24320000	-0.06100000	-0.14350000
15.4	-0.415	-0.24810000	-0.06280000	-0.14530000
15.6	-0.409	-0.25320000	-0.06460000	-0.14720000
15.8	-0.403	-0.25800000	-0.06640000	-0.14890000

Table C.1 Lambda Parameters
(continued)

SYSTEM ANALYSIS FOR SITING NUCLEAR POWER PLANTS: A CASE HISTORY

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ABSTRACT

This paper discusses a multidisciplinary study conducted to select a site for a nuclear power plant. A series of screening steps were carried out to identify candidate sites for the plant, as well as candidate water sources. Multiobjective decision analysis methods were used to evaluate and rank these candidate sites and water sources; a risk analysis was carried out to determine the effects of major uncertainties. The evaluation concerns considered in the study are discussed, as well as the scales used to measure impacts with regard to these concerns.

INTRODUCTION

An investor-owned electric power company in a semi-arid region of the United States, hereafter referred to as the Electric Company, planned to select a site for a proposed nuclear-powered generating plant to begin commercial operation in the late 1980's with a nominal capacity of 2500 megawatts. Although the Electric Company had not made a definite decision to build a nuclear power plant, it wished to determine a site so that the nuclear generating option could be compared with other possible strategies for meeting the Electric Company's future need for electric power.

Woodward-Clyde Consultants was retained to develop and implement a methodology to recommend a site for this plant. The problem had a number of challenging features, including:

- 1) Difficult geology: much of the region in or near the Electric Company's service area is seismically active or has other natural features that might make it unacceptable for a nuclear power plant.
- 2) Limited water: any power generating facility of this size requires large quantities of water for cooling purposes, and water is in short supply in the area.
- 3) Significant uncertainties: these include uncertainties about geology, water availability, and future socioeconomic developments in the area.
- 4) Multiple siting concerns: in addition to system costs, other significant siting

concerns include licensing requirements, public health and safety, environmental and socioeconomic effects, and public acceptance.

- 5) Multiple interest groups: the Electric Company has responsibilities to both its shareholders and rate payers; in addition, a variety of other groups are interested in nuclear power.
- 6) Data limitations: although the Electric Company was willing to put substantial resources into the site selection, there were many data that could not be collected within a realistic budget and schedule or that were not available.
- 7) Regulatory requirements: regulations of the U.S. Nuclear Regulatory Commission and other government bodies impose various requirements on the process that is used to select sites.

Previous site selection studies, discussed below, had utilized multiobjective decision analysis [6,9] within a structured system analysis. Although these earlier selection problems did not have all the complexities of the present one, decision analysis could, in concept, address all the issues listed above.

PREVIOUS RELATED WORK

Keeney and Nair [4,5] and Keeney [2,3] have addressed site selection using decision analysis. Conceptually, this approach proceeds as follows: First, objectives are established and evaluation measures, or attributes, $X_1, X_2, \dots, X_n$ are determined to measure the desirability of any site with regard to each of the multiple siting concerns. A multiattribute utility function $u(x_1, x_2, \dots, x_n)$, where x_i is a specific level of X_i , is assessed to encode in mathematical form the company's attitude toward risk taking and tradeoffs among the X_i . Next, screening criteria are established and applied to eliminate all areas that are unacceptable (for example, because they are national parks or contain active faults).

For the area that remains after screening, probability distributions $p(x_1, x_2, \dots, x_n | a)$, where a is a specific geographic location, are assessed to encode in mathematical form the available knowledge about the desirability of

each location with respect to all the evaluation concerns. Where necessary, professional judgment is used to assess the probability distributions.

Finally, based on the axioms of decision analysis [8], the possible sites are ranked according to their expected utilities:

$$U(a) = \sum_{x_1, x_2, \dots, x_n} u(x_1, x_2, \dots, x_n) p(x_1, x_2, \dots, x_n | a),$$

and sensitivity analysis is carried out to determine how variations in u and p affect the relative ranking of sites.

Conceptually, this approach handles all the complexities discussed in the last section; as a practical matter, the area that remains after screening generally is too large to be completely analyzed. It is not feasible to collect the necessary data for a defensible assessment of the probability distributions p for the entire region. Furthermore, computer software is not available to carry out the expected utility calculations and required sensitivity analysis for this many sites.

It is therefore necessary to screen out considerably more area than what is clearly unacceptable to reduce the remaining area to an analyzable size. For example, a screening criterion might be used that no site could be within one mile of a paved road--the basic concern being that under certain conditions a fog resulting from cooling tower operation might reduce visibility on the road to dangerous levels. Note, however, that this potential difficulty could be reduced by proper design of the plant, although this might add to the cost of the facility. Certain locations within a mile of a paved road might have other desirable characteristics (e.g., good geology for construction) that would make it beneficial to locate a plant there, even if additional money has to be spent to reduce fogging. By screening based on a one-mile distance from roads, this type of special situation could not be considered.

To make the analysis practical, in applications screening criteria are introduced that eliminate areas with one or more undesirable characteristics, even if these do not make a site completely unacceptable. This reduces the area to be considered, but there is generally still too much area to be analyzed in a practical situation. Thus, as a final step before carrying out the complete decision analysis, professionals familiar with the engineering and environmental requirements for a plant site select a relatively small number of specific locations (usually ten to twenty) within the area remaining after screening for consideration in the complete decision analysis.

Underlying this approach to site selection is

the implicit assumption that enough potentially acceptable sites for the plant exist in the region of interest so that screening for undesirable, as well as for unacceptable, characteristics will not seriously limit the usefulness of the results. Recent developments in computerized geographic information processing give promise of reducing the need for this type of analysis "shortcut". These developments will be discussed in more detail below.

ANALYSIS PROCESS FOR THIS STUDY

The general approach outlined in the last section was applied in the study discussed below to reach a recommendation for a suitable nuclear power plant site. However, early in the analysis process we realized that finding an acceptable site which also had a source of water sufficient to supply the cooling needs of the plant would be unlikely. For this reason, it was decided to decouple the initial search for a site from the search for a source of water. Once reasonable candidate sites and candidate water sources had been located, these would be coupled and evaluated as units.

In another modification of the site selection process outlined in the last section, we discovered when we ranked our candidate sites and carried out a sensitivity analysis that certain risks needed to be evaluated further to reach a final conclusion about the most preferable site. Thus, an extra step of risk analysis was added after the initial ranking.

The final site selection process that was used is diagrammed in Figure 1. Each of the steps shown in this figure will now be discussed.

Determine Evaluation Concerns. As noted earlier, the Electric Company had not made a definite decision to build a nuclear power plant; however, it wished to keep this option open as long as it appeared viable. The primary intent of our study was to obtain early assurance that a potentially licensable nuclear power plant site would be available prior to the Electric Company making a major financial commitment to nuclear power. Thus, the principal objectives of the siting study were as follows:

- 1) Identify candidate sites for a nuclear power plant that could be licensed and constructed in approximately ten years,
- 2) Identify candidate sites that meet the rules and regulations of the U.S. Nuclear Regulatory Commission [11,12,13],
- 3) Identify candidate sites that are among the best that could reasonably be found in the region of interest, and
- 4) Select from among the candidate sites a

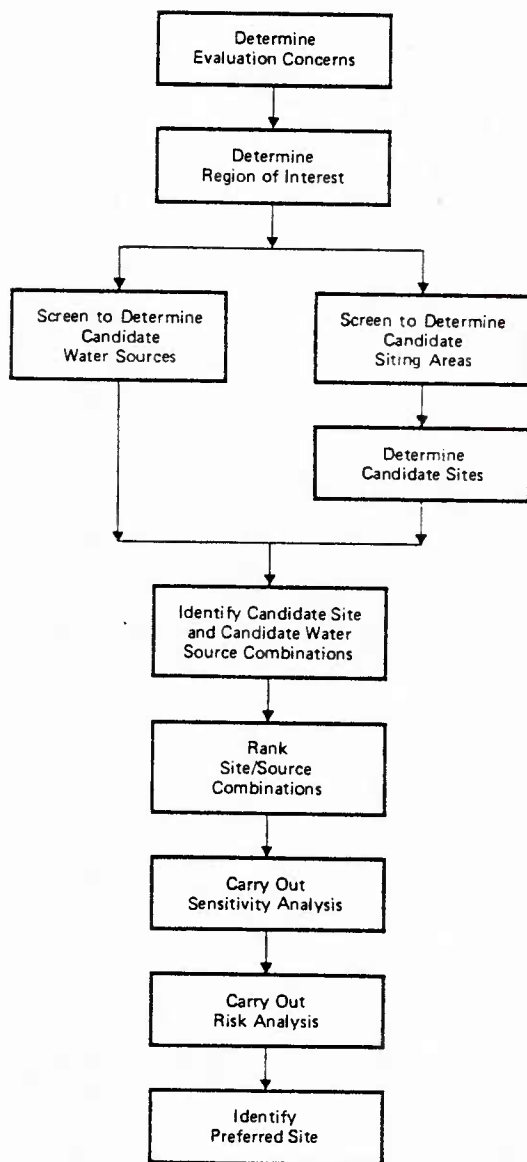


Figure 1. SITE SELECTION PROCESS

primary site and at least one alternative site such that no other candidate sites are obviously superior to them.

In order to meet these objectives, three overall areas of concern were identified as important:

- 1) Public Health and Safety,
- 2) Environmental Impact, and
- 3) System Cost and Reliability.

The specific considerations that needed to be addressed under each of these areas of concern are discussed below.

Determine Region of Interest. The geographic area in which the search for power plant sites was conducted is called the region of interest. For this study the Electric Company selected its home state as the region of interest. This state is one of the larger western U.S. states, and the Electric Company serves a significant portion of the state, including its largest city. The Electric Company is an investor-owned public utility incorporated in the state and is regulated by the state Public Service Commission. The Electric Company's chartered responsibilities are defined in terms of the state and its inhabitants. A region of interest smaller than the state would have placed arbitrary emphasis on one area over another. A region of interest larger than the Electric Company's home state could make it necessary for the company to deal with difficult legal and practical questions with which it has little experience.

Screen to Determine Candidate Water Sources. The candidate water sources were selected by a three-step screening process. The scope of water resources considered included both surface-water and ground-water sources as well as other potential sources such as reclaimed wastewater from sewage treatment plants and mine dewatering operations. The primary objective of the screening process was to identify candidate water sources for which there was a high probability that acquisition, development and use for power plant cooling would be feasible. A screening process with three sequential screening steps was used so that as the process proceeded sources with a lower likelihood of meeting the study objectives were eliminated from consideration and the remaining sources could be examined in greater detail within the time and resource constraints of the study.

The screening criteria used during this process were as follows:

1) Minimum Water Requirements

- a) Source must be able to supply at least 10,000 acre-feet per year for 40 years.

2) Legal Considerations

- a) Source must have unappropriated, purchasable or leasable water rights,
- b) State Engineer's administrative criteria must be straightforward,
- c) Water rights must be geographically concentrated, and
- d) Source must have low potential for competing or conflicting uses.

3) Hydrologic Data

- a) Hydrologic information must be sufficient to evaluate both the availability of water and its production characteristics,
- b) Aquifers must have a minimum saturated thickness of 50 feet (water table aquifers only), and
- c) Aquifers must have a minimum average

well yield of 200 gallons per minute (ground-water sources only).

These were identified by hydrologic specialists familiar with the overall objectives of the siting study as well as the water resources of the region of interest. As a result of applying these criteria, six candidate water sources were identified, including three underground basins, two surface sources, and one mine dewatering operation.

Screen to Determine Candidate Siting Areas.

Candidate areas for siting the power plant were selected by a sequential three-step screening process similar in concept to that used to select candidate water sources. The objective of this screening process was to select from within the region of interest those areas that have the highest likelihood of containing candidate sites that meet the study objectives discussed earlier.

Examples of the screening criteria used during this process are listed in Table 1. These criteria were identified by specialists familiar

TABLE 1
EXAMPLE SCREENING CRITERIA FOR SELECTION OF CANDIDATE SITING AREAS

Issue	Consideration	Measure	Criteria for Inclusion
HEALTH AND SAFETY	Radiological release due to surface fault rupture at site	Distance to faults	Areas > 5 miles from faults
	Collapse or subsidence of plant foundations due to solution	Location of karst topography or soluble lithologies	Areas where no known karst or solution potential exists
	Radiological release due to accident at (or in connection with) nearby hazardous facilities	Distance from airports	Areas > 5 miles from major airports
ENVIRONMENTAL IMPACT	Conflict with existing or proposed land use	Location with respect to designated land use areas	Areas outside of designated land use areas larger than 1,000 acres
	Potential for local socioeconomic impact	Location with respect to population centers and/or industrial development	Proximity to labor and materials markets
	Loss or alteration of important ecological considerations	Location with respect to areas that are biologically unique or diverse	Areas outside of important ecological systems
SYSTEM COST AND RELIABILITY	Rugged terrain	Slope	Areas with less than 10 percent slope

with the overall objectives of the siting study as well as the specific disciplines relevant for this screening. To reduce the licensing uncertainties and their related financial risks, the Electric Company adopted screening criteria to exclude areas that might present licensing difficulties. In particular, it was possible that site-specific geologic and seismic investigations might lead to unacceptable delays in the licensing and construction process. Thus, geologic and seismic screening criteria were imposed such that for areas not screened out there was a relatively high degree of confidence that detailed site-specific studies could be satisfactorily completed and yield a favorable assessment within approximately one year. Note, however, that areas excluded might contain suitable sites.

Determine Candidate Sites. As noted earlier, the screening process did not lead to specific candidate sites, but to areas that have a high likelihood of containing acceptable sites. Within these areas, specific candidate sites were identified by qualitative methods considering site-specific features. These included site-specific considerations of cultural resources, population census, surface or subsurface mineral resources, land use status, land use patterns, meteorology, transmission and pipeline corridor feasibility, site engineering, geological and geotechnical conditions, nearby hazardous facilities, socioeconomic conditions, and terrestrial and aquatic biology.

To obtain necessary information to make a site-specific evaluation, aerial environmental and engineering reconnaissance was conducted by an interdisciplinary team of experts. Based on this evaluation, seven specific candidate sites were identified for further study.

Identify Candidate Site and Candidate Water Source Combinations. As expected, the candidate water sources and candidate sites were not at the same locations. Thus, to assess the relative desirabilities of the various candidate sites, it was necessary to determine which water source or sources should be used with each site. This required assessing the cost of transferring water from the various sources to each site, as well as the associated environmental effects. To do this it was necessary to lay out feasible pipeline routes between the sources and sites. If only one source is needed to supply a site, there would be a total of 6 sources x 7 sites = 42 pipeline routes to be laid out. In fact, some sources did not have sufficient water individually to supply all the needs of the proposed plant, so combinations of sources had to be considered. The process of laying out pipeline routes was relatively straightforward, but time consuming, and sixty different source/site combinations were identified.

Rank Site/Source Combinations. The evaluation

and ranking of the various combinations of candidate water sources and candidate sites was done utilizing standard multiobjective decision analysis methods [6]. The use of these to rank sites has been discussed in detail elsewhere [2,3,4,5], so the process will only be outlined here. It consists of the following steps:

- 1) Determine evaluation measures,
- 2) Assess a utility function over these measures,
- 3) Determine the levels of the various evaluation measures that would result from selecting each site (uncertainties about these levels are encoded into probability distributions),
- 4) Rank the sites in order of their expected utilities, and
- 5) Carry out sensitivity analysis.

Note that this approach is based on well-established principles of decision making under uncertainty [8].

The following specific factors were identified by the study staff as important for evaluating source/site alternatives:

- 1) System cost
- 2) Population near the site
- 3) Environmental impact of water and electric transmission corridors
- 4) Environmental impact of plant construction, including
 - socioeconomic impact
 - biological impact
- 5) Environmental impact at the water source, including
 - long-term socioeconomic effects
 - short-term socioeconomic effects
 - biological impact
 - loss of irrigable land.

The evaluation measures developed for these factors are shown in Table 2.

It was established through standard preferential and utility independence checks [6] that an additive utility function

$$u(x_1, x_2, \dots, x_9) = \sum_{i=1}^9 k_i u_i(x_i)$$

was appropriate, where the x_i are evaluation measures, the u_i are single attribute utility

TABLE 2
EVALUATION MEASURES FOR SITE RANKING

Evaluation Measure	Definition
X_1 : Levelized system cost	Levelized annual cost in year 0 dollars. This includes water-sensitive costs, site-sensitive costs, and baseline reference costs.
X_2 : Site population	Site population factor [4,5,7].
X_3 : Biological impact at plant site	A 13-point constructed scale, as illustrated in Table 3a.
X_4 : Biological impact at water source	A 3-point constructed scale, as illustrated in Table 3b.
X_5 : Environmental impact of corridors	A weighted sum of the distances for the electrical transmission and water supply pipeline corridors, using the weighting factors illustrated in Table 4.
X_6 : Socioeconomic effects at plant site	0 Annual population growth rate due to peak-year construction activities is less than 15 percent. This indicates that there are population centers near the site with existing infrastructure to serve as a base for the new population influx.
	1 Annual population growth rate due to peak-year construction activities is more than 15 percent. This indicates that there are no existing population centers of significance; boom-bust development is virtually certain to occur.
X_7 : Short-term socioeconomic effects at water source	The value of production directly affected by the withdrawal of irrigation due to diversion of water to the power plant, in year 0 dollars.
X_8 : Long-term socioeconomic effects at water source	For each water source, the scale used is: (aggregate annual personal income per annual quantity of water consumption) X (quantity of water supplied to the power plant from the water source) in levelized year 0 dollars.
X_9 : Loss of potentially irrigable land	Weighted square miles of cropland that could potentially be retired from use at a candidate water source, using the following weighting factors on area:
	1 Cropland currently under irrigation
	1 Land highly suitable for irrigation
	0.7 Land moderately suitable for irrigation

TABLE 3
EXAMPLE DEFINITIONS OF LEVELS FOR RANKING EVALUATION MEASURES X_3 AND X_4

a) Example Definitions of Levels of Biological Impact at Plant Site (X_3)

Level	Definition
0	Removal of 6 square miles having > 25 percent of cultivated agricultural use.
4	Removal of 6 square miles of grassland, shrubland, or pinyon-juniper habitat that includes ≤ 10 percent riparian or wetland habitat.
8	Removal of 6 square miles of grassland, shrubland, or pinyon-juniper habitat within 1 mile of significant actual or potential raptor habitat, and of which ≤ 25 percent is actual or potential habitat for threatened, endangered, or otherwise unique species.
12	Removal of 6 square miles of grassland, shrubland, or pinyon-juniper habitat within 1 mile of significant actual or potential raptor habitat and including ≤ 10 percent riparian or wetland habitat and > 25 percent actual or potential habitat for threatened, endangered or otherwise unique species.

b) Example Definitions of Levels of Biological Impact at Water Source (X_4)

Level	Definition
0	Lowering of water table beneath cultivated agriculture; the basin supports only non-phreatophytic vegetation and no riparian or wetland habitat; or ≤ 5 percent of the basin supports phreatophytic vegetation or riparian or wetlands habitats, but these habitats do not support threatened, endangered, or otherwise unique species; essentially no impacts.
2	Lowering of water table beneath a basin with > 5 percent of the area supporting phreatophytic vegetation or riparian or wetland habitat; the phreatophytic vegetation or riparian or wetland habitat supports or potentially supports threatened, endangered, or otherwise unique species; or the basin contains springs which support threatened, endangered, or otherwise unique species.

TABLE 4
EXAMPLE WEIGHTING FACTORS FOR RANKING EVALUATION MEASURE X_5

a) Example Weighting Factors for Electrical Transmission Lines

Raw Mileage	Weighted Mileage	Criteria
1	1	Route traversing unpopulated rangeland; not visible from highways or high-use roadway. Route not affecting any known endangered species or important limited habitats; does not intrude on a "pristine", historic, or culturally significant area.
1	2	Route traversing populated areas. Route traversing Bureau of Land Management or public lands, not utilizing an existing corridor. Route having aesthetic intrusion on primary highways and high-use roadways (parallel to and/or visible from highway); or aesthetic intrusion on a national or state monument or park.
1	10	Route traversing state or national parks or monuments, military bases, or military research areas. Route traversing ecologically sensitive wetlands and migratory wildfowl refuges; or habitats containing unusual or unique communities, endangered species, or introduced game species.

b) Example Weighting Factors for Water Supply Pipelines

Raw Mileage	Weighted Mileage	Criteria
1	1	Route traversing unpopulated rangeland; utilizing existing industrial corridor. Route not affecting any known endangered species or important limited habitats. Route does not intrude on a "pristine", historic, culturally significant, or archaeologic and paleontologic resource area.
1	3	Route traversing state or federal forested lands, wildlife management or critical habitat areas. Route traversing ecologically sensitive wetlands.
1	10	Route traversing state or national parks or monuments, military bases, or military research areas. Route traversing habitats containing unusual or unique communities, endangered species, or introduced game species.

functions, and the k_i are scaling constants.

The u_i and k_i were assessed using standard procedures [6] as follows:

- 1) The lead specialist for a specific evaluation measure assessed the u_i over that measure
- 2) The multidisciplinary group of specialists meeting together assessed the k_i
- 3) The resulting utility function was reviewed by management of the Electric Company.

As would be expected when persons representing such diverse specialties are involved, the assessment of the k_i proved to be complex. A meeting lasting more than eight hours was needed to reach general agreement (but not consensus) on the nine scaling constants. A major disagreement concerned the amount of weight that should be attached to measure X_8 (long-term socioeconomic effects at water source). Some argued that a dollar of X_8 should be counted equally with a dollar of X_1 (levelized system cost), while others argued that X_8 should have a weight of zero. It was decided to settle this disagreement by carrying out a sensitivity analysis that covered this wide range of possible weights for X_8 .

An extensive data collection effort was carried out to estimate the levels of the measures $X_1, X_2, \dots, X_9$ associated with each water source/site combination. This included local data collection in the areas of the water sources and sites. In addition, a detailed cost analysis for the power plant, electric transmission line, water supply pipeline and well field was carried out as a joint effort by the Electric Company, Woodward-Clyde Consultants and the Bechtel Power Corporation. This was used to determine levels for X_1 (levelized system cost).

In cases where there was significant uncertainty, standard probability assessment procedures [10] were used to encode this uncertainty using the judgments of relevant experts.

The utility function and assessed probability distributions for the evaluation measures were analyzed using a standard multiobjective decision analysis computer program [14]. Extensive sensitivity analysis was carried out, and it was concluded:

- 1) The weight attached to X_8 (long-term socioeconomic effects at water source) did not influence the ranking of the more preferable water sources or sites.
- 2) Two of the seven candidate sites were more preferable than the others over a wide range of assumptions about which water source would be used.

3) One of the surface water sources was more preferable from a cost and environmental standpoint than the other five candidate water sources for a wide range of assumptions about which site would be utilized; however, for legal and political reasons it was uncertain whether this source could be utilized.

4) If the most preferable water source could not be utilized, then a specific one of ground-water sources was the next most preferable candidate water source for a wide range of assumptions about which site would be used.

5) The relative ranking of the top two candidate sites was most strongly influenced by:

- whether or not the most preferable (surface) candidate water source could be utilized,
- specifically how much cooling water would be needed for the power plant, and
- the relative likelihood of local support or opposition toward a nuclear power plant at each of the two sites.

Carry Out Risk Analysis. In order to analyze more fully the influence of the factors listed under item 5 in the last paragraph, a formal risk analysis was carried out. A decision tree [1,9] was constructed to represent the choice between the two top-ranked candidate sites. There was significant disagreement among the relevant experts about the probabilities associated with the various factors listed under item 5 above for each of the two sites. However, the risk analysis showed that one of the two sites was more preferred for all of the various probability levels that were proposed by the different experts.

Identify Preferred Site. Based on the results of the risk analysis, as well as the earlier analysis, one site was identified as most preferred. A clear second most preferable choice was also identified. In addition, two sources of water were identified as most preferable, as noted earlier.

RESULTS OF THE ANALYSIS

Following the analysis discussed above, the Electric Company took actions to obtain rights for land at both of the top-ranked sites. In addition, it pursued steps to obtain rights to water from the top two water sources. In particular, land and water rights were obtained for the ground-water source and a testing program was initiated to determine more accurately

how much water is available there.

With the recent regulatory and public opposition to nuclear power, the Electric Company has slowed its timetable for pursuing the nuclear option, and shifted greater emphasis to fossil-fueled generation options. However, active work continues on developing the water sources identified in this study for possible use with some type of generation facility.

CONCLUDING COMMENTS

The site selection study outlined above represented a significant system analysis effort involving over 50 professionals in several divisions of three companies and was carried out over a period of more than a year. The systematic analysis procedures discussed above were important in completing the study and reaching defensible and understandable conclusions.

As noted earlier, the screening procedures used allowed the analysis to be carried out in a practical and timely manner. However, they could potentially eliminate areas from consideration that might be desirable from an overall standpoint. This could occur if an area failed to pass one, perhaps not very significant, screen while being very desirable with regard to a variety of other evaluation concerns.

Computerized geographic information systems that are now starting to come into use will allow consideration of this type of tradeoff. With these systems, geographically-oriented information of the type considered in this study can be entered into a computerized data base and sophisticated analysis can be done. These methods should help to reduce both the need for screening and the amount of tedious and error-prone hand map work now necessary.

ACKNOWLEDGEMENTS

The project manager for Woodward-Clyde's work on this study was William D. Johnson, under the general direction of K.T. Mao. Terry A. Grant led the geologic work, Jeffrey A. Gilman led the hydrologic work, and William R. Anderson led the environmental work. Alan Sicherman helped develop the scales for the evaluation measures used in site ranking. More than fifty other professionals contributed to the study, and I regret that it is not feasible to list their names.

BIBLIOGRAPHY

1. C.A. Holloway, Decision Making Under Uncertainty. Englewood Cliffs, New Jersey:

Prentice-Hall, 1979.

2. R.L. Keeney, "Evaluation of Proposed Storage Sites," Operations Research, vol. 27, pp. 48-64, 1979.
3. R.L. Keeney, Siting Energy Facilities. New York: Academic Press, 1980.
4. R.L. Keeney and K. Nair, "Nuclear Siting Using Decision Analysis," Energy Policy, vol. 5, pp. 223-231, 1977.
5. R.L. Keeney and K. Nair, "Selecting Nuclear Power Plant Sites in the Pacific Northwest Using Decision Analysis," in D.E. Bell, R.L. Keeney and H. Raiffa, Conflicting Objectives in Decisions. Chichester: Wiley, 1977.
6. R.L. Keeney and H. Raiffa, Decisions with Multiple Objectives. New York: Wiley, 1976.
7. J.E. Kohler, A.P. Kenneke and B.K. Grimes, "The Site Population Factor: A Technique for Consideration of Population in Site Comparison," WASH-1235, U.S. Atomic Energy Commission, Washington, D.C., 1974.
8. J.W. Pratt, H. Raiffa and R.O. Schlaifer, "The Foundations of Decision Under Uncertainty: An Elementary Exposition," Journal of the American Statistical Association, vol. 59, pp. 353-375, 1964.
9. H. Raiffa, Decision Analysis, Reading, Massachusetts: Addison-Wesley, 1968.
10. C.S. Spetzler and C.-A.S. Stael von Holstein, "Probability Encoding in Decision Analysis," Management Science, vol. 22, pp. 340-358, 1975.
11. U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, "Environmental Standard Review Plans for the Environmental Review of Construction Permit Applications for Nuclear Power Plants," Draft, Part III, Section 9.2, February 1979.
12. U.S. Nuclear Regulatory Commission, Office of Standards Development, "General Site Suitability Criteria for Nuclear Power Stations," Regulatory Guide 4.7, Revision 1, November 1975.
13. U.S. Nuclear Regulatory Commission, Office of Standards Development, "Preparation of Environmental Reports for Nuclear Power Stations," Regulatory Guide 4.2, Revision 2, July 1976.
14. Woodward-Clyde Consultants, "Environmental Assessment Methodology: Solar Power Plant Applications, Volume 4: Decision Analysis Computer Program," ER-1070, Volume 4, Electric Power Research Institute, May 1979.

APPLICATIONS PANELS SUMMARY

The session on "Practical Application of Risk and Uncertainty Analysis," presented real world projects, programs and case studies. While the published papers reflected the personal experiences and research efforts of the authors, it is difficult to adequately describe the dynamic interaction and intellectual stimulation that occurred during the panel discussions and after the presentation of each paper.

The use of small groups, composed of knowledgeable members from industry, government and academe, interacting on a defined subject for a lengthy period of time (over two hours in most panels), led to a much greater depth of discussion, personal involvement, exchange of ideas and cross fertilization than rarely occurs in a professional meeting. One lively exchange centered around how to incorporate the behavioral aspects into an application of risk and uncertainty analysis.

While papers ranged from programs and projects in functional areas of construction and nuclear plant site selection to DoD contracting case studies, the panels concluded there was considerable value in reviewing the applications of risk and uncertainty analysis.

Applications of risk and uncertainty analysis techniques included: multiobjective decision analysis to evaluate alternatives, a risk analysis to determine the effects of major uncertainties, decision tree and multi-attribute utility and modeling, and the development of a model to assist government contract negotiators (price analysts) in coping with uncertainty.

Models were described involving both parametric and random variable terms, and applying the RS distribution to represent unimodal random variables. In addition, computer simulation was used to model complex bidding environments.

The applications presented were based on real world projects. The degree of success varied in the studies described. Application of the tools was discussed in terms of how well they achieved the study's major objectives.

The following comments are illustrative of the degree to which applications were considered successful:

1. The credibility of multiobjective decision analysis as a valuable tool has increased.

2. The issues of organization of the study effort and channels of communication with the parties involved can be explicitly treated and adjusted as an analysis proceeds.
3. The multiobjective decision analysis provided a recognition that a single best answer may not be a desirable outcome. The value of the tool may be the indication that a few alternatives are clearly superior to many others.
4. The government price analyst (PA) in contract negotiations is a key decision point when attempting to implement change and generate increased attention to risk and uncertainty.
5. The binomial distribution can be used to transform long-term bidding probabilities into short-term bidding probabilities. Also, it can be used to determine which long-term pricing policies are best in the long run and which are best in the short run.
6. Multiobjective decision analysis tools provide a useful aid in the management of risk after the initial purpose of the analysis (the selection of the desired alternative) has been achieved.

The limitations or weakness of the applications and techniques discussed and analyzed by presentators include the following:

1. The range, point estimates and probability distributions are not required or provided for in contractor pricing data. Such data is not generated or reviewed by the procurement agency, unless technical experts are available in their service or branch.
2. Nonlinear regression programs, such as BMDR-3R, are unable to handle models containing two or more nonlinear independent variables.
3. Simulation programs typically are not able to handle correlated distributions.
4. Missing data in regression studies results in the inability to estimate correctly the values of parameters.
5. Specialists responsible for major risk and uncertainty analyses should not be subordinate to the program manager. Competent study results are frequently altered to yield policies to meet the self-interests of superiors.
6. The organizational placement of the decision analysis in relation to the project director and the client is a crucial

issue. There is a need for an appreciation of the role and the limits of the analyst.

7. There is an inherent difficulty in representing the "decision-maker" and "his" utility function. This may be treated explicitly, however, and can be subjected to a sensitivity analysis.
8. The process of model building frequently does not include the decision-maker in the process.
9. Program management must be responsible for the application of risk and uncertainty analysis to a project. Schedules and budgets can be exceeded by substantial amounts unless risk and uncertainty are considered.

RECOMMENDATIONS

Each panel was given the task of recommending methods for improving applications of risk and uncertainty analysis to the real world of large programs. The limitations and weaknesses summarized above in themselves constitute a substantive list of the problems and issues which can be used for further study and research. There were other specific recommendations made by the panels. The major ones, not in any order of importance, dealing with applications were:

1. Experiment with or model a new program during contract negotiations. This would permit the government pricing analyst the option of when to structure FPI and CPIX contracts and the amounts for a) share ratios, b) target cost, c) target profit rates, and d) ceilings.
2. The need to generate or perform a decision analysis impact statement to recognize the scope and limitations of the analytical methods to be used. Can alternatives safely be screened out and limit the analysis so that a project manager can retain an intuitive "feel." Should the search for larger models and processors such as computerized geographic information processing or system dynamics to accommodate the more complex issues be continued?
3. There is a need to better identify and catalogue risk considerations to be managed following the decision analysis. The purpose is to devise strategies and techniques to cope with risk and uncertainty, perhaps through approaches such as the following:
 - a) Apply additional resources to tasks with high risk.
 - b) Keep multiple alternatives as an

open hedge.

- c) Annly "cost containment," i.e. "if it fails, minimize the impact of failure."

4. Explore, study and research other ways to measure and assess risk. In particular, possibilistic risk assessment (fuzzy sets) should be investigated.
5. Study organizational behavior with respect to the role and positioning of the analyst performing risk and uncertainty studies.
6. Develop both training and graduate degree programs to generate a trained core of specialists regularly engaged in analysis and direct thesis and dissertation research toward DoD risk and uncertainty problems and issues.
7. Elicit DoD support for the establishment of a designated national data bank for the study of risk and uncertainty.
8. Have the decision-maker agree on the definition of the problem to be solved early in the program.
9. The decision strategy must reflect the fact that systems analysis should take priority over analysis of independent events.
10. Additional study and research should be conducted on both DoD and defense industry program manager's decision-making approaches to determine how these approaches may affect organizational effectiveness with a program office.

SUMMARY

Many real world problems are depicted by poorly behaved, multimodal distributions with a relatively few number of independent variables (quantitative and/or qualitative). This unexplained variability is greatly reduced and it becomes unimodal (and falls within the range of skewness and kurtosis tables) when properly included in the mathematical models. Distributions outside the range of the tabled values have invariably been found to be reducible by the introduction of an additional explanatory variable (Larew).

Another panel agreed with the presentator that there is often little, if any, "justification for the use of uniform, triangular, trapezoidal, Weibull or PERT-type distributions (they are all typically much too symmetrical and too flat to represent real life data)."

The RS distribution is by far superior to all other percentile-type distributions for approximating unimodal random variables (Larew).

TAXONOMIC CONSIDERATIONS IN RISK AND UNCERTAINTY

by

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Abstract

This article presents a number of ways of constructing a taxonomy of risk and uncertainty terms. It is not meant to be prescriptive, but only to describe ways that authors have treated risk and uncertainty. Four major classifications are described: environmental, functional, informational, and technical. From this description, it is hoped that a more conclusive taxonomy of risk and uncertainty can be developed.

Definition of Risk and Uncertainty

In its simplest form, uncertainty can be defined as the absence of information. Certainty, conversely, is complete or total knowledge. The implications for the decision maker refer to his/her ability to make the correct decision. Depending on the degree of information which the problem solver possesses, he will be located somewhere along a continuum of knowledge which can be called the uncertainty spectrum. This spectrum is illustrated in Figure 1. As the problem is defined, the decision maker will move to the left on this spectrum.

dealing with this subject. It is not intended that this taxonomy be a completely valid and exclusive categorization, but that it represents the majority of significant work written on the subject. This survey is presented as a starting point for further refinement of a risk/uncertainty taxonomy. It is hoped to stimulate further thinking and discussion in the workshop on this subject.

The assumption is made that uncertainty and risk can be treated as synonymous terms. A review of the uncertainty spectrum confirms the difference between the terms as one of degree. Decision makers usually have some information to serve as a basis for decision making. Seldom will a decision be made when no information is available. Rather the decision will be delayed, and action initiated to obtain some information. Risk implies that the probability of future events is known in terms of a probability distribution (10). Uncertainty generally is defined as a situation where the probability of events is not known. From a subjective standpoint, the decision maker usually has intuitive feelings about the future and is able to structure a probability distribution. This subjective estimation of probabilities will move the decision maker into the risk segment of the

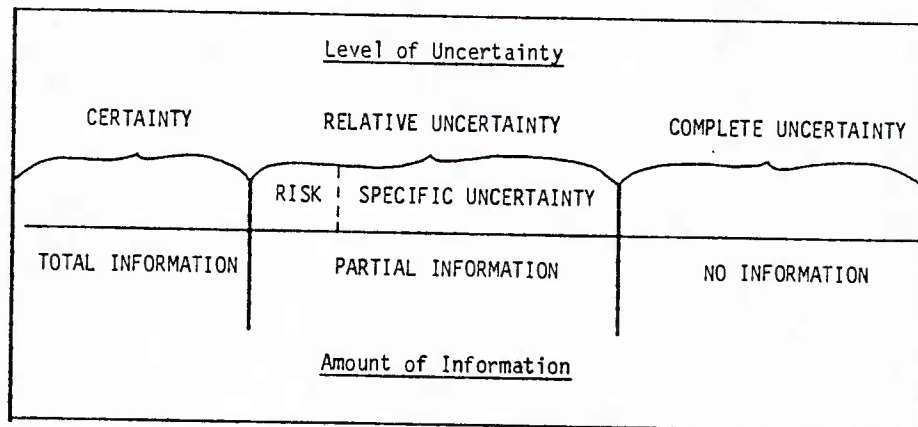


Figure 1 - The Uncertainty and Information Spectrum

The objective of this article is to attempt to construct a taxonomy of uncertainty and risk based on a survey of the literature

spectrum. A careful definition of the problem in terms of past ones of a similar nature will assist in enhancing the visibility of sub-consciously submerged information.

Chance (3), Grayson (6), Bierman and Smidt (1), Robichek and Myers (15), and Lerner and Carleton (11) support this assumption. Knight maintains that the two concepts should be treated as separate entities (10). Hunt supports him (8). Hunt's assertion is based on Dean's treatment of the concepts (4). Dean defines the terms and treats them separately. Hwang in his studies takes this same approach (9). The latter three individuals concentrate their efforts in the risk part of the uncertainty spectrum. The approach taken by both groups to cope with the unpredictability of the future, however, from a conceptual standpoint is basically the same. Therefore, uncertainty will be equated with risk, since the terms are essentially indistinguishable.

TAXONOMIC CLASSIFICATIONS

A survey of the literature reveals that there are various terms which have been used to categorize and describe uncertainty or risk factors. In this article, the various terms have been grouped into four taxonomic classes: environmental, functional, informational, and technical. These classes are explained in the following subsection.

Environmental Uncertainty

The first class of uncertainty is environmental uncertainty. This type of uncertainty relates to the surrounding conditions, influences or forces that affect the problem, project or situation. Environmental uncertainties include all factors bearing on the situation both within and without the project. Within the environmental class, there are several subclasses which will be discussed individually. The first subclass which has been identified includes the four categories listed below:

1. Nature - The uncertainty is related to natural factors, such as storms, floods, earthquakes, climactic conditions and acts of God (7).
2. Social and Political - This term relates to the impossibility of being able to predict with any precision the actions of social and political groups or the effects of social and political influences.
3. Communication Media - The disparities that exist in the access which people have to the various informational media. The differences result in ignorance on the part of many groups and individuals.
4. Time - The passage of time results in changes which can distort the results of decisions based on a past state-of-affairs.

The second subclass of environmental uncertainties addresses the factors internal and external to the project. They are defined as follows:

1. External - Those uncertainties which relate to factors external to a project which can impinge on final results (13).
2. Internal - Internal uncertainties comprise those stemming from the technical approach taken, internal management approach or other elements inherent in the project itself.

The third subclass is similar to the second; however, it approaches uncertainty from a systems perspective. It will consider the influences of all the projects within an organization on the specific project, thus the systems perspective. This subclass has two elements: exogenous and endogenous.

Exogenous factors refer to the stimulus, initiating a given change, which comes from outside the organization. Endogenous factors refer to the stimulus, initiating the change which originates within the organization.

Functional Uncertainty

Functional Uncertainty is the second major class of uncertainty. In this context, it refers to the broad functional areas which are inherent in a major project. The four categories of Functional Uncertainty are business risk, financial risk, technological risk, and production risk which are defined below:

1. Business Risk refers to the uncertainty that a firm has about its future income stream. The risk is associated with the firm's operation (17).
2. Financial Risk is the uncertainty that is generated by the ratio of debt to equity in the capital structure or the amount of earnings available to common stockholders. For contracting the risk of profit or loss on an individual contract is involved (16).
3. Technological Risk refers to the changes in the state-of-the-art that can render a system or product obsolete. Thus, uncertainty exists as to how long an item can remain in the operational inventory (14).
4. Production Risk refers to the uncertainty resulting from the assembly, manufacture or integration of component parts. Should a part not be available, or other production problems arise, then the finished product, construction project, etc., cannot be ready on time and its cost can be affected (12).

Informational Uncertainty

Informational Uncertainty is the third class of uncertainty that has been identified in the literature. The context of this type of uncertainty centers on the degree of awareness of decision makers of the relevant information that impacts the situation. Drake mentions one subclass of uncertainty which is anticipated unknowns and unanticipated unknowns (5). He observes these classifications in the environment of contractor organizations performing projects or programs under contract to a customer, as in the situation of a Department of Defense (DOD) acquisition organization charged with managing the development and production of a new weapons system. In this environment, a civilian company would normally do the engineering, development and manufacture of the system, under a formal written contract with the DOD. Within this subclass, anticipated unknowns (5), are those unknowns that the decision maker is aware of. He realizes that there will be a problem and anticipates it. In these situations the decision maker is not caught completely unaware of the problem. The converse of the anticipated is the unanticipated unknowns. This refers to those unknowns that the decision maker does not foresee. When they do occur, it takes the manager completely by surprise. Within this subclass, the unknowns under consideration are only the ones that affect the program or project at hand.

A separate category of informational uncertainties are discussed by Burnham, which he calls the known unknowns and the unknown unknowns (2). Unlike the previous category, these factors include all such uncertainty factors, whether they directly influence the project or not. The known unknowns are those facts that the contractor knows that he does not know. Within this same category are the unknown unknowns. These are the factors that the decision maker does not anticipate - factors that he does not know he doesn't know.

Technical Uncertainty

The fourth category of uncertainty is Technical Uncertainty. Unlike the other categories, technical uncertainty addresses the meaning of uncertainty in its technical sense. It deals with a more rigorous definition of the meaning of uncertainty, certainty and risk. Within the technical aspects of uncertainty two constructs can exist. The first deals with the three concepts of uncertainty, risk, and certainty. The second construct considers uncertainty as being either subjective or objective. These terms are explained below.

From a technical viewpoint, there are three situations which deal with uncertainty.

The first is certainty where each decision leads to a predictable outcome. In this situation, the decision maker has no doubt as to the final outcome of his action. The next situation is called uncertainty. Uncertainty occurs when the known is completely dominated by the unknown. Uncertainty denotes that probability distribution for future events are not known. In the case of risk (10), a special case of uncertainty, a decision will result in a specific number of well defined alternatives. The totality of the outcomes for this situation can be described by a probability distribution. When the term "uncertainty" as defined in the previous paragraph is considered, probabilities can be either objective or subjective. For subjective uncertainty, the probabilities assigned to an event are based solely on the observation choice (18). In the other situation, objective uncertainty, the probabilities are derived by specific procedures independent of the problem being confronted.

Summary

Upon examining the various definitional categories described in the previous section, it becomes apparent that from a generic standpoint, the environmental, informational, and technical taxonomic classes can be combined. It is also seen that the functional class is another way of describing the informational class of variables.

Uncertainty relates to events which will happen in the future, and it is in this context that a definition takes on its importance. The challenge for the decision maker is to identify and understand uncertainty factors as they relate to future problems. The decision maker's most significant task is to identify those factors which have uncertain aspects, and attempt to cope with the scarce or incomplete information which is available about those factors. By developing an improved taxonomy of uncertainty factors, the decision maker should be better able to both identify where uncertainty exists, and cope with it.

Bibliography

- (1) Bierman, Harold, Jr. and Seymour Smidt. The Capital Budgeting Decision. New York: The MacMillan Company, 1967, p. 196.
- (2) Burnham, Frank. "Plotting the Unk-Unks," Armed Forces Management. February, 1970, p. 55.
- (3) Chance, William A. Statistical Methods for Decision Making. Homewood, Illinois: Richard D. Irwin, Inc., 1969, p. 3.

- (4) Dean, Joel. Managerial Economics. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1951, pp. 7-8.
- (5) Drake, Hudson B. "Major DOD Procurements at War With Reality," Harvard Business Review. January-February 1970, pp. 119-140.
- (6) Grayson, C. Jackson, Jr. "The Use of Statistical Techniques in Capital Budgeting," Financial Research and Management Decisions. New York: John Wiley & Sons, Inc., 1967, pp. 90-91.
- (7) Hardy, Charles O. Risk and Risk Bearing. Chicago: The University of Chicago Press, 1923, pp. 2-3.
- (8) Hunt, Raymond G. Department of Organization and Human Resources, State University of New York at Buffalo. Personal letter, 8 July 1971.
- (9) Hwang, John D. Analysis of Risk for the Materiel Acquisition Process, Part 1: Fundamentals. U.S. Army Weapons Command, Rock Island, Illinois, 1970, pp. 9-17.
- (10) Knight, Frank H. Risk, Uncertainty and Profit. New York: Houghton Mifflin Company, 1921, pp. 19-21.
- (11) Lerner, Eugene M. and Willard T. Carleton. A Theory of Financial Analysis. New York: Harcourt, Brace & World, Inc., 1966, pp. 99-101.
- (12) Lindsay, Robert and Arnold W. Sametz. Financial Management. Homewood, Illinois: Richard D. Irwin, Inc., 1967, p. 53.
- (13) Peck, Merton J. and Frederick M. Scherer. The Weapons Acquisition Process. Boston: Harvard University Press, 1962, pp. 17-54.
- (14) Peck and Scherer. op. cit. pp. 45-48.
- (15) Robichek, Alexander A. and Stewart C. Myers. Optimal Financing Decisions. Englewood Cliffs, New Jersey: Prentice-Hall, Inc. 1965, pp. 68-69.
- (16) Stekler, Herman O. The Structure and Performance of the Aerospace Industry. Berkeley, California: University of California Press, 1965, p. 84.
- (17) Van Horne, James C. Financial Management and Policy. Englewood Cliffs, New Jersey: Prentice-Hall Inc., 1968, p. 145.
- (18) White, D. J. Decision Theory. Chicago: Aldine Publishing Company, 1969, p. 53.

A DIMENSIONAL APPROACH TO UNCERTAINTY IN
THE SYSTEMS ACQUISITION PROCESS

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ABSTRACT

For the purpose of identifying the "key parts of (risk and) uncertainty relating to (the systems acquisition process)" from the viewpoint of the (program) manager, it is proposed that "the process" or any part of interest be described in terms of one or more ordinal dimensions. As one approach (and, it is proposed, a preferred approach), dimensions are described with respect to three "parts" of the process: the plan, the program, and the relationship of the program manager to others.

To provide a context for this use of a dimensional approach, a brief discussion is presented of other dimensions related more generally to uncertainty, together with appendices describing the dimensions and the notation. Because the purpose of the paper is to provide a basis for discussion rather than agreement, it is presented, admittedly, in "rough" form and without explicit citation to the relevant literature.

SECTION I

INTRODUCTION

"Winning is never having to say,
'If ...'" (Quote from Jesse Thompson
on the television program "NFL Today,"
November 27, 1980.

A. BASIS FOR THIS PAPER

This paper was written in response to an invitation to participate in a workshop session which would examine the intersection of "uncertainty," "taxonomic concepts," and "major systems acquisition." These three areas have been, to varying degrees, of great interest to the writer over a period of about twenty-five years, and ranging from the relatively abstract to very pragmatic. It is recognized that each of these areas subtends a very large set of disciplines and practices, often characterized by mutual isolation (and disdain), requiring, it is proposed, a posture of modest inquiry.

The remainder of this introductory section will briefly comment on the focus of the paper.

Section II will discuss uncertainty in general; Section III will present a brief model which will be used to introduce the main argument which appears in Section IV. Section V provides a brief summary.

B. RISK AND UNCERTAINTY

The terms "risk" and "uncertainty" are associated not only with a variety of commonplace meanings but also with extensive formal inquiries variously identified with decision making, the area of probability or likelihood, utility theory, etc. These inquiries range from abstract (and mathematical) to pragmatic (and experimental), and it is not unlikely that the language and interests of one inquirer may not even intersect, let alone agree, with those of another. The present paper draws upon some modest acquaintance with these several fields and has no (present) intention of showing disrespect. It is believed, but not here proposed, that a common framework can be described which would account for (and, perhaps, reconcile) most, if not all, of the parts of the several areas of inquiry.

In this paper risk and uncertainty will be limited to the sense of "likelihood" as distinguished from utility, and the emphasis will be on examining the former. Similarly, the paper will limit itself to problem identification rather than the development of explicit solution strategies or tactics. It should be clear that this choice is not intended to indicate a (present) denigration of the importance of either utility or of approaches to solution.

C. WHY USE ORDINAL DIMENSIONS?

While "taxonomy" suggests "the systematic distinguishing, ordering, and naming of type groups within a subject field," its extensive development and application in several fields implies, at least, that there is some "order" to be found or that it would be "useful" to impose some order. Taxonomies have been "found" or "imposed" in the natural sciences and, in some cases, in the social sciences, e.g., organization theory. A taxonomy, if appropriate, would have some, or all, of the advantages and uses of a model. It is here proposed, however, that a taxonomy, in the sense of a strictly hierarchical ordering or classi-

fication, would be dysfunctional, introducing more error and confusion than order.

It is not argued that a taxonomy would not be "nice" to have. The power and rigor, and ability to build upon the prior art, which a schema of a set of clearly described and articulated concepts, supported with quantitative measures and data, provides is well established in science. It is, however, argued that, with the possible exception of theoretical or limited experimental inquiries, the art does not yet support such a science. If this is true, it is proposed that the (practical) problem of dealing with risk and uncertainty be approached through use of a series of "dimensions," dimensions which do not require (nor imply) a rigorous interdependence, e.g., mutual exclusiveness or inclusiveness. It is proposed that the set of dimensions be defined in name and form as ordinal, representing a series of viewpoints (or views) of the "problem," rather than a formal ordering (see Appendix I).

It seems clear that the choice of form or dimension (or scale) is properly the function of the data and what one wants to do with it. A poet might well prefer a nominal scale with its freedom in choice of data and manipulation; a physicist dealing with complex phenomena might well require a ratio scale to take advantage of the "order" in the phenomena and the convenience in using advanced mathematical analysis. Only where the "order" is there in the phenomena and the need for analytical techniques to achieve one's purpose exists is the use of more "ordered" scales clearly appropriate. Of these conditions, it is proposed that only the second is presently met.

It is proposed that there are some considerable advantages in using an ordinal scale for examining uncertainty in relation to the systems acquisition process. Ordinal scales are convenient, they are easy to define and apply, they tend to be stable over a set of problems (in management), and they are easily recognized as "inappropriate" (when that is true) and changed to a more "correct" scale. Most of the variables ("things") to be measured appear to take on, at least, ordinal variations, although, in some cases, such as "awareness," it may appear that a nominal scale is sufficient. Changes in uncertainty are easily described in ordinal terms, as are "matches" of achieved levels of uncertainty to levels "required" for some decision process.

D. SYSTEMS ACQUISITION

The relationship of uncertainty to systems acquisition depends, to a large extent, on the viewpoint of the individual concerned. In this paper, the viewpoint will be assumed to be that of the program manager (in the government).

There are, of course, other important, and relevant, viewpoints. From the viewpoint of a (prospective) contractor, the concern may vary considerably. A senior executive might view risk and uncertainty (almost) solely in economic terms: what is the expected profit or loss, what is the (likely) effect on long term growth and equity, what is the effect on liquidity? A technical executive might view uncertainty in terms of technical performance: what is the likelihood that the specifications can be met, at all, within budget and schedule? The using (or operating) organization within the government may well have different priorities in viewing uncertainty: how will the system perform, will it meet specifications, and even if it does, will it do the job, and will it be available on schedule, and when required during its time in the inventory? Policy level executives in the government may well be concerned with all of the above viewpoints as well as broad uncertainties in the system's relationship with other competing, or interacting, or higher level systems.

SECTION II

DIMENSIONS OF UNCERTAINTY (IN GENERAL)

A. UNCERTAINTY (AND CONFIDENCE)

At a relatively abstract and general level, the concept of "uncertainty" would appear to be reasonably "certain" — it seems to mean "how certain some 'thing' is," and can be stated or described in terms of a dimension which extends from UNCERTAINTY ---- CERTAINTY, or vice versa (see Appendix II for a more complete definition). While there is a considerable literature describing the dimension (and/or its scale), and means for obtaining measures, it seems clear that, for at least most purposes, the concept is associated with (one or more) sentient being(s), and with respect to some object, event, relationship, etc. Restated, "uncertainty" is a perception of some person (or persons) with respect to some relationship between two or more objects, events, relationships, etc. And, for at least some purposes, the concept of "confidence" may be used, reciprocally, for "uncertainty."

B. THE DIMENSIONS OF UNCERTAINTY

It is proposed that "changing (one's) uncertainty" (or changing one's confidence) is not only ubiquitous but is also a (the) unique characteristic of sentient (human) beings. The individual achieves (or seeks to achieve) some LEVEL OF CONFIDENCE (Appendix II) with respect to what he sees, or feels, or perceives, and

may even achieve (or seek to achieve), with respect to that confidence (C), some level of CONFIDENCE IN C. While this concept of a change in confidence is proposed as a ubiquitous epistemological process, it has been examined and formalized, with a considerable degree of self-consciousness, in the research (and/or academic) process. The "relationship" which is the object (or subject) of uncertainty (confidence) is conventionally described as an "hypothesis," some specified relationship between two or more variables, and it is this relationship which is the focus of the EFFECT UPON UNCERTAINTY (CONFIDENCE). It is further proposed that the reduction of uncertainty (increase in confidence) is achieved only by decreasing the relationship of "other" variables, PARAMETERS, with the variable(s) specified in the hypothesis. There are many dimensions which might be used to describe parameters, including, for example, those associated with isolating the hypothesized phenomenon both in LENGTH OR DEPTH and in BREADTH. The literature of research methodology includes categories such as endogenous and exogenous, experimental threats, experimenter threats, etc.

C. SOME SELECTED DIMENSIONS OF THE UNCERTAINTY REDUCTION PROCESS

The research process may be considered a self-conscious subset of the more general epistemological process, and one which has developed a rich, and often confusing, language to describe the various parts of the process.

Certainly early in the process is acquiring some awareness of the focus of the inquiry, the "problem" to be solved, i.e., identifying the relationship for which one wishes to increase one's confidence (to reduce one's uncertainty). Identifying the "problem" might be characterized by a number of dimensions, including at least these:

1. How well can the problem be identified, i.e., to what degree is it UNSTRUCTURED ---- STRUCTURED?
2. How well can the problem be isolated or separated from other problems (or systems), i.e., is it OPEN ----CLOSED?
3. Assuming the problem is big enough or important enough to work on, i.e., not trivial, is it small enough, i.e., not cosmic, so that, with reasonable effort, one can hope to "solve" it, i.e., is it KNOWABLE?

Assuming the researcher has been able to identify his problem, and assuming it is, at least, related to phenomena in the real world, he must consider his relation to the problem, i.e., how he will go about solving it, including:

1. Where is the "problem" from a

time point of view, i.e.,
RETROSPECTIVE ---- PROSPECTIVE?

2. Is he interested in exploring the problem (because he knows little about it) or is he interested in testing (or proving) a solution he is pretty sure of, i.e.,
EXPLORATORY ---- A PRIORI?
3. Is he just going to observe the phenomena or is he going to introduce some changes, i.e.,
STUDY ---- EXPERIMENT?
4. Will he make direct measurements or will he use secondary sources of data, i.e., NORMATIVE ---- EMPIRICAL?

Given that the researcher has been able to identify his problem and decided how to approach it, he, normally, will gather data and analyse it. This, again, is a multi-dimensional process, including:

1. Is he looking for facts or opinions, i.e., FACT ----VALUE?
2. And, in either case, where will he get them, i.e.,
SUBJECTIVE ---- OBJECTIVE?
3. And will the measures he uses (and the phenomena he measures) facilitate his analytical process, i.e., NOMINAL ---- RATIO?
4. And will he be able to use different measuring techniques, i.e.,
VALIDATION - MULTI-METHOD?
5. And will he be able to get different measures, i.e.,
VALIDATION - MULTI-TRAIT?

D. A PARTIAL VIEW OF THE DIMENSIONS OF (UNCERTAINTY WITH RESPECT TO) UTILITY

While it may be argued that uncertainty (or confidence) is not properly considered without also considering utility, it is proposed, for purposes of this paper, to assume that there is something called "utility" which bears some relation to uncertainty but to treat it only at the nominal level.

Nominally, in parallel with the dimensions of uncertainty discussed in B., above, the individual will be concerned with LEVEL OF CONFIDENCE (WITH RESPECT TO UTILITY). While it appears clear that the "practical man," i.e., the program manager, will be concerned with utility, it should also be made clear that the researcher, whatever his preoccupation with "confidence," is also concerned with utility, at least at the nominal level. It is proposed that it would be desirable to separate the two concerns analytically by interposing a separate set of variables between utility and the variables of the "hypothesis" when the concern is the EFFECT UPON UTILITY (PURPOSE, GOALS, ETC.). For this purpose, it is proposed that three kinds of variables will be sufficient:

1. Variables which account for "cost," including "time," i.e., RESOURCES/CONSTRAINTS
2. A variable (or variables) which account(s) for the desired (or proposed, or expected) "result" of the hypothesis, i.e., SUBSEQUENT EFFECT
3. Variables which account for "other effects," i.e., SPINOFF.

E. SOME SELECTED DIMENSIONS OF THE DECISION MAKER

The above discussion provides a general description of the epistemological process, applicable without distinction across all decision makers. However, the program manager is a specific decision maker, with specific characteristics and dealing with specific decisions. His interest, to apply the above, is in the relationship of uncertainty to some decision he will (may) make, i.e., LEVEL OF CONFIDENCE (DECISION MAKING), and LEVEL OF CONFIDENCE WITH RESPECT TO UTILITY (DECISION MAKING).

As a decision maker "embedded" in the real world, he must determine how much freedom he has to make a (the) decision, i.e., his AUTHORITY/INDEPENDENCE (WITH RESPECT TO UNCERTAINTY), and (WITH RESPECT TO UTILITY). And, even if he has the necessary "freedom" or choice, with respect to others, he himself may be limited by his own characteristics, including the following:

1. KNOWLEDGE, SKILLS AND PROBLEM SOLVING ABILITY
2. TOLERANCE OF AMBIGUITY
3. NEED TO STRUCTURE
4. RISK AVERSION.

Given that all of the above dimensions "match" appropriately with the decision he is considering, he must then consider the uncertainty (and utility) related substantively to the decision itself, in the form of the following:

1. FEASIBILITY (CREDIBILITY)
2. TIMELINESS
3. COSTLINESS.

F. COMMENTS

These general dimensions are not now proposed to be complete in terms of coverage or in terms of exposition. They are presented solely to provide a context for considering the dimensions to be presented in Section IV, below.

SECTION III

IDEALIZED PROGRAM MANAGER'S POINT OF VIEW (IN THE ABSENCE OF UNCERTAINTY)

A world without uncertainty may provide a useful simplification, somewhat analogous to a frictionless mechanical model. The functions, activities, etc., of a program manager might be described in relatively simple terms. First, he is assigned or given responsibility (and authority) to do all of the things necessary to carry out the program. The program is described to him (is given to him) in the form of a program plan. The plan describes the program (at least) in terms of its beginning or initiation and its completion or end point. As a minimum, the plan specifies the end point in terms of three dimensions:

1. performance - the desired characteristics or capabilities of the system or equipment which is planned or desired
2. schedule - the planned or desired time at which the system will be in existence or available
3. cost - the planned or desired amount and type of resources which will be expended or used in obtaining the system.

The description of the desired performance might include not only its nominal capability (i.e., technical equipment specification) but also other desired characteristics (e.g., how long it will perform, under what range of environmental conditions, how it will interface with other systems). In addition, information describing the above may be desired in the form of data to allow other systems to interact with it (e.g., training, operating, installing, and maintenance instructions).

The description of the desired schedule might include not only the desired end delivery schedule but also the desired schedule for intermediate products (e.g., information on technical interfaces) or intermediate inputs (e.g., information on technical interfaces).

The description of cost might include not only a total (dollar) budget but also specification of particular resources (e.g., personnel, facilities, contractors, etc.)

In classical management terms, the program manager will then do the following:

1. planning - break down the program plan into a set of smaller plans (sub-plans), interrelated in sequence and/or in parallel
2. organizing - establish the form of organization which will be used to carry out the plan

3. staffing - obtain and assign specific individuals to the organization
4. directing - provide the plan to the staff
5. controlling - observe (from time to time) the actual dimensions of the program (or its parts), compare with the plan, and provide direction to bring the actual into agreement with the plan.

While the absence of uncertainty would suggest that the process might be even simpler (e.g., there would be no need to control), this process will, at the end point, result in an actual system which agrees with the planned performance description, and at the scheduled (planned) time and planned cost.

Unfortunately, this scenario seldom, if ever, occurs in programs of any size or complexity. Either the actual system does not agree with the program plan, or the program plan changes during the course of the program, or both, and usually in ways which are not desired — less performance, more time, more cost.

SECTION IV

PROGRAM MANAGER'S POINT OF VIEW (INCLUDING UNCERTAINTY)

A. INTRODUCTION

It may be useful to introduce uncertainty in terms of the idealized model presented above, recognizing that the idealized model is an abstraction from practice or conventional wisdom which itself operates in the presence of uncertainty. If it can be assumed that practice is, itself, evidence (if imperfect) of a (or the) way to model the real world, it may be useful to comment on how this practice relates to uncertainty.

The idealized model includes at least two major elements: a PLAN and a PROGRAM. In the systems literature (and practice) we find a similar division: planning and execution. In the management literature (and practice) we find a similar division: planning and organizing/staffing/directing/controlling. It is suggested that this division is a common thread, ubiquitous in a variety of forms throughout the prior art and practice. In terms of uncertainty (and utility), it is proposed that this division provides a powerful (and useful) basis for modeling in the following way. The function of the plan is to provide a "boundary" between the uncertainties (and utilities) of the rest of the real world and that part of it which is the program. It provides (or is in-

tended to provide) some nominal level of certainty (and utility) sufficient to (make decisions to) carry out the program. Within this closed system, the uncertainties (and utilities) are limited to those with respect to relationships within the program, and with respect to relationships between the program and the plan.

Introducing uncertainty into the idealized model suggests at least two critical dimensions:

1. Uncertainty with respect to the PLAN
2. Uncertainty with respect to the PROGRAM (both within the PROGRAM and in relation to the PLAN).

These uncertainties, however, introduce another complication in terms of decision making (and decision makers). In the idealized model, the PLAN is the concern of decision makers outside of the PROGRAM, and the PROGRAM is the concern of decision makers within the PROGRAM (here, the program manager and those he represents). The uncertainties with respect to the plan and the program, in practice, become the concern (usually) of both sets of decision makers, resulting in uncertainties in the relationships between (at least) the two sets of decision makers. This suggests the addition of a third dimension:

3. Uncertainty with respect to the (authority) relationships.

It is proposed that these three dimensions provide a useful base or framework for the key parts or elements of uncertainty (and utility) from the program manager's point of view.

While the above is proposed as the major framework, it should be clear that there are others which focus on other dimensions, e.g., the steps or phases in the acquisition cycle.

The dimensions described above will provide the outline for the sections which follow.

B. UNCERTAINTY WITH RESPECT TO THE (PROGRAM) PLAN

Identifying uncertainties with respect to the PLAN may start by focusing on the relation of the PLAN to the program manager. First of all, the PLAN proposes to describe three interrelated changes which will (can, should) occur during the period of the program, as follows:

1. A change in performance from some (usually) unstated level of performance at t_1 to some specified level of performance at t_e
2. A change in time from t_1 to t_e , usually stated only in terms of t_e
3. A change in "cost" or resources from some initial specified level to zero (or from zero to some

specified end level).
The PLAN assumes (or proposes) that these three specified changes are related in such form that they will all occur during the program, but this may not be certain, i.e., it may cost more (or less) and take more (or less) time to achieve a higher (or lower) level of performance. This "uncertainty" may be described as the "feasibility" of the PLAN, and provides the first dimension:

PLAN FEASIBILITY

The degree to which the plan (performance, schedule, and cost; or the combination or interrelation) can be (or is) in agreement with (or performance is equal to or greater than, and schedule and cost is equal to or less than) the state (achieved, actual, measured) at the time of completion (t_e) of the planned activity (PROGRAM).

In a conventional sense, this dimension describes the primary question a program manager is faced with: "Can I (or anyone) deliver what they want with the amount of time and money they've given me?"

The second major dimension of uncertainty with respect to the PLAN arises out of its major purpose — to provide the program manager with a statement of his (and the program's) relation to the world outside of the program. The PLAN proposes that this combination of performance/cost/schedule will meet or exceed some level of utility (or some level of uncertainty with respect to utility). While this may not, nominally, be a concern of the program manager, as a practical matter it does, and may be described as the "utility" of the PLAN, and provides the second dimension:

PLAN UTILITY

The degree to which the plan agrees with (or exceeds) some preferred external state (i.e., some preference standard, or some preferred state with relation to some external plan).

In a conventional sense, this dimension describes the secondary question a program manager is faced with: "If I deliver what they want (what the plan says they want) on time and on schedule, will the program be a 'success'?"

In addition to these two basic dimensions, a number of other dimensions may describe specified uncertainties. First, plans are imperfect descriptions, i.e., vary in "clarity":

PLAN CLARITY

The degree to which the description of the plan agrees with the PLAN.

Second, the PLAN as initially stated may change by the end of the program, i.e., may lack "stability":

PLAN STABILITY

The degree to which the initial PLAN (at t_i) is in agreement with the final PLAN (at t_e).

Third, the PLAN may change one or more times during the program (as distinguished from

the above), i.e., it may have "variability":

PLAN VARIABILITY

The degree to which the initial PLAN (at t_i) is in agreement with the PLAN at t_n (where t_n is $t_i > t_n > t_e$; and t_n may vary in timing and frequency, i.e., the frequency and distribution of the set of t_n).

Fourth, the plan may be described in terms of nominal states, e.g., delivery scheduled for February 10, 1982, which may not agree with the range of preferred states, i.e., may or may not include "flexibility":

PLAN FLEXIBILITY

The degree to which the PLAN specifies a range of preferred states (or combinations) at t_m .

Fifth, the PLAN may include a number of inter-related details which are assumed to be consistent, i.e., introduces "complexity":

PLAN COMPLEXITY

The degree to which the plan includes intermediate (sequential) and/or detail (parallel) states which may affect feasibility.

Sixth, a variation on the above occurs in what is known as "process" versus "product" specification:

PLAN SPECIFICATION (PROCESS/PRODUCT)

The degree to which the plan is limited to a description of the state at t_e (product) as distinguished from a description of states at t_n (process). (Note: a PLAN may include both, which introduces feasibility issues; and a plan may include neither, which introduces flexibility issues).

These dimensions, with the possible exception of the first two, may be considered to represent a selection of the salient dimensions of uncertainty with respect to the plan. It is suggested, however, that they do represent a reasonable starting point.

C. UNCERTAINTY WITH RESPECT TO THE PROGRAM

The uncertainties with respect to the program are, particularly in research and development, the major focus of a program manager. Even assuming the PLAN is feasible, the program manager must select and carry out a set of decisions which reflect that feasibility. For purposes of this paper, the uncertainties here will be limited to those which are summarized in the classical management functions: planning, organizing, staffing, directing, and controlling.

The first of these, planning, is, in one sense, accomplished by the PLAN. However, in most programs, the program manager will find it desirable, if not necessary, to break up the program into a series of sub-programs. This planning function introduces a number of uncertainties, but, as a "plan," these uncer-

tainties, at a different level, will be similar if not identical with those already described.

While for each of the other four functions a comparable set of dimensions with reference to uncertainty could be developed, for present purposes a brief summary for each will be made:

PROGRAM MANAGEMENT (ORGANIZING)

The degree to which the specified sub-programs and their relationships agree with the program plan

PROGRAM MANAGEMENT (STAFFING)

The degree to which the specified (personnel) resources agree with the program plan

PROGRAM MANAGEMENT (DIRECTING)

The degree to which the specified information about the plan and its communication to staff agree with the program plan

PROGRAM MANAGEMENT (CONTROLLING)

The degree to which specified information about variation between the plan and sub-plans agrees with the program plan.

The above set of dimensions is only one of several general sets of dimensions. For example, the program manager might limit himself to the two dimensions of "effectiveness" and "efficiency," with various definitions and, perhaps, a set of sub-dimensions. Another set, still at the general level, might include the dimensions of "understanding the problem," "present or proposed approach," and "present or potential capability to solve the problem." Each of these sets, including the set of five functions, might be applied to the program as a whole, or to any sub-part.

At a somewhat less general level, sets of dimensions might be identified with specific sub-parts of the program. Particular technical problems, or the set of specific technical problems, are easily associated with uncertainty. Similarly, problems related to cost or schedule may be identified. Alternative specific sets may be based upon any method used for identifying sub-parts of the program.

D. UNCERTAINTY WITH RESPECT TO PROGRAM AUTHORITY

In the absence of uncertainty, a PLAN might determine the "authority" relationship, i.e., establish the bounds of decentralization, the limits on discretion or choice of the program manager, with respect to execution of the program, i.e., program management. However, with uncertainty in plan and program, there may also be uncertainty in the relationship between those outside the program and the program manager. During the period of the program those outside of the program may wish to provide input or obtain output concerning inter-

nal program management decisions; and the program manager may wish to "cross the boundary" in the other direction with respect to decisions affecting the PLAN. While the uncertainties here might be subsumed under the PLAN dimensions, it is proposed that they are sufficiently important, and different, to warrant a parallel category. In general, this dimension relates to "program authority" and may be described as follows:

PROGRAM AUTHORITY

The degree to which one's decision (on planning and/or execution) is not dependent upon (affected by or directed by) input (present or future) from others

And, following the three divisions of the PLAN, three component dimensions can be identified as follows:

DESIGN AUTHORITY

The degree to which one's decision on choice of technical means (X_{iv}) and results (X_{dv}) is not dependent upon (affected by or directed by) input (present or future) from others

SCHEDULING AUTHORITY

The degree to which one's decision on choice of when a particular activity will begin and/or be completed is not dependent upon (affected by or directed by) input (present or future) from others

COST AUTHORITY

The degree to which one's decision on allocations of resources to a particular activity is not dependent upon (affected by or directed by) input (present or future) from others.

It should be noted that these dimensions which arise from the boundary between "outside" the program and "inside" can be replicated for any similar boundary, e.g., between the program manager and managers of sub-programs.

E. COMMENTS

These three categories of dimensions are proposed as a useful framework for identifying the uncertainties the program manager faces. They draw upon, and parallel, categories which have been developed and tested and appear in conventional wisdom and practice. The thrust of the presentation here is to present them in terms of the relation with uncertainty.

SECTION V

SUMMARY

This paper is, and was intended to be, a discussion paper — to present some concepts on the relation of uncertainty to program management. The central proposal is the use of or-

dinal dimensions to identify the key parts of uncertainty associated with the program plan, the program itself, and the relationship of the program manager with others. This approach is proposed to appropriately reflect not only the nature of uncertainty but also the salient, related characteristics of the systems acquisition process.

APPENDIX I

NOTATIONS

A. Presentation of "dimensions"

1. Where only the name of a dimension appears in the text, reference may be made to Appendix II for the description of the dimension.
2. The names of dimensions appear in two forms: some describe the end point of the dimension, e.g., "L ---- R," and others describe one or the other end point, e.g., "R."
3. The (word) description of all dimensions is always in terms of the ordinal dimension, i.e., "...the degree to which..."; however, only a few of the dimensions will include uncertainty.
4. The end points of the scale used for all dimensions are described as follows: "Not at all ---- Completely."

B. Basic notations

1. X. The set of all "things" can be (will be) described in terms of "any conceptually held change in state." For convenience "change in state" and "state" may be considered interchangeable, depending only upon the level of analysis. The notation will be X, sometimes further described by a subscript, e.g., X_{iv} .
2. $X \text{---} X$. The relationship between two (or more) states can be (will be) described with a horizontal connecting line (---), e.g., $X_{iv} \text{---} X_{dv}$. The set of possible relationships is not limited.

C. Basic concepts

1. Time. Changes in state (or states) of time are conventionally described as a "point in time" (or "event") or a "period."
2. Space. Changes in state (or states) of space are conventionally described as a "point in space" or "object."
3. Confidence (uncertainty). Changes in state (or states) of confidence are conventionally described as "level of confidence (or uncertainty)" or "increase/decrease in confidence (or uncertainty)."
4. (Utility). Changes in state (or states) of utility are conventionally described as "level of preference" or "increase/decrease in preference."

D. Other notations

1. DM (and PM). For convenience here, man is considered a decision maker (DM) who not only "holds" (or observes) the above changes in state (or states) but also may make changes (decisions) in (or with respect to) those states. Further, the term program manager (PM) will be used for the decision maker who (primarily) makes decisions about some "program."

2. Program. The term PROGRAM will be used for a set of related changes which occur (or can occur) over a period of time.

3. (Time notations). With relation to a program, the beginning or initial point will be noted as t_i , and the ending or end point will be noted as t_e . In addition, times within the program will be noted as t_n , i.e., $t_i < t_n < t_e$; and times within the program but including the end points will be noted as t_m , i.e., $t_i \geq t_m \geq t_e$.

4. (Variables notations). For describing or examining any change (in part or all of the program) which is of interest, the following notations may be used:

X_{iv} = independent variable(s)
 X_{dv} = dependent variable(s)
 X_{par} = parameter(s)
 X_{bkgd} = background
 X_{rc} = resources and/or constraints
 X_{se} = subsequent effects
 X_{so} = spin-offs.

APPENDIX II

SOME SELECTED DIMENSIONS

UNCERTAINTY ---- CERTAINTY

The degree to which a specified relationship (including phenomena, abstract constructs, objects, events, etc.) is certain.

LEVEL OF CONFIDENCE

The degree to which one is certain that a particular relationship is as stated.

CONFIDENCE IN C

The degree to which one is certain that the (perceived) uncertainty in some specified relationship is as stated.

EFFECT UPON UNCERTAINTY (CONFIDENCE)

The degree to which the effect of the relationship of other variables (X_{par}) to the relationship of the variables of interest X_{iv} , X_{dv} can be (or is) determined.

PARAMETERS

The degree to which a specified relationship is not affected by other relationships.

LENGTH OR DEPTH (PARAMETERS)

The degree to which the relationship between two variables of interest (X_{iv} and X_{dv}) is

limited to the "same" time, i.e., not separated in time to the extent that other variables (X_{par}) may "affect" the relationship.

BREADTH (PARAMETERS)

The degree to which the relationship between a variable of interest (X_{dv}) and the variable(s) (X_{iv} , X_{par}) which may "affect" it can be (or is) limited to a single relationship at the "same" time.

UNSTRUCTURED ---- STRUCTURED

The degree to which the variables of interest (X_{iv} and X_{dv}), other variables (X_{par}) which may "affect" their relationship, and the relationships among them can be identified (or described, or are certain).

OPEN ---- CLOSED

The degree to which the variables of interest (X_{iv} , X_{dv}) and other variables (X_{par}) which may "affect" their relationship can be distinguished from the set of other variables (X_{bkgd}).

KNOWABLE

The degree to which the specified relationship is capable (at some specified level of cost and time) of being certain.

RETROSPECTIVE ---- PROSPECTIVE

The degree to which the phenomenon of interest occurs much later rather than much earlier than the time of some decision (or observation).

EXPLORATORY ---- A PRIORI

The degree to which the researcher predetermines the effect of new data on his results.

STUDY ---- EXPERIMENT

The degree to which the researcher manipulates the phenomena under observation.

NORMATIVE ---- EMPIRICAL

The degree to which the researcher obtains new data directly from the phenomena.

FACT ---- VALUE

The degree to which uncertainty with respect to a specific relationship is not shared across a set of individuals.

SUBJECTIVE ---- OBJECTIVE

The degree to which the source of data is not the assertion of a specific individual.

NOMINAL ---- RATIO

The degree to which the set of data is inter-related (and can be manipulated mathematically).

VALIDATION - MULTI-METHOD

The degree to which the relationship is determined by the convergence of measures obtained by "many" methods.

VALIDATION - MULTI-TRAIT

The degree to which the relationship is determined by the convergence of measures of "many" traits.

LEVEL OF CONFIDENCE (WITH RESPECT TO UTILITY)

The degree to which one is certain of the relationship between a specified state (existing, planned, or expected) and one's preferred state.

EFFECT UPON UTILITY (PURPOSE, GOALS, ETC.)

The degree to which the variables of interest (X_{iv} , X_{dv}) are related to other variables which are related to utility.

RESOURCES/CONSTRAINTS

The degree to which a variable of interest (X_{iv}) is related to (dependent upon) some other variables which are related to utility.

SUBSEQUENT EFFECT

The degree to which a variable of interest (X_{dv}) is related to some other variable (X_{se}) which is related to utility.

SPINOFF

The degree to which some other variables (X_{so}) which are related to utility are related (dependent upon) the variables of interest (X_{iv} , X_{dv}).

LEVEL OF CONFIDENCE (DECISION MAKING)

The degree to which the (perceived) uncertainty with respect to some relationship is equal to (or less than) that required for the purposes of some decision.

LEVEL OF CONFIDENCE WITH RESPECT TO UTILITY (DECISION MAKING)

The degree to which the (perceived) uncertainty with respect to the relationship with one's preferred state is equal to (or less than) that required for the purposes of some decision.

AUTHORITY/INDEPENDENCE (WITH RESPECT TO UNCERTAINTY)

The degree to which the identification of other variables (X_{par}) which may be related (affect) the relationship of interest (X_{iv} -- X_{dv}), and the determination of their relationship, is not dependent upon (affected by or directed by) input (present or future) from others.

AUTHORITY/INDEPENDENCE (WITH RESPECT TO UTILITY)

The degree to which the identification of the variables which are related to one's preferred state, and the determination of their relationship, is not dependent upon (affected by or directed by) input (present or future) from others.

KNOWLEDGE, SKILLS AND PROBLEM SOLVING ABILITY

The degree to which the decision-maker's awareness and understanding of the relevant states of nature and/or prior art is equal to (or exceeds) that required for the purpose of some decision.

TOLERANCE OF AMBIGUITY

The degree to which the uncertainty in a specified (or set of specified) relationship(s) is equal to (or less than) that required for the purposes of some decision.

NEED TO STRUCTURE

The degree to which the uncertainty in a specified (or set of specified) relationship(s) is equal to (or greater than) that required for the purposes of some decision.

RISK AVERSION

The degree to which the uncertainty in a specified relationship is equal to (or greater than) that required for the purposes of some decision.

FEASIBILITY (CREDIBILITY)

The degree to which the (perceived) uncertainty with respect to some relationship is equal to (or more than) that required for some decision.

TIMELINESS

The degree to which the (perceived) uncertainty with respect to some relationship is equal to (or less than) that required for some decision at (or before) some specified time of decision.

COSTLINESS

The degree to which the (perceived) uncertainty with respect to some relationship is equal to (or less than) that required for some decision at (or less than) some specified level of cost.

RISK AND UNCERTAINTY IN NETWORK ANALYSIS ACTIVITY ESTIMATES

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ABSTRACT

Previous research on the accuracy of activity time estimates in programs using network based management systems are reviewed, and the conflicting results of previous research are documented. Two studies designed to extend the program manager's knowledge of factors affecting estimating accuracy, and to integrate previous findings, are summarized. The earlier conflicting results are explained, and managerial actions necessary to reduce the level of uncertainty inherent in network estimates are suggested.

A time estimate has been described as the manager's experience and knowledge reflected in a numerical guess (4, p. 87). If this view is accepted, then uncertainties in the estimates must be influenced by characteristics of both the activity itself and the estimator. The studies summarized in this paper examine these characteristics to determine the effect they have on activity estimates and on the level of uncertainty involved in the overall project or program. The purpose is to provide the background necessary to develop a classification scheme for projects which will allow the manager to roughly forecast the uncertainty inherent in his project estimates.

INTRODUCTION

The use of network analysis techniques on military programs and projects began with applying the Program Evaluation and Review Technique (PERT) to the Navy's Polaris Program in the early 1960s. Since that time network analysis has developed through a number of modifications. The DOD's current Cost/Schedule Control System Criteria (C/SCSC) allows flexibility in selecting the specific technique to be used. Since the days of Polaris, however, the prime contractor and major subcontractors on almost every major weapon system development program have been required to use some form of network-based planning and progress reporting technique. The purpose has been to reduce the uncertainties involved in planning and executing major weapon system programs. The continuing cost and schedule overruns experienced by major programs demonstrates that at least some sources of uncertainty are being inadequately dealt with.

In applying network analysis, the total program is divided into relatively small and independent activities. The duration and resources required for each activity are estimated. These activities are then assembled into a time-phased network or "map" for analysis of the overall program. Thus the purpose of using network analysis techniques lies in reducing program uncertainties--improving the accuracy with which the overall program schedule and resource requirements can be estimated and managed. These uncertainties can obviously be reduced only to the extent that the underlying activity estimates are accurate. Much has been written about the ability to develop and meet program schedules using network techniques, yet only a very limited literature exists dealing with the accuracy of individual activity estimates and the effect of uncertainties in these estimates on the overall program.

BACKGROUND

Time estimates for individual project activities are critical to the use of network analysis techniques. They form the basis of all analytical operations carried out on the network, and the resulting work schedule can be no more accurate than the basic estimates from which it is calculated. It is therefore highly advantageous to obtain the most accurate activity estimates feasible. The difficulty of developing accurate estimates is inherent in the high technology, advanced development type of project characteristic of weapon system development programs, and for which network analysis techniques are most suited. Absolute accuracy is virtually impossible to achieve (17, p. 87) since the previous experience on which estimates would normally be based either does not exist or does not exactly apply. It is inevitable, therefore, that individual time estimates will contain errors.

Current research directed at investigating the accuracy of activity estimates for project networks centers on two main sources of error; the quantitative assumptions of the network, and the estimating behavior of those managers who must provide the estimates. In the quantitative area, MacCrimmon and Ryavec (14) published what is considered the classic survey of error sources in the network assumptions. Other authors have recommended changes to the basic network calculations in order to reduce these errors (11; 13). These changes have not achieved wide acceptance, possible because of the complexity they introduce into the techniques. While the basic quantitative assumptions do lead to significant errors in the overall network predictions (14), they can be compensated for by using a Monte Carlo sampling approach to predicting the project durations (5). However, they have little effect on the

individual activity estimates and the uncertainty created for the project by activity estimation errors.

Research on the estimating behavior of managers has principally investigated the existence of a learning curve to determine if estimates improve as the project progresses, as the estimator's experience with the project increases, or as the activity start date approaches. The existence of a consistent learning curve, or indeed any consistent bias, might allow the estimates to be adjusted based on a history of the estimator's performance and on the activity's relative location during the project. Archibald and Villoria (4) report that the Navy conducted extensive studies of activity time estimates in the early 1960s as part of the Polaris Missile Project. They compared the actual with the estimated activity times and found that the estimates tended to fall short of the time required to complete the activity. As the estimators gained experience over a two-year period, however, activity time estimates became increasingly realistic, implying the existence of the learning curve effect. More recently, Abernathy (1), using data obtained from a first-of-a-kind electronic space module project, found estimating accuracy was a function of several variables taken together: the estimate's nearness in time to the activity start rate, the estimate's nearness in time to the project start date, the number of completed project activities, and the error in previous estimates of the same activity's duration. Of course, this last variable cannot be known until after the activity has been completed, a fact which would limit the application of his findings. Abernathy used the number of days difference between the estimated and actual activity durations as his measure of "estimation error".

On the other hand, King and his various colleagues (10; 11; 12) report that no such learning curve exists. Based on data obtained from a U.S. Air Force weapon system acquisition project, King and Wilson (12) concluded that no improvement in the accuracy of time estimates exists as the activity start or completion date approaches. Kidd and Morgan (9) supported this conclusion in their study of overhauls, construction, and plant reliability work controlled by the Midlands Regions of the Central Electricity Generating Board in Great Britain. The conclusions reached in the above studies were all based on using the ratio of estimated to actual times as the measure of accuracy.

There has, of course, been much generalized research conducted on the motivation of professionals and managers. For example, both McClelland (15) and Kahn (8) have reported that managers and business executives appear particularly driven by a high need for achievement. Meyer's work (16) indicates that managers improve their performance most when specific goals are established. Hall and Lawler (7) have

demonstrated that pressures for quality (a professional concern) and financial responsibility (an organizational concern) are both related to the organizational performance of professionals. No research was found which specifically related individual estimator characteristics to the accuracy of the activity estimates they produced.

Beyond the above referenced research, little has been done to investigate what factors affect the accuracy of activity time estimates. Since the data for studying the learning curve phenomena were drawn from widely different projects, and a variety of analysis techniques were used in the studies, there seemed to be no way to reconcile the conflicting results without additional research. Only by reconciling these differences could generalizable results be obtained which would aid the practicing project manager to obtain more accurate activity estimates. Further, this line of research seemed sterile in its failure to consider the impact of individual differences among estimators.

THE STUDIES

Two studies were conducted to deal with the concerns identified above. These studies have been reported elsewhere separately and in detail (3; 2) so are only summarized below. First, however, it is important to understand three separate aspects of the estimating situation.

Project Differences

All of the previously reported studies drew their conclusions from analyses of single projects, yet projects by their nature differ markedly in terms of the uncertainty involved in the technical aspects of the work being performed. The level of technical uncertainty in a maintenance or construction project, for example, would generally be accepted as lower than that in an advanced research and development project. If generalizable results are to be obtained, such critical cross-project variables must be addressed even if this can only be accomplished subjectively.

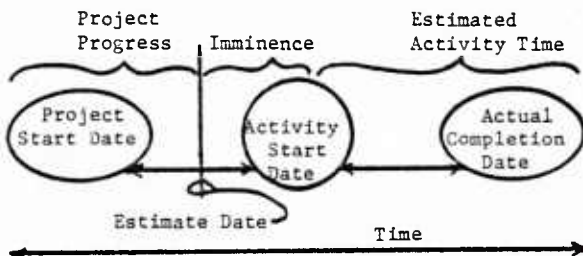
Time Relationships

There is really no single time estimate for an activity. Rather, a series of estimates are made for each activity. Most projects require an updated estimate each two to four weeks. Note, however, that each estimating situation is different (see Figure 1). As the project proceeds, the estimate is projected over a shorter period of time (imminence); there is more experience with and knowledge of the project (project progress); there is also a continual increase in knowledge about the techni-

cal requirements of the activity and about progress on related activities. After the start of the activity (activity start date), the task being estimated changes as portions of it are completed, while knowledge of progress on and problems with the activity become available. Thus each estimate reflects a separate situation and should be considered separately in studies of estimating behavior. The following independent variables define these time relationships:

FIGURE 1

TIME RELATIONSHIPS IN THE ESTIMATING SITUATION



1. Imminence (I_{ijk}). Imminence is the nearness in time of the estimate date (ED) to the activity start date (ASD) for estimate i of activity j in project k .

$$I_{ijk} = (ASD)_{jk} - (ED)_{ijk} \quad (1)$$

2. Project Progress (P_{ijk}): Project progress represents "experience" with the project. It is the difference between the project start date (PSD) and the estimate date (ED) for estimate i of activity j in project k .

$$P_{ijk} = (ED)_{ijk} - (PSD)_k \quad (2)$$

3. Activity Time (A_{jk}). Activity time represents the actual duration of activity j in project k .

4. Estimated Activity Time (E_{ijk}).

Estimated activity time is the duration forecasted by estimate i for activity j in project k .

Accuracy Measures

The dependent variable of interest represents the deviation of the estimate from the actual activity time. Accuracy has several aspects, any one of which may be critical at different times. The absolute value of the error may be useful for evaluating an estimator's ability and assigning the "best" estimator to the most critical activities, for example. Further, the amount and direction of error may be critical to scheduling and allocating scarce resources.

The following three measures of accuracy were used to allow interpretation of both the magnitude and direction of estimating errors, and a comparison of the measures used by both King and Abernathy:

1. Accuracy #1 is the time by which the actual time (A_{jk}) exceeded or was less than the activity time estimate (E_{ijk}) for estimate i of activity j in project k , and provides the error in terms of days.

$$(ACC \#1)_{ijk} = A_{jk} - E_{ijk} \quad (3)$$

2. Accuracy #2 is the absolute value of the difference between the activity time estimate (E_{ijk}) and the activity time (A_{jk}) for estimate i of activity j in project k . This provides the error in days ignoring the difference between positive and negative errors.

$$(ACC \#2)_{ijk} = A_{jk} - E_{ijk} \quad (4)$$

3. Accuracy #3 is the ratio of the activity time estimate (E_{ijk}) to the actual activity time (A_{jk}) for estimate i of activity j in project k . This provides a measure of accuracy as a ratio, with perfect accuracy indicated by a value of one, optimistic estimates (the result of underestimation) indicated by values from zero to one, and pessimistic estimates (the result of overestimation) indicated by values greater than one. This measure of accuracy is clearly nonlinear with respect to time.

$$(ACC \#3)_{ijk} = E_{ijk} / A_{jk} \quad (5)$$

ACC #1 was previously used in the Abernathy study, while ACC #3 was used by King and his associates.

Study I

The first study was designed to investigate the conflicting results reported by King and Abernathy. Data were obtained on over 100 activities from each of three separate and diverse Air Force sponsored projects carefully selected to represent a wide range of technical uncertainty. For each project, all available estimates for all completed activities were included in the sample. This provided a total of 936 estimates for 381 separate activities. The projects selected for study are typical of many large, government-sponsored efforts conducted under contract by several private corporations and with very close government supervision. Project 1 involved a major, advanced "state-of-the-art" modification to an existing weapon system, and clearly represented a relatively high level of technical uncertainty. Project 2 involved the design and implementation of an advanced management information system, probably reflecting an intermediate level of technical uncertainty. Project 3 involved the design and construction of an advanced engineering test facility which

was unusual in design but clearly within the "state-of-the-art". This project represented a relatively moderate level of uncertainty.

The analysis began by grouping the initial estimates for each activity according to their optimistic or pessimistic bias. Table 1 demonstrates that the majority of the activities for all projects were underestimated with relatively few compensating overestimations, providing support for the frequently reported optimistic bias in network estimates. The inference can be drawn that if no learning exists, all projects would be expected to exceed their estimated completion dates.

TABLE 1

PERCENTAGE OF ACTIVITIES BY PROJECT IN WHICH THE INITIAL ESTIMATES UNDERESTIMATED, OVERESTIMATED, OR CORRECTLY ESTIMATED THE ACTUAL ACTIVITY DURATION

	PROJECT 1 2 3			COMBINED DATA
UNDERESTIMATED (OPTIMISTIC)	52.5	52.4	44.1	49.7
OVERESTIMATED (PESSIMISTIC)	27.7	3.9	15.7	15.7
CORRECT (± ONE DAY)	19.8	43.7	40.2	34.6

TABLE 2

ACCURACY OF THE ACTIVITY TIME ESTIMATES BY PROJECT AND MEASURE OF ACCURACY*

	ACC #1	ACC #2	ACC #3
MOST ACCURATE	Proj. 1	Proj. 2	Proj. 3
	Proj. 3	Proj. 1	Proj. 2
LEAST ACCURATE	Proj. 2	Proj. 3	Proj. 1

*Rank ordered based on the mean values achieved by the respective accuracy measures for the individual projects.

Table 1 also implies that Project 1 was the least accurately estimated. Table 2, however, demonstrates that any of the three projects can be the "most accurately estimated", depending on the measure of accuracy used. Such an out-

come should not be surprising. ACC #1 measures the actual number of days error in the estimate. Thus a ten-week and a one-week activity, both underestimated by one day, would carry the same weight in determining the mean value of all estimates. The direction of the error also influences the value of ACC #1. For example, a one-day overestimate and a one-day underestimate cancel each other out, resulting in a mean error of zero. In ACC #3, however, the ratio E/A allows the duration of the activity to influence the results. A one-day error would be more serious in a one-week than in a ten-week activity. ACC #2 produces a mean of the absolute values of the deviations of actual from estimated times, eliminating consideration of the direction of the error. The conflicting results shown in Table 2 serve to point out that it is possible for both the King and Abernathy findings to be correct for the measures of accuracy each used. While the critical path could not be taken into account in these calculations, the practical management of projects and programs requires resources be allocated to each activity being conducted. The accuracy of each estimate is therefore important to the project. Further, since these resources must be allocated on a calendar day basis, ACC #1 would appear to be the most useful indicator of accuracy to the practitioner.

The correlations among the accuracy measures and imminence, activity time, and project progress are presented in Table 3. The findings are supported by regression analyses. The only independent variable that was consistently significant across projects was activity time. Scattergrams further indicate that the estimates for long duration activities tend to be less accurate than those for shorter activities. The nonsignificant and relatively low correlations between ACC #3 and other variables are explained by the fact that correlation is a measure of the linear association between two variables. Since ACC #3 is non-linear, high correlation coefficients between it and other variables are not to be expected.

Abernathy, in his study using ACC #1, found a pronounced learning curve. In this study, the high correlations between accuracy and imminence tend to confirm his finding, but only for Project 1. This is the project that most nearly duplicates the type of project Abernathy used as a data source. Both projects apparently demonstrated a high level of technical uncertainty. King et al., in their studies using ACC #3 and the independent variable imminence, failed to find a learning curve. This study confirms their findings as well, but only for Projects 2 and 3. King et al. do not provide sufficient information about their data source to evaluate the level of technical uncertainty, but Projects 2 and 3 in this study certainly involve significantly less technical uncertainty than does Project 1. The existence of a learning curve is clearly project dependent. The data presented

TABLE 3

SUMMARY OF RELATIONSHIPS IDENTIFIED
FROM CORRELATIONS BY PROJECT
AND ACCURACY MEASURES*

	Accuracy Measure Number	Significant Relationships		
		Imminence	Activity Time	Project Progress
Proj. No. 1	1	-.31(.99)	.50(.99)	NS
	2	.18(.95)	NS	-.24(.98)
	3	.24(.98)	-.28(.99)**	NS
Proj. No. 2	1	NS	.99(.99)	NS
	2	NS	.99(.99)	-.20(.95)
	3	NS	NS**	NS
Proj. No. 3	1	NS	.56(.99)	NS
	2	NS	.61(.99)	NS
	3	NS	-.20(.95)**	NS
Com- bined Data	1	NS	.51(.99)	NS
	2	NS	.51(.99)	NS
	3	NS	-.18(.95)**	

* Simple Pearson Product Moment correlations. The statistical significance ($1 - \alpha$) is indicated in parentheses for each significant relation. NS indicates significance ($1 - \alpha$) below 0.95.

** Regression analysis indicates a highly significant nonlinear relationship between accuracy measure #3 and activity time for all projects.

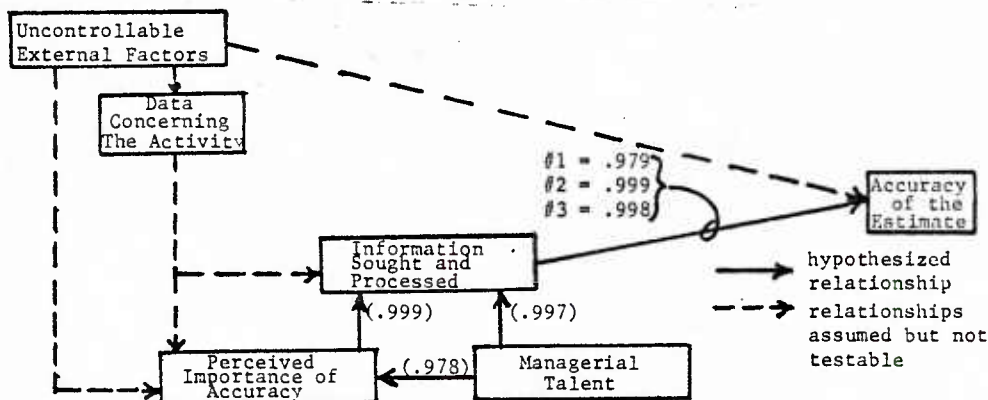
here strongly implies that the existence of a learning curve may be related to the level of technical uncertainty inherent in the project.

Study II

The second study was designed to investigate the impact on estimating accuracy of factors which reflect individual estimator differences but which might be influenced by management. It was hypothesized that certain personality, situational, and decision methodology factors could affect the estimator's accuracy. A model was developed to graphically demonstrate the hypothesized relationships and the effect of uncontrollable external factors on these variables. In essence, this model (see Figure 2) indicates that managerial talent, both directly and in combination with the estimator's perceived importance of accuracy, influences the gathering and processing of information to affect estimating accuracy.

The project selected for study was again typical of large, government-sponsored efforts, in this case involving three government and six large private industry corporations. Its purpose was to supply advanced state-of-the-art aerospace technology to a developing aircraft system, a task involving moderate levels of technical uncertainty. Ninety-four percent of the individuals who had provided initial estimates of activity durations were studied in depth. The project network records yielded data for calculating each estimator's accuracy index as the mean value of his estimating errors. Data from project records and extensive personal surveys were analyzed using correlation analysis, while data from intensive interviews proved invaluable for interpreting the statistical results.

FIGURE 2

MODEL OF THE SIGNIFICANT RELATIONSHIPS^a

^a The significance ($1 - \alpha$) levels achieved for significant relationships are shown in parentheses.

TABLE 4

SIMPLE PEARSON CORRELATION COEFFICIENTS AND SIGNIFICANCE (1 - α)
LEVELS BETWEEN THE MAJOR STUDY VARIABLES

	Perceived Importance of Accuracy	Information Sought and Processed	Accuracy Indices		
			#1	#2	#3
Managerial Talent	0.405 (.987)	0.534 (.997)	0.383 (.967)	0.223 (.852)	0.388 (.969)
Perceived Importance of Accuracy	--	0.661 (.999)	0.318 (.943)	0.405 (.980)	0.234 (.875)
Information Sought and Processed	--	--	0.410 (.979)	0.679 (.999)	0.551 (.998)
Accuracy Index #2	--	--	0.406 (.980)	--	--
Accuracy Index #3	--	--	0.703 (.999)	0.642 (.999)	--

"Managerial talent" represents the sum of scores for nine personality characteristics, categorized as abilities, personality traits, and motivational traits, which have been shown by Ghiselli (6) to be highly correlated with managerial success. All members of the sample were successful managers holding responsible positions and were expected to obtain a certain minimum score. Above this, however, extensive variation was noted in the measure. "The perceived importance of accurate estimates" represents the extent to which the estimator perceives the accuracy of his estimates to be important to the organization, to his career, and to himself as an individual. "Information sought and processed" represents a collection of indicators which measure the amount and type of technical and human information collected, the methods employed in analyzing that information, and the experience of the estimator.

The correlation matrix of results is presented in Table 4, while the key results are indicated on the model in Figure 2. The relationships in the model were strongly supported. The high correlations among the three accuracy measures supports the following interpretations of the results.

Accuracy is highly associated with information sought and processed for all accuracy measures. While the more accurate estimators estimate more precisely (ACC #2), they also tend to underestimate slightly (ACC #3). Apparently those who develop the greatest information base relative to the activity being estimated have more confidence in their estimates, for they use a smaller "contingency factor" or "pad" (some said they used no contingency factor at all). While

all respondents indicated that this relationship should exist, all mentioned some uncontrollable factor such as weather, strikes, or political actions, which would cause the estimate not to hold. Yet regression analysis demonstrates that over 65 percent of the variation in accuracy is explained by the information sought and processed.

Information sought and processed is also highly associated with the perceived importance of accuracy. A more detailed analysis demonstrates that the principle components of these two variables are all significantly related (1 - α) above the .95 level, supporting the association between the primary variables. Those individuals who believed that accurate estimates were important to themselves, their career, or their organization devoted more time and effort to gathering information for their estimates. This is an area that could be readily influenced by managerial personnel. Yet not one of the nine organizations involved had any formal system in effect to provide information to the estimator on the accuracy of his estimates, or to differentially reward the accurate estimator.

Managerial talent, as defined by Ghiselli, is highly correlated with both information sought and processed and the perceived importance of accurate estimates. In the short term, however, the personality characteristics defined as constituting managerial talent would probably be relatively constant for a specific individual and would certainly be difficult for management to influence. Thus the relationships with managerial talent, though important for other purposes, have little relevance to this paper.

CONCLUSIONS

Estimating the duration of an activity in a network management system is a situation fraught with risk and uncertainty at best. The estimate is, in reality, only the estimator's knowledge and experience expressed as a numerical guess. The level of uncertainty should be directly related to the estimator's familiarity with the task and the frequency with which it has been performed before. Particularly in advanced R & D efforts where many of the activities are being performed for the first time, absolute accuracy is impossible to obtain. The studies summarized in this paper demonstrate, however, that a few fairly simple managerial actions can control and reduce the level of uncertainty inherent in most projects.

The first study offers the project manager two clues to improving the accuracy of his project's estimates. The first involves subjectively evaluating the overall level of technical uncertainty inherent in his project. If his project involves a moderate to low level of technical uncertainty, then the manager cannot expect to obtain significantly improved estimates as the project progresses. That is, no "learning curve" is likely to exist. Apparently, similar activities to those performed in this type of project have been performed frequently before, and estimators have a good base of knowledge to work from. Uncertainties in these projects apparently stem from the truly uncontrollable factors. The project manager would probably profitably reduce his efforts to obtain updated estimates. On the other hand, projects with moderate to high levels of technical uncertainty are likely to experience an estimating learning curve as more information becomes known about the technical problems being encountered. Thus, later estimates can be given increased credibility. Second, the most accurately estimated activities in all projects (in terms of ACC #1) are those lasting six weeks to two months. Longer duration activities tended to be severely underestimated, yet many networks for major weapon system development programs contain activities estimated to last six to nine months or longer. The project manager could readily divide such lengthy activities into several shorter activities for estimating purposes, increasing the level of detail in the network. This is the same philosophy used in creating the network for the project in the first place. This research indicates that carrying that philosophy on to the point of estimating no more than approximately two-month periods could improve the accuracy of the estimates.

Study II demonstrated clearly that it is possible to improve the accuracy of activity estimates relative to those obtained by the usual organizational methods. Over 65 percent of the variance in estimating accuracy was explained by information sought and processed, a variable

which in turn was strongly influenced by the perceived importance of accuracy. In the organizations studied, no formal feedback system existed to inform the estimator after the fact about the accuracy of his estimates. As a minimum, this makes it extremely difficult for the estimator to improve his performance, or even to know if and when he has done so. Certainly individuals who develop a reputation for consistently poor estimates see their job security and promotion potential reduced by their poor performance, but it is difficult to understand how this reputation would develop and how it could be verified. Note also that this is in the form of a negative reward. There was apparently no system for rewarding those who estimated well. The key to improving estimates in this environment apparently lies in convincing the estimator of how important it is to him, to his career, and to his organization that his estimates be accurate. One essential element of this is to document how accurate he actually was, and to differentially reward the good and poor estimators. Project managers could easily establish such a feedback system, given the network records already in existence. Significant improvements in estimating accuracy would likely result.

In sum, these studies have demonstrated that uncontrollable factors play a much smaller role in determining the accuracy of activity estimates than was previously believed, either by project managers or by the estimators themselves. Project unique variables, in particular the level of technical uncertainty, do play a more vital role in determining estimating accuracy than previous researchers considered. Certainly much more research is needed to define these project unique variables, and an easy-to-use quantifiable scale for measuring a project's level of technical uncertainty would be of particularly great benefit. Nevertheless, even with the limitations of current knowledge, these studies have shown that relatively simple and inexpensive project management actions can improve estimating accuracy and, to some extent at least, control the level of uncertainty in activity and project estimates.

BIBLIOGRAPHY

- (1) Abernathy, W.J., "Subjective Estimates and Scheduling Decisions", Management Science, Vol. 18 (October 1971), p. B80-B88.
- (2) Adams, J. R., and L. A. Swanson, "Information Processing Behavior and Estimating Accuracy in Operations Management", Academy of Management Journal, Vol. 19 (March 1976), p. 98-110.

- (3) Adams, J.R., S.E. Barndt, and F.P. Lawrence, "Time Estimating Accuracy of Non-Repetitive Production Activities", 37th Academy of Management Proceedings, Orlando, Florida (August 14-17, 1977), p. 164-168.
- (4) Archibald, R.D., and R.W. Villoria, Network Based Management Systems (PERT/CPM) (New York: Wiley, 1967).
- (5) Elmaghraby, S.E., Activity Networks: Project Planning and Control by Network Models (New York: Wiley, 1977), p. 258-308.
- (6) Chiselli, E.E., Explorations of Managerial Talent (Pacific Palisades, California: Goodyear, 1971).
- (7) Hall, D.T., and E.E. Lawler, "Job Characteristics and Pressures and Organizational Integration of Professionals", Administrative Science Quarterly, Vol 15 (September 1970), p. 271-281.
- (8) Kahn, R.L., et al., Organizational Stress: Studies in Role Conflict and Ambiguity (New York: Wiley, 1964).
- (9) Kidd, J.P., and J.R. Morgan, "The Use of Subjective Probability Estimates in Assessing Project Completion Times", Management Science, Vol. 16 (November 1979), p. 266-269.
- (10) King, W.R., D.M. Wittevrongel, and K.D. Hezel, "On the Analysis of Critical Path Time Estimating Behavior", Management Science, Vol. 14 (September 1967), p. 79-84.
- (11) King, W.R., and P.A. Lukas, "An Experimental Analysis of Network Planning", Management Science, Vol. 19 (August 1973), p. 1423-1432.
- (12) King, W.R., and R.A. Wilson, "Subjective Time Estimates in Critical Path Planning-A Preliminary Analysis", Management Science, Vol. 13 (January 1967), P. 307-320.
- (13) Klinge, A.R., Jr., "Bias in PERT Project Completion Time Calculations for a Real Network", Management Science, Vol. 13 (December 1966), p. B194-B201.
- (14) MacCrimmon, K.R., and C.A. Ryavec, "An Analytical Study of the PERT Assumptions", Operations Research, Vol. 12 (1964), p. 16-37.
- (15) McClelland, D.C., "That Urge to Achieve", in Readings in Management, ed. Richards and Nielander (Chicago: Southwestern, 1969), p. 579-583.
- (16) Meyers, S.M., "Who Are Your Motivated Workers", Harvard Business Review, Vol. 42 (January-February, 1964), p. 73-88.
- (17) Woodgate, H.S., Planning by Network (New York: Brandon/Systems Press, 1967).

A STATE-OF-THE-ACQUISITION-PROCESS EVALUATION

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This paper relies primarily on results of a recent Rand study led by Edmund Dews and Giles Smith. The summary and findings of that study** follow:

STUDY OBJECTIVE AND APPROACH

The primary objective of this study is to assist the Office of the Secretary of Defense in its current reassessment of defense acquisition policy by providing some quantitative insights into the effectiveness of the policy changes adopted at the beginning of the 1970s at the initiative of David Packard, then Deputy Secretary of Defense. Related objectives are (1) to identify policy areas where new initiatives seem desirable or further research would be profitable, and (2) to provide a set of organized, quantitative, cross-program data as a basis for future studies and comparisons.

The approach emphasizes quantitative analysis. The principal source of data is the Selected Acquisition Reports (SARs) issued quarterly for each major defense system being acquired. The most recent SARs analyzed in detail here are those for March 1978. Of the total of nearly 60 major systems now reported on in the SARs, some 30 were selected for study as being most representative of 1970s experience under the Packard guidelines. Among the systems excluded were those that had already entered full-scale development before 1969 and therefore presumably reflected earlier acquisition policies.

The report addresses five main questions:

- o Has there been a positive response to the new policy guidelines established early in the 1970s?
- o How have the results achieved in the 1970s acquisition programs compared with the goals established at the time the programs entered full-scale development?
- o In terms of these result-to-goal comparisons, are the 1970s programs doing better than the 1960s programs?

*Director, Resource Management Program. Views expressed are the author's own, and are not necessarily shared by Rand or its research sponsors.

**Edmund Dews, et al., *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, The Rand Corporation, R-2516-DR&E, October 1979.

- o Is it now taking longer to develop and field systems than it did in the past? (The comparison is limited to fixed-wing aircraft.)
- o What new initiatives and further research are suggested by these quantitative results?

The answers to these questions constitute the major findings of the study and are summarized below.

RESPONSE TO THE PACKARD POLICY INITIATIVES

Of the 10 major elements in Mr. Packard's policy initiatives, 6 led to positive changes in organizational structure or standard operating procedures: (1) the Defense Systems Acquisition Review Council (DSARC) was established to provide systematic, high-level program reviews; (2) the Cost Analysis Improvement Group (CAIG) was established to provide OSD with independent cost estimates; (3) "design-to-cost" was instituted, with a specific cost goal identified as a major program objective for each system; (4) responsibility for operational test and evaluation was shifted from the developing agencies to other, independent commands; (5) training courses and schools were established to prepare officers for program management; and (6) program managers were given written charters as a means of establishing their authority.

The remaining four elements required more discretionary responses, often involving program-by-program decisions at Service level; these responses were examined using a quantitative approach.

Our quantitative analysis of *program manager qualifications* suggests a trend in the direction of better-qualified managers, but the results depend on limited data and are generally not statistically significant. From interviews and other qualitative evidence we conclude that most program managers are now reasonably well qualified for the job, and some are very well qualified indeed. Compared with other groups for which data were available on *promotion experience*, program managers appear to have done very well on the promotion ladder in recent years, but questions can be raised about the composition of the groups compared, and we regard the results as suggestive rather than conclusive. Because of the inconclusive nature of these results, and because of the widely divergent views expressed by program

managers and other program personnel about program management as a Service career, we believe OSD and the Services should not relax their attempts to attract superior officers to program management through favorable promotion opportunities and other incentives.

Job tenures for program managers have clearly been increasing, as called for in OSD policy, and are now between 2 1/2 and 3 years on the average; but the increase had begun by the mid-1960s, well before the new guidelines were established. Length of tenure may now be in the right ballpark, but guidance may be needed concerning the timing of program manager assignments so as to coincide with natural breakpoints in program evolution.

The call for *early hardware testing* has had a strong positive response. Testing prior to both DSARC Milestone II (approval for full-scale development) and DSARC Milestone III (approval for production) increased markedly during the 1970s, so that by 1978 the hard data available at major decision milestones was much greater than it had been previously. The call for a *decrease in development/production concurrency* has also been answered, as shown by the high percentage of performance goals now achieved before DSARC Milestone III.

The response to Mr. Packard's call for *increased use of hardware competition* during development has also been positive, but not so clearly marked as in the case of hardware testing. About two-thirds of the programs that have reached DSARC Milestone II since 1973 involved significant use of hardware competition either before they entered full-scale development or subsequently. This change from the situation in the 1960s, when hardware competition in development was rare, was achieved in part because of the Advanced Prototyping Program, which provided direct dollar incentives for the Services to opt for an acquisition strategy involving hardware competition. However, for some programs that reached Milestone II in 1976 and afterward, favorable opportunities for hardware competition may not have been exploited. The Advanced Prototyping Program has not been continued, and there is as yet no strong commitment to hardware competition in OSD's formal policy documents, although there is a cross-reference to OMB's Circular A-109. The future of this key element of the Packard initiatives therefore appears somewhat in doubt, and a strong affirmation of OSD's commitment to hardware competition may be desirable, especially in view of the superior cost-growth record (discussed below) of the programs with hardware competition.

On balance, all policy elements being considered, the Packard guidelines appear to have been generally complied with. The result is an acquisition environment in the 1970s substantially different from that of the 1960s.

1970s EXPERIENCE: PERFORMANCE, SCHEDULE, AND COST

In comparing performance, schedule, and cost results with goals for the 1970s acquisition programs, the metric used was the ratio of results and goals, arranged so that in all cases the preferred outcome--higher performance, shorter schedule, lower cost--was represented by a ratio less than unity. The goals are those established at DSARC Milestone II when systems are approved for full-scale development. The results are those reported in the SARs through March 1978. The aggregate outcomes for the programs examined were as follows:

- o For *system performance parameters*, the distribution of ratios was nearly symmetrical around unity, with a range from about 0.5 to 2.1, and a mean ratio of 1.0. On the average, performance goals were achieved for the parameters tested.
- o For *scheduled program events* accomplished, the distribution of ratios was skewed slightly toward higher values (schedule slippage), with a range from about 0.8 to 2.1, and a mean ratio of 1.13. (These ratios reflect mainly experience in full-scale development, because the schedules established at DSARC Milestone II are heavily weighted toward development events and events early in the production phase.)
- o For *program costs* as projected in March 1978, the distribution of ratios was skewed moderately toward higher values (cost growth), with a range from about 0.7 to 2.2, and a mean ratio of 1.20. The dollar-weighted mean ratio was 1.14, and the median ratio was 1.06. Thus *more than half of the programs had cost growth of less than 10 percent*. (In these comparisons, costs are calculated for the production quantity planned at DSARC Milestone II and are adjusted to eliminate the effects of inflation.)

Cost-growth ratios of the size found here for defense programs appear to be in the same ballpark as the cost-growth ratios observed for large nondefense projects involving new technology or other substantial uncertainties, although further research is needed to confirm this conclusion.

The sample of programs involving substantial hardware competition during or before start of full-scale development was characterized by considerably lower cost growth than the sample without hardware competition (a cost-growth ratio of 1.16 compared with one of 1.53). The sample with hardware competition also did somewhat better in terms of program schedules and system performance goals. The only program to pass DSARC III with negative cost growth (the

UH-60) had full prime contractor competition through full-scale development. Although these samples are small, this result suggests that hardware competition deserves further attention, if only to identify more clearly the conditions in which it is likely to be advantageous.

As programs mature, the projected constant-dollar cost to complete them tends to increase, as might be expected. No program in our cost analysis sample of 31 programs had reached full term completion, but 17 had passed DSARC II by more than three years. For these 17 more mature programs, the mean cost-growth ratio was 1.34 compared with 1.20 for the whole sample including the younger programs. The average (linear) rate of cost growth for both the mature sample and the full sample was between 5 and 6 percent per annum. (This is somewhat greater than the annual cost-growth rates recently calculated by the Office of the Assistant Secretary of Defense (Comptroller), but the calculations are for different samples, and the OSD results are expressed in terms of compound rather than linear growth rates.)

Apart from inflation and changes in quantity, the major drivers of cost growth for the programs of the 1970s were schedule changes, engineering changes, and estimating errors. For the full 31 program cost analysis sample, schedule changes alone contributed about 40 percent of the total cost growth, or about \$5 billion. There is a clear need to understand more concerning the underlying causes of schedule change.

The record strongly suggests that a substantial part of the cost growth is not within the area of control and responsibility of program managers, and in some cases it is even beyond the scope of control measures available to top level acquisition managers in the Services and OSD. Obviously this has important implications for OSD acquisition policy, and suggests that the search for better cost control should include consideration of changes in government policy and procedures outside the Department of Defense.

The conventional wisdom is that when programs experience difficulties, cost is the first constraint relaxed and schedule the second, but that performance goals are adhered to more rigorously. For 1970s experience, this view is supported by an examination of the result-to-goal ratios summarized earlier. But, for the 1970s at least, it must be added that constraints are relaxed (cost increases are accepted) for unit costs but not, generally, for total program costs. In the aggregate, total program costs in constant dollars have remained very close to the amounts projected in the Development Estimates (DEs) made at the time the programs entered full-scale development. For the 31 programs in our cost analysis sample, reductions in quantity almost precisely

canceled out the sum of the cost changes due to the other variance categories. In other words, the real flexibility in the acquisition process is found in the quantities of units procured, not in the aggregate cost of acquisition programs.

This kind of flexibility raises important questions about the validity of the procurement quantities established in the requirements process and the manner in which quantity-quality tradeoffs are made.

1970s AND 1960s COMPARISONS

In terms of the degree to which program results approach program goals, the sample of 1970s programs shows improvement over the 1960s sample.

The 1970s programs are achieving their performance and schedule goals to at least the same degree as the 1960s programs did, and are probably doing slightly better.

The 1970s programs, moreover, are coming closer to their *cost* goals by some 10 to 20 percentage points. (The calculation is in terms of constant-year dollars and DSARC Milestone II production quantities.) This is a substantial reduction in cost growth. For the 31 1970s programs in our cost study the dollar sum corresponding to percentages of this magnitude would be from 9 to 18 billion 1979 dollars. Cost-growth avoidance is of course not the same as cost savings, but substantial cost savings are implied.

The average *annual linear rate* of program cost growth is also less--a rate of about 5 to 6 percent in the 1970s compared with 7 to 8 percent in the 1960s.

In this comparison of acquisition experience in the two decades, some caveats must be borne in mind: the somewhat different maturities of the 1960s and 1970s samples, the possibility of differences in program technical difficulty, and the influence of factors apart from OSD policy and beyond the control of program management, for example, the much higher rate of inflation in the 1970s. Nonetheless, we find it plausible that the changes in acquisition strategy and management introduced since 1969 have been the main contributors to the observed improvements. If the 1970s programs had not suffered from the unusually high rate of inflation they experienced, these improvements might well have been greater.

ACQUISITION INTERVALS: A SLOWDOWN IN THE DEVELOPMENT/PROCUREMENT PROCESS?

A recent study by the Defense Science Board identified lengthening acquisition intervals (slower fielding rates) as a critical defense issue. The DSB concluded that the times required for full-scale development had not changed appreciably, but that there had been some lengthening in the early phase of the acquisition process, before DSARC Milestone II, and also in the production phase, after DSARC Milestone III.

Because of the importance of this issue, we examined trends in aircraft fielding times, using a data base developed at Rand in connection with earlier studies. The sample included 34 U.S. aircraft acquired over a period of about 30 years. We lacked good data for the front end of the acquisition process, and therefore examined the time trends only for full-scale development (FSD) and production. The trend lines differed markedly for these two phases of the acquisition process.

The time taken to move from the start of development to first flight has changed little over the last 30 years, perhaps increasing very slightly. Total development time (measured from the start of development to the delivery of the first production item) also appears to have changed little (for the fighters in the sample), or even to have decreased somewhat (for the larger sample including bombers and transport aircraft). These results appear roughly consistent with the conclusions of the Defense Science Board.

The production phase, however, is taking much longer than it used to, as measured by the time between the delivery of the first and the 200th unit; this interval more than doubled in the course of 30 years. Again, this result is consistent with the DSB's findings. The cause of the lowered production rate is apparently fiscal rather than technical: higher production rates are generally quite feasible in terms of manufacturing capabilities and are often planned, but program funding rates for production have failed to keep pace with the increasing unit costs. The trend line for aircraft investment rates (constant-year dollars expended per month for the procurement of aircraft in the production phase) has remained almost level over time.

Even with the marked increase in production times, the net effect of the different trends in the successive phases of the acquisition process has been only a modest increase in total fielding times. The interval between the start of development and the delivery of the 200th production item has increased by less than 10 percent over the 30-year period--an average linear rate of increase of only a

fraction of one percent per year. This does not, as explained earlier, take into account any lengthening that may be occurring in the pre-Milestone II phases of the acquisition process.

The results just summarized refer to a sample that excludes three recent aircraft programs each characterized by a distinct prototype phase preceding DSARC Milestone II--the A-10, the F-16, and the F-18. These aircraft were excluded from the trend analysis because of a conceptual problem concerning the proper timing for the start of development. Should Milestone II be the baseline date, or is it more realistic in these three programs to consider development as beginning earlier with the initiation of the prototype phase?

For these aircraft we examined both data points. If the development phase baseline is dated from the initiation of the prototype phase, the data points lie above the trend lines and thus suggest a continuing (or possibly accelerating) increase in total fielding times. If DSARC Milestone II is regarded as the correct development baseline, the data points for these aircraft generally fall below the trend lines and thus suggest either a reversal of the trend toward longer total fielding times, or some reduction in the historical rate of increase.

SUGGESTED POLICY INITIATIVES AND TOPICS FOR ADDITIONAL RESEARCH

Improve the Acquisition Information Data Base

Any systematic attempt to improve acquisition policy should be supported by an equally systematic attempt to improve the quality and extent of program data. The Selected Acquisition Reports already represent a major improvement in program data tracking compared with what was available before they were initiated in the late 1960s. However, because of their specialized and limited focus, the SARs are not a fully satisfactory source of data for analysis of broad acquisition policies.

A policy-oriented data base should be established in OUSDRE. Such a data base could utilize SAR information but should go beyond the present SARs in at least two areas. First, original baselines should be retained throughout the life of the program, together with a full documentation of all formally approved program changes. To the extent possible, the reasons for such changes in approved program goals should also be recorded (e.g., milestone slipped because of budget reduction, or technical difficulty) so that cause-effect relationships might be established. Second, to facilitate comparison of cost growth among

many programs on an internally consistent basis, a different method of calculating cost variances should be used when there are changes in the buy size.

Reduce the Instability in Program Funding and Scheduling

No major acquisition program can be planned and managed with high efficiency if it faces frequent and unpredictable changes in year-by-year program funding and production scheduling, even if total program funding eventually reaches the originally planned amount. Schedule slippage and cost growth are the closely related and mutually reinforcing effects of program funding instability. According to the SARs we examined, about 40 percent of program cost growth is attributable to schedule changes. Schedule changes, especially in operational testing and production, are a typical response to changes in annual program budgets. Presumably a large--but undetermined--share of this cost growth is therefore ultimately due to funding instability. We suggest three approaches to this problem:

- o Provide what is now lacking: strong OSD policy guidance as to the desirability and means of reducing program budget fluctuations and schedule changes. For this purpose we offer a draft policy statement in Section VI.
- o Institute a study of the relationship between annual funding instability, schedule slippage, and cost growth to quantify more definitively the effects of annual budget fluctuations on acquisition efficiency.
- o As a part of the policy-oriented data base discussed above, methods should be established for routinely collecting information on changes in program budgets and the consequent changes in program structures so that the effects of budget fluctuations can be more accurately assessed and their causes identified.

Strengthen Guidance on Hardware Competition in Development

The evidence offered in Section III of this report presents at least a *prima facie* case in support of Mr. Packard's emphasis on hardware competition. However, in the latest OSD policy statements we have seen, hardware competition receives little attention; the topic is handled essentially through cross-references to OMB Circular A-109. As the Advanced Prototyping Program has not been continued, this indirect way of stating policy can be interpreted as a lessening of emphasis on hardware

competition before and during full-scale development. If, as we believe, this interpretation is not intended, a partial solution can be achieved by means of a suitable statement inserted in DoD Directive 5000.1 and related documents, affirming OSD's commitment to competition beyond the paper proposal stage.

More than this affirmation appears to be needed, however. A general prescription in favor of competition where "beneficial" or "practical" is not enough. What is needed is guidance that will help the Services to decide when, under what circumstances, for what kinds of systems and contractors, and how far into development hardware competition appears desirable. Guidance of this kind should be based on experience. This suggests a need for a more detailed examination of program histories than could be attempted in this study. Recent samples of programs with and without hardware competition should be compared in detail.

Emphasize Production Quantity as an Element in the Requirements Process

This study did not directly examine the requirements process, but our results suggest that at the time the need for a new system is established the probability of attaining the planned production quantity may not receive sufficient management attention. As has been observed before and confirmed by this study, system performance goals and planned program costs are adhered to rather closely in the aggregate. For many reasons, however, acquisition costs per unit tend to rise above the cost goals. The eventual reconciliation with near-fixed total program costs is typically achieved by means of a substantial decrease in production quantity. This apparent flexibility as to the acceptable size of the operational inventory raises questions about the validity of the original requirement and suggests that production quantity and quantity-quality tradeoffs should receive greater emphasis in the requirements process.

Continue Incentives To Make Program Management an Attractive Service Career

Although there are indications that the status of program managers improved somewhat during the 1970s and that their promotion experience was favorable relative to some other groups of officers, the evidence is inconclusive and perceptions are mixed. The interviews suggest that many senior and middle-level officers now in the program management career field still have doubts about what it has to offer. Efforts to attract superior officers to program management should not be relaxed.

Examine the Timing of Program
Manager Assignments

Average job tenures for program managers have been steadily increasing since the mid-1960s and may now be in the right ballpark. What is less clear is that program manager assignments are individually well timed with respect to natural transition points in program evolution. OSD policy is silent as to the preferred time phasing of assignments. Our impression is that there is insufficient understanding about what constitutes good timing in terms of program needs, and that this question deserves examination.

TAXONOMIC CONCEPTS PANELS SUMMARY

Taxonomic is a derivative of the word taxonomy, meaning the study of the general principles of scientific classification. The first task of the panels discussing "Taxonomic Concepts" was to identify the key aspects of risk and uncertainty as they related to major projects within DoD and the civilian sector. All of the panels in these sessions, in addition to most of the panels in the entire workshop, had great difficulty with terminology not only in a definitional but also a communicative sense.

While none of the panels stated assumptions concerning structural considerations or approaches, the level of uncertainty discussed ranged from certainty, to relative uncertainty, to complete uncertainty. This was used as a spectrum for defining risk and uncertainty based on the amount of information by Golden and Martin. However, they did make the assumption that risk and uncertainty could be treated synonymously.

As a baseline to stimulate further thinking and discussion one taxonomy classified uncertainty into four classes. These were:

- Environmental Uncertainty
- Functional Uncertainty
- Informational Uncertainty
- Technical Uncertainty

The four classes were described, defined and refined with several subclasses. For example, the first subclass to Environmental Uncertainty included the following categories:

- Nature
- Social and Political
- Communication Media
- Time

Other subclasses were defined for Environmental Uncertainty, each with several categories. There were four subclasses for Functional Uncertainty, each with other categories that were also defined and discussed.

There was no order implied in the classification. However, the panel did suggest the possibility that the primary structure might be rearranged by the "degree of control" available to the decision maker.

Another serious discussion dealt with the definitions of the category of Information Uncertainty. The subclasses were divided into anticipated (or unanticipated) unknowns, and known (or unknown) unknowns. There were based on the effect the factors will have on programs versus the second subclass that includes factors for all uncertainty, whether they directly influence the project or not. There were questions as to whether this category was similar to the others, or in fact was a different way of explaining or defining the levels

of uncertainty. In any event, the panel recommended the combination of the subclasses.

Another approach to classification might be by type of phenomena, or analysis. This could range from high to low probability, small to large variance, subjective to objective probability and distribution type.

A different tack or method, described by Thompson, was to categorize the uncertainties of the acquisition process using the following: the plan, the program manager, and the relationship with the environment. This taxonomy was not so much a model with the causal characteristics or classification normally associated with a taxonomy, but rather presented dimensions to serve as a basis for the analysis of uncertainty.

The less structured aspect of this approach is akin to what might be called "blob theory" where a field is analyzed from multiple perspectives paying particular attention to the relationships between the various perspectives. The methodology discussed in this panel was characterized as speculative theorizing of an exploratory nature and used an ordinal scale. Such a scale is easy to define and apply by an operating manager and can also be easily converted to an interval or ratio scale if necessary.

The proposed taxonomy for research provided normative objectives and dealt with the approaches that should be applied to procurement and acquisition research.

The second objective of the panels was to describe the present state-of-the-art in the area of risk and uncertainty and analysis. First and foremost, the paramount issue in all of the panels was the need for agreement on the definitions of risk and uncertainty. Those working in the field of risk and uncertainty come from diverse experience and academic backgrounds and thus have different meanings for the same terms and words.

With the mix of participants (academe, government and industry) the need for the identification of differences from the mathematical to the practical usage of terms in discussions was most apparent and frequently frustrating. The same terms were used for many very different concepts and methodologies.

One model (Thompson) is a substructure for deterministic descriptions and leads to a method for combining ordinal variables with such items as the product life cycle. Industry can be segmented using the model's dimensions, particularly for the purpose of looking at behavioral patterns within these sectors.

The state-of-the-art as discussed by the panel reviewing the estimating network analysis
175.1

activity paper (Adams and Busch) provided information of value to project managers and others concerned with estimating accuracy. In general, it can be expected that estimators, who have the responsibility to eventually perform the task being estimated, may be likely to introduce some bias into the estimate. Estimators are also subject to influence by management to bias values in order to conform to specified targets and objectives. For project activities which have a "fluid" completion date (e.g. software development) there is a tendency for the manager to "legislate" the end date to be as close as possible to the estimator's date.

It was obvious that the state-of-the-art in risk and uncertainty is still in the phase of random applications. The need for defining categories and developing taxonomies is essential to order and progress. For, without well defined and understood terminology the semantics required to translate or integrate applications into state-of-the-art via a taxonomy and to flush out the skeletal framework will be extremely difficult, if not impossible.

While the panels were to analyze existing taxonomies of risk and uncertainty analysis for weakness and omissions, this was considered in depth by only one panel. Here a suggestion was made for the reordering of categories by degree of control (noted above) and the combination of the subclasses of business risk and financial risk into one category. A taxonomy, by definition, is a classification that in turn specifies order. Consideration should be given how to order after general agreement is achieved on categories and subclasses.

There were other weaknesses and omissions noted by most of the panels in these sessions. However, they dealt primarily with methodology so they are not included in this summary.

The final task for the panel was the description (or development) of a comprehensive taxonomy of risk and uncertainty analysis relating to major projects (DoD and civilian sectors). For many of the reasons noted, this was not accomplished to the satisfaction of the workshop participants. However, significant strides were made in the direction of identifying the areas needing further research.

These panels, more than others in the workshop, were confronted by the need for basic definitions. Words such as: risk, uncertainty, risk analysis, state-of-the-art, concurrency, risk assessment, risk avoidance, risk transfer, and so on, need general agreement on definition and usage.

RECOMMENDATIONS

Finally, the discussions of the participants in the taxonomic concepts panels provides insight and perspective into what needs to be done to advance the field. These recommendations, not arranged by priority, included:

1. Reexamine the definitions of risk, uncertainty and related terms derived from past work in various areas and disciplines.
2. The continued development and research for a taxonomy to include risk management and the subclasses of:

Risk assessment, risk analysis, risk turnover, risk avoidance, etc.
3. Study and research risk analysis and risk management as related to the life cycle phase or stages.
4. Investigate the behavioral aspects of decision making under uncertainty in the acquisition process. Consider the type of contract employed as one of the important variables.
5. Use existing publications, training programs, and educational programs to communicate to users and decision makers the results of the above research efforts. This will require translation into terms meaningful to the users.
6. Education in risk analysis is needed by project managers as well as senior executives. This should not be limited only to cost estimators.
7. Mathematical models can provide rapid answers to risky problems that can not normally be handled by other methods.
8. Practically any decision is in fact a risk analysis, but the state-of-the-art ranges from subjective analysis to sophisticated model building. However, program managers require a better understanding of the problem.
9. Study the behavioral aspects of estimating, including the development of guidelines designed to minimize estimator bias.
10. Develop procedures and techniques for evaluating estimates under uncertainty.

NETWORK MODELS FOR RISK ANALYSIS

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ABSTRACT

This paper traces the development of network models for program management under conditions of risk. The history of analytical methods is reviewed briefly, and an interactive model for the simulation of complex development and acquisition programs is described.

INTRODUCTION

The uncertainty faced by the acquisition manager in today's complex research, development, and acquisition environment is considerable. A new military weapon system program may involve many components, many developers and suppliers, and new and untested technologies. There may be uncertainty at every step of the program--uncertainty as to the success or failure of each program element, uncertainty as to the time required, and uncertainty as to the cost of each program element. The successful management of this process requires, in addition to a measure of good fortune and clairvoyance, first-class analytical tools and techniques.

The Department of Defense requires that risks be assessed at each stage of the development and acquisition process and that system performance, cost, and schedule be considered in the light of the risks involved [2]. While there is no prescribed format for this process, a simplistic approach to the problem might include subdividing the development and acquisition program into clearly defined program elements, assessing the risk components of each program element, constructing a model of the acquisition program, and exercising the model in some way to gain insight into the effects of risk on program completion.

This paper considers the history of analytical methods and modeling in addressing the problem of program management under conditions of risk. Some developments in modeling are reviewed briefly, and a computer routine which permits interactive initialization and modification of the model of the acquisition process is described.

NETWORK MODELS

There is nothing new about network models for program management. Indeed, a variety of network models suitable for program scheduling have been developed. Perhaps the earliest of these was the Gantt Chart, developed by Henry Gantt during World War I [1]. The Gantt Chart is still widely used for planning and control and is the predecessor of many other network models.

A need for planning and control techniques for increasingly complex programs and projects led to the development of critical path analysis in the 1950s--Critical Path Method (CPM), developed for DuPont in 1957 by James Kelley and Morgan Walker for the planning and control of complex construction projects [3], and Program Evaluation and Review Technique (PERT), developed in 1958 for the Polaris program by Booz, Allen, and Hamilton, in conjunction with Lockheed [4]. These two techniques, which differ slightly in detail but are essentially similar, identify the "critical path" (the longest path through an oriented network) and are widely used.

While PERT permits some variability in the activity times (optimistic, most likely, and pessimistic time estimates), neither technique permits probabilistic branching at nodes, and neither permits specification of probability functions for activity times. Both are essentially deterministic procedures and are solved in a variety of ways using relatively simple algorithms.

A logical extension of critical path analysis was the development of probabilistic network models permitting probabilistic branching at nodes and some choice of activity time distributions. Two such models are Risk Information for Schedule and Cost Analysis (RISCA), developed for the Army Logistics Management Center at Fort Lee [6], and Venture Evaluation and Review Technique (VERT), developed by Gerald Moeller for the Army Armament Command at Rock Island Arsenal [5].

RISCA and VERT are essentially similar, differing primarily in size and generality. RISCA considers two system variables, time and cost, and has a limited assortment of built-in time distributions (constant, uniform, triangular, and normal). VERT considers three variables, time, cost, and performance, and

has a wider choice of built-in probability functions (constant, uniform, triangular, normal, lognormal, Poisson, Erlang, gamma, beta, and tabulated distributions).

RISCA is easy to use and has relatively modest memory requirements. VERT, with its greater flexibility, is more difficult to use and requires substantially more memory. Both are "Monte Carlo" simulation techniques, executing the network model of the development program repeatedly and presenting results in statistical form at the conclusion of the simulation.

Both RISCA and VERT were developed for card input and batch-mode operation, and neither was intended for terminal use. In order to enhance the utility of the simulation approach, an interactive version of RISCA has been developed at the University of Dayton which features fully-prompted initialization and modification of the network from the terminal keyboard and which returns simplified results to the terminal and complete output to the system printer. The interactive version parallels the card-input version and is written for the UNIVAC 90/80. Additional information is available upon request from the author.

SUMMARY

Network models play an important role and can be of assistance to the acquisition manager in dealing with the risks associated with complex development and acquisition programs. A variety of models have been developed to handle increasingly complex situations, ranging from Gantt Charts and PERT networking to interactive network simulation models.

REFERENCES

1. Clark, Wallace. The Gantt Chart. New York: Ronald Press, 1922.
2. Department of Defense Directive 5000.2. "Major System Acquisition Process." Department of Defense, Washington, D.C.
3. Kelley, James E., and Morgan R. Walker. "Critical Path Planning and Scheduling." Proceedings of the Eastern Joint Computer Conference. 1959.
4. Malcolm, D. G., J. H. Roseboom, C. F. Clark, and W. Fazar. "Applications of a Technique for Research and Development Program Evaluation." Operations Research, Vol. VII, No. 5. 1959.
5. Moeller, Gerald. "Venture Evaluation and Review Technique." U.S. Army Armament Command, Rock Island, Illinois. 1972.
6. "Risk Information for Schedule and Cost Analysis (RISCA)," U.S. Army Logistics Management Center, Fort Lee, Virginia.

AN ENTROPIC COST MODEL FOR THE DEVELOPMENT CONTRACT*

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INTRODUCTION

The early planning phases for a new weapon system are characterized by a high degree of technical and cost uncertainty as related to the development and production of a new weapon system. During these early planning stages, cost estimates are formulated for the potential investment necessary to acquire and maintain a system (9). As knowledge increases and better information becomes available, initial cost estimates are revised and updated at various points of the acquisition life cycle. There are many tools available to managers and their staffs for generating cost estimates during early planning and development phases of a weapon system. However, very few of these methods include a formal technique for evaluating the magnitude of the uncertainty associated with the technical aspects of a program. These considerations form the basis of several research efforts which are the basic theme of this paper. Each research effort and its results will be described. Then, the implications of these results will be presented.

COMPLETED RESEARCH

The series of research effort conducted at the Air Force Institute of Technology (AFIT) evolved from an entropic cost model formulated under Air Force sponsorship at the University of Oklahoma in 1971 (8). Before discussing the research studies, a brief description of the entropic cost model is in order.

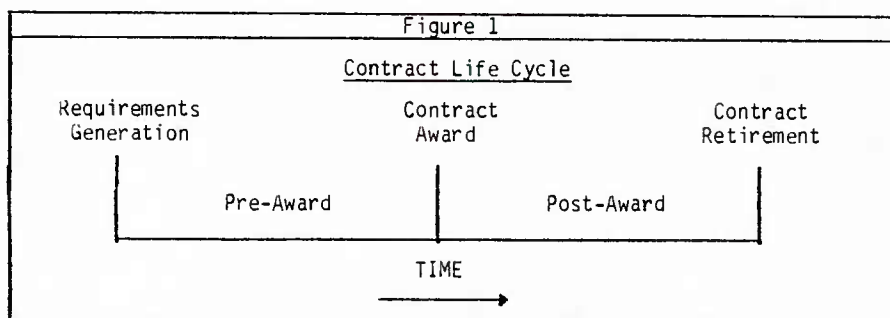
The Entropic Cost Model:

To facilitate understanding of the entropic cost model, a few points must be introduced concerning the environment relative to the development contract, that is, one awarded in the conceptual or validation phase of the weapons acquisition process.

From a contractual perspective, there are two key time periods which relate to potential cost growth: pre-contract award (pre-award) and post-contract award (post-award). (See Figure 1)

During the pre-award time frame of the contract life cycle, management is primarily concerned with strategy formulation to deal with the development of a weapon system. Plans are made to transform these strategies into tactics to, if possible, preclude cost growth during development. To accomplish these tasks, management has at its disposal certain information that should permit the structuring of decisions at the time of award of the pertinent development contract. This information includes technical information, cost estimates, and the results of risk analysis. Technical information includes engineering estimates and feasibility studies conducted by the government or government contractors. Cost estimates are usually available from four sources: the Cost Analysis Improvement Group (CAIG); Independent Cost Analysis (ICA); the buying organization or program office (PO); and finally, defense contractors. An assessment of uncertainty is critical; however, rigorous and formal treatment of this element has not been an integral part of management's information system. Only recently have serious efforts been attempted to structure the process of analyzing the uncertainty which confronts managers responsible for the development contract and the related program (11).

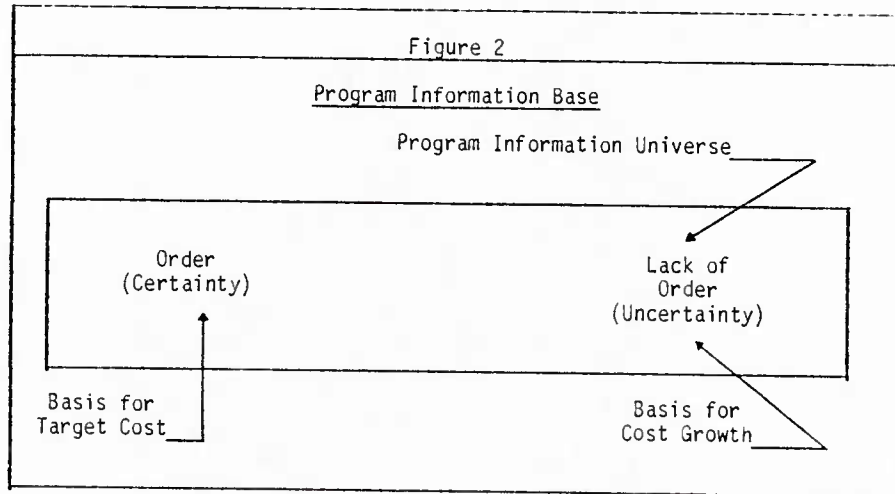
During the post-award time frame (see Figure 1), management must monitor its information system and take actions to preclude or minimize cost growth. However, the information which makes up the control base of the development contract has its roots in the pre-award time frame. The most critical point in time for model effectiveness from a planning standpoint is just prior to contract award (see Figure 1).



* Much of the data collection for this paper was accomplished by Capt. William L. Glover. Research

The information set relative to the development contract consists of two subsets: an ordered set and a set that is disordered (lacks order). The ordered set is composed of factors which appear to have certain outcomes during development. This ordered set forms the basis for the target cost (or the theoretically "most likely" cost) for the development contract. The disordered set relates to factors with uncertain outcomes and forms the basis for cost growth during the post-award time period. This information set is illustrated in Figure 2.

In the entropic cost model, when order is maximum or at unity, the final cost is certain or known with certainty. However, when lack of order or some degree of disorder is present, there are several possible outcomes and final cost is not certain. Therefore, uncertainty relates to multiple outcomes. The purpose of the entropic cost model is to estimate final cost by using a quantitative expression of the disorder or uncertainty concerning development.



The disorder or uncertainty, in information provides the foundation for the entropic cost model. In set-theory terminology, disorder is the complement of order in the information set. For the entropic cost model, this disorder portion of the information set is approximately equal to entropy. The theory of entropy derives from thermodynamics. In a physical system, the amount of disorder is a function of its molecular state at different temperatures. The concept of entropy was extended to information systems in the development of communication and information theory by Shannon and Weaver when they attempted to explain noise in such systems (10). The concept is further extended to form the basis for the entropic cost model which is formulated as follows:

$$\begin{aligned} \text{Final Cost} &= \frac{\text{Target Cost}}{\text{Order in Information}} \\ &= \frac{\text{Target Cost}}{1 - \text{Disorder in Information}} \\ &= \frac{\text{Target Cost}}{1 - \text{Entropy}} \end{aligned}$$

The basic goal of the first two research efforts at AFIT was to test the validity of the model using simulated data from development contracts and programs. The third effort was conducted to determine if a best method was available to structure and generate data to feed the model. The following paragraphs provide a description and the results of each effort.

Initial Model Validation Effort:

Research Description. Glover and Lenz gathered data from the Short Range Attack Missile (SRAM) development program for use in testing the model (4). The researchers reviewed contract files and program documentation to determine the data availability for the test. During this review, it was found that the data (element weights) necessary to test the model was contained in source-selection files. However, these files were not readily available because of their sensitivity. Validation required the creation of the information set in existence immediately after the award of the SRAM development contract. Limited access to source selection records required the researchers to develop a method to simulate and quantify the uncertainty of

information. The method had to meet the requirements of research and be potentially useful to management to capture and measure uncertainty.

The work of C. Jackson Grayson in his study of uncertainty and risk and its application to oil and gas drilling decisions was known to the researchers (6). Jackson's technique relied on the use of probability statements by experts in oil and gas exploration and drilling relative to success in terms of production. Grayson considered both individual and group risk preferences in his work. A similar approach based on subjective probabilities was perceived to be applicable to the development contracting environment in the DOD.

Consequently, Glover and Lenz conducted an exhaustive review of the techniques available for measuring subjective opinions of experts. The review identified the DELPHI method, developed at the RAND Corporation, as the best approach to be used to simulate the development contract award environment for the SRAM. Generally, the DELPHI technique is used to solicit expert judgment to forecast what might happen in the future. Glover and Lenz used the structure and method of DELPHI to simulate what happened. They used a series of controlled interviews with feedback directed at individuals who actually participated in SRAM source selection. The researchers solicited statements of probability concerning outcome measures of unacceptable, acceptable, and exceptional for each of nine (2) factors of concern, such as range, speed, etc.

Using this approach, Glover and Lenz were able to identify some 19,683 possible factor-outcome combinations and a probability for each. The calculation base was the three categories of outcome identified during the simulation for each of the possible factors. Therefore, there were 3⁹ or 19,683 possible outcomes for the development program.

Entropy was then calculated as follows:

$$\text{Entropy} = \frac{\text{System Entropy}}{\text{Maximum Entropy}}$$

$$\begin{aligned} & 19,683 \\ & \sum_{i=1} p_i \log p_i \\ & \frac{1}{\log 19,683} \\ & = 0.686 \end{aligned}$$

Where: $0 \leq \text{Entropy} < 1$, and

p_i = probability of the i^{th} factor outcome (2).

Using the entropy value of 0.686, an estimate for total program cost as follows:

$$\begin{aligned} \text{Total Program Cost} &= \frac{\text{Target Cost}}{1 - \text{Entropy}} \\ &= \frac{\$143.3\text{M}}{1 - 0.686} \\ &= \frac{\$143.3\text{M}}{0.314} \\ &= \$456.4\text{M} \end{aligned}$$

The findings which resulted from this effort were considered significant relative to the validation objective.

Research Findings. The actual cost for the SRAM development program was \$439 million. The estimate for this cost obtained by applying the entropic cost model was \$456 million. This estimate was based on encountering the worst possible cost conditions during development. There were some adjustments to final cost data based on approved changes which were not contemplated during source selection. Thus, the results of the study indicated that the entropic cost model had merit for use as an estimator of development cost. The unique feature of the model is its inclusion of a variable for measuring uncertainty - entropy. The results of this one research effort were not considered adequate to validate the model. Therefore, another team of researchers at AFIT, Babiarz and Giedras, attempted to replicate the Glover and Lenz approach (1).

Model Validation Replication Effort:

Research Description. Babiarz and Giedras continued the effort to test the entropic cost model by replicating Glover and Lenz's work. The researchers selected the F-5E TIGER II Aircraft Development Program as their data source for the test. The procedures were identical to those used by Glover and Lenz including the use of DELPHI to attempt to simulate the uncertainty at the time of contract award. However, Babiarz and Giedras obtained results that were different from those of Glover and Lenz.

Research Findings. Babiarz and Giedras found that the application of an approach such as DELPHI did not provide evidence to substantiate the use of the entropic cost model as a forecasting tool. Their effort produced a final result that was different from the Glover and Lenz's result. Consequently, they concluded that the use of an approach such as DELPHI leaves much to be desired (1).

Using the results of their uncertainty assessment, Babiarz and Giedras obtained subjective probabilities for only the "poor" (or unacceptable) and "acceptable" categories for twelve (12) factors of concern at the time of F-5E development contract award. Therefore, there were 2^{12} or 4096 possible outcomes. Entropy was then calculated as follows:

$$\begin{aligned} \text{Entropy} &= \frac{\text{System Entropy}}{\text{Maximum Entropy}} \\ &= \frac{4096}{\sum_{i=1}^{4096} p_i \log p_i} \\ &= \frac{1}{\log 4096} \\ &= 0.910 \end{aligned}$$

Where, $0 \leq \text{Entropy} < 1$, and

p_i = probability of the i^{th} factor outcome

Using this result, total program costs were then calculated as follows:

$$\begin{aligned} \text{Total Program Cost} &= \frac{\text{Target Cost}}{1 - \text{Entropy}} \\ &= \frac{\$83.635\text{M}}{1 - 0.910} \\ &= \frac{\$83.635\text{M}}{0.09} \\ &= \$929.278\text{M} \end{aligned}$$

The actual cost for the development of the F-5E was \$89.322 million. Thus, the model forecast of total program cost was 10.4 times greater than the actual cost (1, 81). Based on this result, the researchers questioned the use of a device such as DELPHI to generate measurements of uncertainty. The problems encountered did not relate to the model, but measurement of uncertainty. Although the basic approaches used by the researchers on both efforts were the same, there were also some subtle differences which need to be discussed before describing the last research effort which specifically addresses measuring uncertainty (5).

A Critique of Previous Efforts:

Lanclos critiqued the application of DELPHI to simulate uncertainty at the time of contract award (7). Lanclos treated the two efforts as case studies and assessed the differences between them. The following is a discussion of Lanclos' study findings (7, 9-11).

Glover and Lenz selected four persons as their expert panel who were actually members of the SRAM Source Selection Evaluation Board (SSEB). Further, Glover and Lenz followed up their research effort by gaining access to SRAM SSEB files and were able to verify their uncertainty assessments in all but one area of concern. Therefore, the team was strongly confident in the assessment.

Babiarz and Giedras decided to use the DELPHI approach from the start of their effort and did not attempt to review SSEB files for the F-5E. Their panel members were not members of the F-5E SSEB, but had managerial positions in the F-5E program office during the development of the F-5E, one of which had to drop out of the assessment due to a temporary duty assignment, not at contract award. Some of the areas of concern identified occurred as late as two years into the F-5E development program.

Having studied the significant differences between the first two efforts to test the entropic cost model, Lanclos concluded that both efforts would have been more realistic if they had been conducted "real-time." Also, Babiarz and Giedras' choice of experts and problem areas did not give a true representation of the uncertainty in F-5E development at the time of contract award. Finally, the validity of DELPHI as an approach to measuring uncertainty was not proved or disproved by either effort. However, its use to structure the assessment of uncertainty does have merit (7, 11-12).

The concern of measuring uncertainty was addressed by a third research effort at AFIT in 1976 (5).

The Measurement of Subjective Probability:

Research Description. Grayson and Lanclos' research objective was to evaluate existing techniques for assessing subjective probability (5, 9-10). Their objective was to propose an approach to assess and measure the uncertainty which existed relative to a given weapon system development. Their study addressed the following research question: "What existing subjective probability

assessment technique would best assess the magnitude of uncertainty in a given weapon system's development effort?" Grayson and Lanclos conducted an in-depth review of the critical literature available concerning techniques and methods for assessing risk and measuring uncertainty concerning future events. In their study, the researchers considered the statistical and psychological aspects of subjective probabilities and applied content analysis to six techniques for assessing subjective probabilities which have been used in the past.

The Choice-Between-Gambles is a technique that employs betting-type situations relative to gambling in an attempt to obtain probability and cumulative density functions. To accomplish this, experts are offered choices between a "real-world" gambling situation which includes values for an item with unspecified probabilities and a hypothetical situation about two outcomes with probabilities specified. A series of iterations that include varying probabilities are conducted to derive the density functions desired.

The Standard Lottery is a technique for deriving a probability density function which covers all possible values of a given item characteristic. It is similar to the Choice-Between-Gambles in that it is used to present an expert with two gambling situations. The technique involves selecting a number of lottery tickets from a pool of 100 that is varied to achieve the point of indifference. The expert can choose as many as he wants. After the choice is made, a ticket is drawn at random. The lottery is used as a standard comparison to assist the expert to decide on a probability value for a certain outcome which relates to a characteristic of performance for an item.

The Churchman-Ackoff technique does not use a gambling-type situation or a level of indifference concerning characteristics or outcomes. The expert is confronted with evaluations using judgments that require ranking of relative probabilities between sets of values. For example, "greater than," "equal to," or "less than" choices are used. The expert must decide ranges of possible values for "real-world" events and these are then converted to a probability density function (5, 30-33).

The DELPHI technique is used to solicit group consensus about possible outcomes or events in the future. Members of the group of experts are not privy to the other participants' identities. This feature minimizes the possibility of dominant personalities and group pressure in obtaining final results. The method involves rounds of

interrogation which include controlled feedback between rounds. Each participant can change his previous choice based on the feedback from each round. These iterations continue until no change occurs. The results are then used to assess and form a measure of group consensus.

The DeGroot Consensus technique also uses experts to reach a group consensus. However, each member is required to evaluate a probability for an unknown value of a parameter. Then each participant is exposed to the inputs from other participants and revises his own judgment after assessing the others' importance, expertise, etc. This process continues until no more changes occur (5, 39).

Direct Estimation involves an estimating effort that gives it its name; each expert approximates or estimates probabilities directly with no exposure to other probabilities or situations. These results are used directly to derive a probabilities distribution for future events or outcomes (5, 40).

Research Findings. Grayson and Lanclos applied content analysis to each technique studied to determine which technique(s) was(were) commonly used for measuring uncertainty. The researchers found that DELPHI has been widely critiqued in the literature, and its use is widespread and popular.

The team also found that critical analysis and testing of the six techniques were fragmented and lacked continuity and consistency. Based on these findings, Grayson and Lanclos recommended that a series of tests be conducted to determine which techniques or combinations thereof apply to measuring uncertainty for weapon systems development. They suggested that the entropic cost model could be used to measure and compare the results of these tests.

Overall Conclusions from Completed Research:

Obviously, validity testing of the entropic cost model is not complete. The Grayson and Lanclos effort supports DELPHI as a popular and widespread tool for measuring uncertainty. But, popularity and widespread use does not indicate that a technique is the "one best way." However, the research does provide some implications for procurement and acquisition researchers and managers. These implications provide a logical baseline for early identification of uncertainties concerning outcomes for weapon system development. Once uncertainty is known to exist concerning development, management can better use its information base to deal with

risks related to the uncertainty. Development of such a capability presents a challenge to researchers and managers.

IMPLICATIONS AND CHALLENGES

Although intensive and widespread, research has not progressed to the point of providing management with an effective set of tools for realistically forecasting the ultimate cost of a new system. Costing methodologies vary and few emphasize the formal use of methods for capturing and measuring technical uncertainty. The research challenge is to invent, design, and innovate methods for quantifying uncertainty to feed models such as the entropic cost model. These efforts will be difficult at best; there will be failures and hopefully successes. However, this series of research efforts have implications for management also. The qualitative aspects of the research may be useful for structuring the assessment evaluations of doubt, reviewing status, and improving planning baselines.

Each of the techniques for assessing and measuring uncertainty which were studied by Grayson and Lanclos depends on identification of areas or factors that have uncertain outcomes. These areas should be solicited from program participants early in the planning cycle prior to contract award. Current directives specifically address minimizing uncertainty and risk (3, 6) during the acquisition cycle. Uncertain factors should be identified early. Such an exercise provides a structured approach to capturing the judgment of managers, evaluators, and experts; key participants usually have a knowledge and experience base that they draw on to "judge" and in turn identify concern or uncertainty based on available information. Management could do well to capitalize on this knowledge and experience by soliciting participant concerns and uncertainty early in the pre-award planning. This effort should be a combined exercise by both the contracting officer and program manager supported by their functional staff. One major criticism of such exercises is that of time--but some time spent early may have some long range payoffs in terms of readiness to respond to contingencies during development and to minimize downstream costs.

Once this "uncertainty baseline" is established, it could be updated at major milestones during performance of the development contract. Such an approach could also benefit the staff in preparing for major system milestones required by addressing such factors in the Decision Coordinating Paper (4).

The baseline should be updated immediately after development contract award to capture specific information relevant to the particular contractor(s) involved and evaluator's beliefs in their capability to perform the contract.

The thrust of the implications are not really new. But the main purpose of this discussion is to prompt management to use their talent and ability to establish such a baseline for dealing with uncertainty. The ultimate benefits should be obvious: better visibility and understanding of uncertainty assessment problems which are encountered by contract and program managers. A structured "audit trail" should help managers to get at the "root cause" of some of our problems and treat them accordingly.

If a problem is identified which cannot be treated readily, at least the researcher can shed some light on an approach to help better address the problems and issues at hand. This approach takes time, but the potential payoffs may greatly exceed the investment.

BIBLIOGRAPHY

1. Babiarz, Anthony S. and Peter W. Giedras. A Model to Predict Final Cost Growth in Weapon System Development Programs, Unpublished Master's Thesis. Wright-Patterson AFB, Ohio: Air Force Institute of Technology, 1975.
2. Glover, William L. and John W. Lenz. A Cost Growth Model for Weapon System Development Programs, Unpublished Master's Thesis. Wright-Patterson AFB, Ohio: Air Force Institute of Technology, 1974.
3. DOD Directive 5000.1, Major System Acquisition. U.S. Department of Defense: 18 January 1977.
4. DOD Directive 5000.2, Major System Acquisition Process. U.S. Department of Defense: 18 January 1977.
5. Grayson, Anthony S. and Harold J. Lanclos. A Methodology for Subjective Assessment of Probability Distributions, Unpublished Master's Thesis. Wright-Patterson AFB, Ohio: Air Force Institute of Technology, 1976.
6. Grayson, C. Jackson, Jr. Decisions Under Uncertainty. Boston, Massachusetts: Harvard Business School, Division of Research, 1960.

7. Lanclos, Harold J. The DELPHI Technique in Subjective Probability Assessment: Two Test Cases, Unpublished Term Paper. Wright-Patterson AFB, Ohio: Air Force Institute of Technology, 1975.

8. Martin, Martin D. A Conceptual Cost Model for Uncertainty Parameters Affecting Negotiated, Sole-Source Development Contracts, Unpublished Doctoral Dissertation. University of Oklahoma, Norman, Oklahoma, 1971.

9. Martin, Martin D. and William L. Glover. "An Empirical Analysis of the Relationship Between Cost, Cost Estimation, and Cost Analysis." Ninth Annual DOD/FAI Acquisition Research Symposium, Annapolis, Maryland, June 9-11, 1980.

10. Shannon, Claude E. and Warren Weaver. The Mathematical Theory of Communication. Urbana, Illinois: The University of Illinois Press, 1949.

11. Worm, George H. Application of Risk Analysis in the Acquisition of Major Weapon Systems, Unpublished Final Report, Contract F49620-79-C-0038 (AFOSR). Wright-Patterson AFB, Ohio: Air Force Business Research Management Center, 1980.

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ABSTRACT

A new form of uncertainty called possibilistic uncertainty is introduced. As opposed to probabilistic uncertainty, which is based upon an additive measure and is applicable in cases of repeated experiments, possibilistic uncertainty is based upon a non-additive measure and is a generalization of the idea of ease of attainment in a situation. We discuss the properties of possibilistic uncertainty and describe some prototypical examples. We discuss the idea of language as being a generator of possibilistic variables. We introduce fuzzy subsets as a means of translating linguistic values into possibility distributions. We discuss the idea of approximate reasoning as a means of simulating a large class of human reasoning operations. We introduce a measure of specificity of a possibility distribution. We discuss applications of fuzzy set theory to intelligent querying of data bases and multiple objective decision making. Finally, we introduce some ideas from fuzzy arithmetic.

INTRODUCTION

There appears to exist, in addition to the concept of probability, another idea of uncertainty. This concept of uncertainty is a generalization of the idea of ease of attainment with which a variable can assume a value. This new concept of uncertainty has been called possibilistic uncertainty (1).

Consider an optimization problem in which the set of possible alternatives consist of a set X . Assume we have some objective function which we are trying to optimize. We can observe that we are uncertain as to which element $x \in X$ is the optimal. Hence, there exists some uncertainty as to the optimal value, however, this uncertainty is not of a probabilistic nature. As we investigate the objective function we may find some information about the optimal value. This process reduces the uncertainty by reducing the possible values which the optimal can assume.

We can consider a house which has a number of windows and we are interested in the ease of burglarization of this house. It appears that the concept which most closely approximates

our analysis of the situation is the possibility of entry.

A quantitative framework has been suggested by L.A. Zadeh (1) into order to investigate and apply the concept of possibility.

Assume V is a variable which can assume values in the set X . A possibility distribution Π is a mapping from X into $[0,1]$,

$$\Pi: X \longrightarrow [0,1]$$

such that for each $x \in X$, $\Pi(x)$ indicates the possibility of V assuming the value x . It should be noted that the larger $\Pi(x)$ the more possible the circumstance that $V=x$. Furthermore, if A is a subset of X then the

$$\text{Poss } [V \in A] = \max_{x \in A} \Pi(x).$$

In order to understand the rationale behind the selection of this operation, we shall use our burglar example as a framework. If X is the set of all the windows in our house then $\Pi(x)$, for each $x \in X$ indicates the ease or possibility of getting in window x . Let A be some subset of windows, $A \subseteq X$, we may ask how easy it is for a burglar to enter the house through any window in this subset. The answer is that the ease of entering the house through a window in the subset A is equal to the possibility or ease of entering the most accessible window in A . Thus, the possibility of entry through any window in A is equal $\max_{x \in A} \Pi(x)$.

Thus, while both possibilistic and probabilistic uncertainty are mappings from a set into the unit interval they have different properties. First we note that the possibility associated with a subset is the maximum possibility of the elements in that subset, whereas the probability associated with a subset is the sum of the probabilities associated with the elements in the set. A second distinction is that the sum of the probabilities must sum to one which is not the case for possibilities.

It should be also noted that probability and possibility are addressing two different questions. When using a probabilistic type model, we are answering a question about what percentage of the number of times we perform an experiment will a given outcome occur. Whereas with possibility, we are addressing questions about how easy it is for a particular outcome

to occur in a given time.

LINGUISTIC VARIABLES

In many instances the information with respect to the possibility distribution associated with a variable can be inferred from information conveyed via natural language. We shall discuss the connection between natural language and possibility theory based upon the concepts of linguistic variables and fuzzy subsets.

The idea of a fuzzy set was first suggested by L.A. Zadeh (2). A complete bibliography on fuzzy sets and related topics can be found in (3).

Assume X is a set of elements a fuzzy subset A of X associates with each element a grade of membership $A(x)$ contained in the unit interval. A distinction between fuzzy subsets and classic or crisp subsets is that the membership grades for fuzzy subsets are in the unit interval whereas, crisp subsets are in essence a special case of fuzzy subsets. Fuzzy subsets provide us with a mechanism for describing concepts which have some imprecision in their definition. For example, if X is a set of people and A is the subset of "tall" people, it would seem more natural to use a fuzzy subset to describe A than a crisp set.

Extensions of the usual set theoretic operations to fuzzy subsets have been suggested (2).

Assume A and B are two fuzzy subsets of X and let x be a typical element in X .

The union $C = A \cup B$ is also a fuzzy subset of X , where

$$C(x) = \text{Max } [A(x), B(x)].$$

The intersection $D = A \cap B$ is also a fuzzy subset of X , where

$$D(x) = \text{Min } [A(x), B(x)].$$

The negation A' is also a fuzzy subset of X , where

$$A'(x) = 1 - A(x).$$

It can be easily shown that these operations collapse to the usual set theoretic operations when the membership grades are drawn from $\{0,1\}$.

It should also be noted that while these operations are the most often used they are not necessarily the only possible definitions (4,5).

We can also generalize the concept of a relationship to include fuzzy relationships. Recalling that if X and Y are two sets, a relationship S

is a subset of $X \times Y$ such that the pair (x,y) is contained in S if they are related by the property defining S . In many instances the idea defining the relationship is imprecise. For example, if $X = Y = \text{Reals}$ and if $S = \text{"close to"}$ it would appear that we could best describe S by a fuzzy relationship. A fuzzy relationship is a fuzzy subset of $X \times Y$.

From the above discussion we can see that many concepts are best defined by fuzzy subsets, particularly those used in natural language.

Assume V is a variable, for example, let V be the speed of a car. In many instances, particularly in human discourse, the value assumed by V is an imprecise value, i.e., "about 75 miles per hour" or "very fast" or "slow." With the aid of fuzzy set theory, we can represent this type of information in a quantitative fashion. Let X be the set of values which the variable V can assume. In our example, it would be $\{0,100\}$, the set of speeds the car can assume. If our car is going 75 miles/hour, we would say

$$V = 75.$$

If the car is going "about 75," we could say

$$V = \text{"about 75,"}$$

V then becomes a linguistic variable.

Furthermore, the concept "about 75" is an imprecise concept which could be represented as a fuzzy subset A of X . Thus, we can say

$$V = A,$$

where A is a fuzzy subset of X .

Thus, the value of a linguistic variable can be equated to the fuzzy subset representing the linguistic value, in this case "about 75."

We note that the statement

$$V = \text{"about 75"}$$

tells us something about the value of V but there exists some uncertainty as to its exact value. This type of uncertainty with respect to our knowledge of V is what we have previously called possibilistic uncertainty. It has been suggested that the possibility distribution associated with the variable V can be obtained from the fuzzy subset A representing the value of V .

Thus, if V is a variable with base set X such that $V = A$, where A is a fuzzy subset of X , then A induces a possibility distribution over the set X s.t. for each $x \in X$

$$\pi(x) = A(x),$$

where $A(x)$ is the membership grade of x in A .

In order to see the validity of this relationship we consider the following. Assume B is an ordinary set we can define $POSS(B)$, as the possibility of finding an element in B . Thus,

$$POSS(B) = \max_{x \in X} B(x).$$

If B is a fuzzy subset of X the definition also holds. Furthermore, assume that A is also a fuzzy subset of X then the possibility of obtaining an element in $A \cap B$ is

$$POSS(A \cap B) = \max_{x \in X} [C(x)],$$

where $C = A \cap B$ and hence

$$C(x) = A(x) \wedge B(x). \quad (\wedge = \min)$$

Let us consider the special case when $A = x_i$. Then C is such that

$$C(x) = 0 \quad x_i \neq x$$

$$C(x) = 1 \wedge B(x_i) = B(x_i) \quad x = x_i.$$

This is then the possibility of x_i , which is denoted $\Pi(x_i)$, hence

$$\Pi(x_i) = \max_{x \in X} C(x) = B(x_i).$$

APPROXIMATE REASONING

Much of the reasoning performed by human beings involves a type of reasoning which we shall call approximate reasoning. By approximate reasoning, we shall mean a type of logical inference in which the information used may be imprecise.

An example of approximate reasoning would be the following:

"If x is near 50, then y is much greater than 100"

x = about 45

what is y ?

In a structural sense approximate reasoning consists of the following:

- 1) A set of statements describing the relationships between variables, i.e., "if x is near 50 then y is much greater than 100." These rules in general involve imprecise values for the variables.
- 2) Imprecise data on values for some of the variables, i.e., x = about 45.

- 3) The question of what possible values can we infer for the variables based upon the information contained in one and two.

In the following we shall describe a language which will enable a decision maker to computerize complex approximate reasoning problems. This language based upon the theory or possibility and fuzzy sets is called PRUF (6).

PRUF consists of two aspects translation rules and inference rules. The translation rules allow us to convert our data and our statements of relationships between variables into possibility distributions. Our rules of inference allows us to make inferences, in terms of possibility distributions, about the variables desired.

Assume V is a variable which can assume values from the set X . The statement $V = F$, where F is a linguistic value expressed as a fuzzy subset F of X translate into a possibility distribution Π_V on X such that

$$\Pi_V(x) = F(x)$$

for each $x \in X$. The statement

$$V = mF$$

where m is a modifier, such as not, very, sort of, etc., translates into a possibility distribution Π_V on X such that

$$\Pi_V(x) = F^+(x)$$

where F^+ is the modification of F induced by m . For example, if m = not then $F^+(x) = 1 - F(x)$, if m = very, then $F^+(x) = F^2(x)$ or if m = sort of, then $F^+(x) = F^{1/2}(x)$.

As a simple illustration, consider the variable V where

$$X = \{0, 1, 2, 3, 4, 5, 6\}.$$

Consider the statement $V = \text{small}$, where

$$\text{small} = \left\{ \frac{1}{0}, \frac{1}{1}, \frac{.8}{2}, \frac{.5}{3}, \frac{.3}{4}, \frac{0}{5}, \frac{0}{6} \right\}.$$

Then not small is

$$\left\{ \frac{0}{0}, \frac{0}{1}, \frac{.2}{2}, \frac{.5}{3}, \frac{.7}{4}, \frac{1}{5}, \frac{1}{6} \right\}$$

and very small induces the possibility distribution

$$\left\{ \frac{1}{0}, \frac{1}{1}, \frac{.64}{2}, \frac{.5}{3}, \frac{.09}{4}, \frac{0}{5}, \frac{0}{6} \right\}.$$

Assume again V is a variable taking values in the set X and U is another variable taking values in the set Y . Let F and G be fuzzy subsets of X and Y representing the linguistic

values associated with V and U respectively.

The statement

V is F and U is G

induces a possibility distribution on the binary variable (V,U) defined over the set $X \times Y$ such that

$$\Pi_{V,U}(x,y) = \min [F(x), G(y)]$$

for each $(x,y) \in X \times Y$.

As a very simple illustration consider

$$X = Y = \{1, 2, 3\}$$

$$F = \left\{ \frac{1}{1}, \frac{.6}{2}, \frac{.1}{3} \right\}$$

$$G = \left\{ \frac{0}{1}, \frac{.3}{2}, \frac{1}{3} \right\}$$

then the statement

"V = F and U = G,"

induces the joint possibility distribution

$$\Pi_{V,U} = \left\{ \frac{0}{(1,1)}, \frac{.3}{(1,2)}, \frac{1}{(1,3)}, \frac{0}{(2,1)}, \frac{.3}{(2,2)}, \frac{.6}{(2,3)}, \frac{0}{(3,1)}, \frac{.1}{(3,2)}, \frac{.1}{(3,3)} \right\}.$$

The statement

V is F or U is G

induces a possibility distribution on the binary variable (V,U) defined on the set $X \times Y$ s.t.

$$\Pi_{V,U}(x,y) = \max [F(x), G(y)].$$

The statement

if B is F then U is G

induces a possibility distribution on the binary variable (V,U) defined on the set $X \times Y$ s.t.

$$\Pi_{U/V}(x,y) = \min [1, 1 - G(x) + F(y)].$$

A fundamental rule of inference in approximate reasoning is the rule of fuzzy compositional inference.

Assume $\Pi_{U/V}$ is a possibility distribution over the binary variable (V,U). Let Π_V be a possibility distribution representing the value of the variable V, then from this, using the rule of fuzzy compositional inference we can infer the possibility distribution associated with the variable "u" as

$$\Pi_U(y) = \max_{x \in X} [\min(\Pi_V(x), \Pi_{U/V}(x,y))].$$

As a simple illustration of the above procedure, we can consider the following.

Let U and V be variables measured over the sets $Y = \{1,2,3\}$ and $X = \{a,b\}$, let G and F be fuzzy subsets of Y and X

$$G = \left\{ \frac{1}{1}, \frac{.6}{2}, \frac{.1}{3} \right\}$$

$$F = \left\{ \frac{.5}{a}, \frac{.9}{b} \right\}$$

Assume we have the following information

P' : if V = sort of F then U = G

P'' : if V = very F then U = not G

V = F.

First we can see that

$$\text{sort of } F = F^{1/2} = \left\{ \frac{.7}{a}, \frac{.94}{b} \right\}$$

$$\text{very } F = F^2 = \left\{ \frac{.25}{a}, \frac{.81}{b} \right\}$$

$$\text{Not } G = 1 - G = \left\{ \frac{0}{1}, \frac{.4}{2}, \frac{.9}{3} \right\}$$

Using our translation rules, we obtain that P' translates into

$$\hat{\Pi}_{U/V} = \left\{ \frac{.7}{(a,1)}, \frac{.6}{(a,2)}, \frac{.1}{(a,3)}, \frac{.94}{(b,1)}, \frac{.6}{(b,2)}, \frac{.1}{(b,3)} \right\}$$

and P'' translates into

$$\hat{\Pi}_{U/V} = \left\{ \frac{0}{(a,1)}, \frac{.25}{(a,2)}, \frac{.25}{(a,3)}, \frac{0}{(b,1)}, \frac{.4}{(b,2)}, \frac{.81}{(b,3)} \right\}.$$

Since the logical connection between our two statements is that P' and P'' then together they generate an overall possibility distribution,

P' and P'' $\rightarrow \Pi_{U/V}$ where

$$\Pi_{U/V}(x,y) = \min [\hat{\Pi}_{U/V}(x,y), \hat{\Pi}_{U/V}(x,y)]$$

thus we get

$$\Pi_{U/V} = \left\{ \frac{0}{(a,1)}, \frac{.25}{(a,2)}, \frac{.1}{(a,3)}, \frac{.94}{(b,1)}, \frac{.4}{(b,2)}, \frac{.1}{(b,3)} \right\}.$$

Then using the compositional rule of inference we get:

$$\Pi_U = \left\{ \frac{.9}{1}, \frac{.4}{2}, \frac{.1}{3} \right\}$$

as the possibility distribution associated with the variable U.

Assume a variable V has an associated possibility distribution F defined over the finite base set X .

An α level set associated with F is the crisp subset of X denoted F_α defined by

$$F_\alpha = \{x/F(x) \geq \alpha, x \in X\}.$$

F_α then is the set of all elements have possibility at least α .

Using this concept of level sets we can introduce the idea of the specificity of a possibility distribution as

$$S(F, X) = \int_0^{\alpha_{\max}} \frac{1}{\text{Card } F_\alpha} d\alpha.$$

$\text{Card } F_\alpha$ is the number of elements in F_α and $\alpha_{\max}$ is the maximum possibility associated with any element in X . (7)

Example:

$$\text{Assume } F = \left\{ \frac{.3}{a}, \frac{.6}{b}, \frac{1}{c} \right\}$$

then

$$\begin{array}{lll} \alpha \leq .3 & F_\alpha = \{a, b, c\} & \text{card } F_\alpha = 3 \\ .3 < \alpha \leq .6 & F_\alpha = \{b, c\} & \text{card } F_\alpha = 2 \\ \alpha \leq .6 & F_\alpha = \{c\} & \text{card } F_\alpha = 1 \end{array}$$

$$S(F, X) = \int_0^1 \frac{1}{\text{card } F_\alpha} d\alpha = \frac{.3}{3} + \frac{.3}{2} + \frac{.4}{1} = .65$$

The measure of specificity, which always lies in the unit interval, measures the degree to which the possibility distribution points to one and only one of the elements of X as its manifestation. The specificity measure in possibility theory is analogous to the concept of entropy in probability theory.

The measure of specificity plays an important role in evaluation of the performance of forecasters. Assume we have a forecaster whose forecasts are in terms of linguistic variables representable as possibilistic distributions. Let F be a fuzzy subset of X representing a forecast. A good forecast should have two characteristics--it should be specific thereby giving us the most information and it should be correct. Assume that the true value of the forecasted variable is $x \in X$, then the degree of truth of the forecast is $F(x)$. We can measure the specificity of our forecast as $S(F, X)$. The product of these two terms measures the performance of the forecaster. By calculating the average of these products over a sampling of situations, we can obtain a mean measure of performance of a forecasting system.

Fuzzy sets provide a methodology for intelligently quering a data base via applying certain rules for interpreting quantified statements. (8,9)

Assume we have a data base consisting of the heights of the people in a set X . Assume we ask the question, "How true is it that most people in the set are tall?" The question involves two concepts which need definition: tall and most. We must first ask the questioner what he means by tall. Since tall is an imprecise concept, he can use a fuzzy subset to represent the concept of tall. Let us assume that this is supplied via the fuzzy subset F

$$F: Y \rightarrow I$$

where Y is the set of heights 30 to 80 inches. Since each $x \in X$ has a height belonging to Y , we can construct a fuzzy subset,

$$F^*: X \rightarrow I$$

where if y_i is the height of $x_i \in X$ then $F^*(x_i) = F(y_i)$.

Next, we must inquire as to the meaning of the word "most." Again, this being an imprecise concept, it can be described by a fuzzy subset,

$$M: I \rightarrow I,$$

where for each $u \in I$, $M(u)$ indicates the degree to which u portion of the people being tall satisfies our concept most.

Finally, using the translation rule for quantified statements supplied by PRUF, we can express the truth of the question as:

$$T = M\left(\frac{1}{N} \sum_{i=1}^N F^*(x_i)\right)$$

where N is the number of elements in X .

MULTIPLE OBJECTIVE DECISION MAKING

Fuzzy set theory provides a framework in which to construct models for multiple objective decision making (10).

Assume we have a decision in which we have a set X of alternatives and a class $A_1, A_2, \dots, A_p$ of objectives. We can represent each objective as a fuzzy subset of X , where $A_i(x_j)$ indicates the degree to which x_j satisfies the i th objective.

Next we must consider how our objectives should be combined to formulate our decision function D .

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If our problem requires the satisfaction of A and A_1 and $A_2 \dots$ and A_n , then we can formulate D as

$$D = A_1 \cap A_2 \cap A_3 \dots \cap A_n$$

D in this case becomes a fuzzy set of X and we select as our optimal alternative the element which the largest grade of membership in D.

More complex decision criteria can be modeled using the operations of fuzzy sets.

One such case was suggested by Yager (11) to handle situations in which the objectives have differing degrees of importance. He suggested that we associate with each objective a number in the unit interval indicating its importance and then raise each fuzzy subset corresponding to an objective to the power equal to its importance.

Thus,

$$D = A_1^{\alpha_1} \cap A_2^{\alpha_2} \cap A_3^{\alpha_3} \cap \dots \cap A_n^{\alpha_n},$$

where α_i is the importance of the i th objective and $A_i^{\alpha_i}$ is defined as the fuzzy subset of X where

$$A_i^{\alpha_i}(x) = (A_i(x))^{\alpha_i}.$$

FUZZY ARITHMETIC

A fuzzy number is a fuzzy subset of the set R of reals. Thus, if F is a fuzzy number then:

$$F: R \rightarrow [0,1] \quad (12,13)$$

In the following we shall assume F and G are fuzzy numbers. The sum of two fuzzy numbers, $F + G = H$ is also a fuzzy number such that

$$H = \left\{ \frac{F(x) \wedge G(y)}{x-y} \right\} \quad \text{for all } x, y \in R$$

$$\text{ex: } F = \left\{ \frac{.2}{3}, \frac{.5}{4}, \frac{.7}{5}, \frac{1}{6}, \frac{.6}{7}, \frac{.1}{8} \right\}$$

$$G = \left\{ \frac{.6}{-1}, \frac{.1}{0}, \frac{.5}{1} \right\}$$

$$H = F + G = \left\{ \frac{.2}{2}, \frac{.5}{3}, \frac{.6}{4}, \frac{.6}{5}, \frac{.1}{6}, \frac{.2}{7}, \frac{.5}{3}, \frac{.7}{4}, \frac{1}{6}, \frac{.6}{7}, \frac{.1}{8}, \frac{.2}{4}, \frac{.5}{5}, \frac{.5}{6}, \frac{.5}{7}, \frac{.5}{8}, \frac{.1}{9} \right\}$$

$$H = \left\{ \frac{.2}{2}, \frac{.5}{3}, \frac{.6}{4}, \frac{.7}{5}, \frac{1}{6}, \frac{.6}{7}, \frac{.5}{8}, \frac{.1}{9} \right\}$$

The difference of two fuzzy numbers, $F - G = H$ is also a fuzzy number such that

$$H = \left\{ \frac{F(x) \wedge G(y)}{x-y} \right\} \quad \text{for all } x, y \in R.$$

The division of one fuzzy number by a second, $H = F/G$, is also a fuzzy number such that

$$H = \frac{F(x) \wedge G(y)}{x/y} \quad \text{for all } x, y \in R.$$

A methodology for comparing fuzzy numbers has been suggested by Yager (14).

Assume F is a fuzzy number with maximal grade of membership one. Let F_α be the α -level set associated with F. Let M_α be the mean of the elements contained in F_α . Then

$$V(F) = \int_0^1 M_\alpha \, d\alpha.$$

is a mapping from the set of fuzzy subsets of R into R. We can use $V(F)$ to compare the magnitudes of fuzzy numbers.

CONCLUDING REMARKS

In the preceding we have sketched very briefly some of the areas of applications of fuzzy set theory and the related idea of possibility theory. We feel that this new tool provides a fertile framework in which many of the problems facing our complex society and many of the opportunities presented by the new technologies can be best handled.

REFERENCES

1. Zadeh, L.A., "Fuzzy sets as a basis for a theory of possibility," Fuzzy Sets and Systems 1, 3-28, 1978.
2. Zadeh, L.A., "Fuzzy sets," Information and Control 8, 338-353, 1965.
3. Kandel, A. & Yager, R.R., "A 1979 bibliography of fuzzy sets and their applications," in Gupta, M.M., Ragade, R.K., R.R. (eds.), Advances in Fuzzy set Theory and Applications, North-Holland, Amsterdam, 621-744, 1979.
4. Yager, R.R., "On a general class of fuzzy connectives," Fuzzy Sets and Systems, to appear.
5. Dubois, D., "Triangular norms for fuzzy sets," Proc. 2nd Seminar on Fuzzy Sets, Lin, Austria, 1980.
6. Zadeh, L.A., "PRUF - A meaning representation language for natural languages," Int. J. Man-Machine Studies 10, 395-460, 1980.
7. Yager, R.R., "A measure of information in possibility distributions," Proc. Round Table on Fuzzy Set Theory, Lyon, France, 1981.
8. Zadeh, L.A., "Precisiation of human communication via translation into PRUF," Memo #M79/73,, University of California, Berkeley, 1979.
9. Yager, R.R., "Quantified propositions in a linguistic logic," Tech Report #RRY 80-07, Iona College, New Rochelle, New York, 1980.
10. Bellman, R.E. & Zadeh, L.A., "Decision making in a fuzzy environment," Man. Sci. 17, B 144-174, 1970.
11. Yager, R.R., "Multiple objective decision making using fuzzy sets," Int. J. Man-Machine Studies 9, 375-382, 1977.
12. Yager, R.R., "On solving fuzzy mathematical relationships," Information and Control 41, 29-55, 1979.
13. Dubois, D. & Prade, H., "Operations on fuzzy numbers," Int. J. Sys. Science 9, 613-626, 1978.
14. Yager, R.R., "A procedure for ordering fuzzy subsets of the unit interval," Tech. Report #RRY 79-12, Iona College, New Rochelle, N.Y., 1979.

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ABSTRACT

This is a brief description of GAC's methodology to assess and reduce risk during the preliminary product design stage. Fundamental to this approach is the expression of program element costs in terms of a range of probable costs, rather than as a single cost associated with a point design. These element costs are combined to a program cost expressed as a probability function, rather than one unique number. This not only provides a clearer picture of what is possible, but the procedure itself contains the means to identify the principal causes of cost uncertainty.

For this methodology we assume:

- a system made up of a set of elements or subsystems
- total system cost is the sum of the element costs
- a Cost Estimating Relationship (CER) for each element
- the inputs to the CER are treated as random variables
- the element costs are stochastically independent.

We have a set of inputs with assumed density functions, a corresponding set of CERs and a set of outputs, which are summed to arrive at the total cost probability. We wish to estimate for each output, and for the total, a confidence limit (i.e., state that the probability is 90% the cost will lie between two stated limits), and for any arbitrary cost, estimate the probability that that cost will be the arbitrary value or less. In the usual case, we use the first four additive moments of each output to determine our confidence limits and probability statements, then add these moments to determine the cost probability characteristics for the total project.

To determine the output characteristics, we may use either a transformation of variables and determine the output density function, or

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use an analytical approximation involving a Taylor expansion of the CER. The end result is an analytical approach that is relatively simple, economical, and provides excellent viability at the subsystem or element level.

INTRODUCTION

Defining program costs in terms of a probability function, rather than a point estimate, has been discussed for a long time. Sobel (21) and Dienemann (3) proposed the use of Monte Carlo in military cost estimating in the early 1960s.

By 1973, Fisher's paper (9) on uncertainty, along with definitions of risk and various forms of uncertainty, listed seven basic types of analysis that can be used to deal with uncertainty. They included Monte Carlo, sensitivity analysis, "range of estimates", adjustment factors (allowances), supplemental (additional) discounting, a fortiori (worst case) analysis and special studies. This variety and his mentioning that he would only comment briefly on each method, as they should be familiar to most, implies a healthy growth process. Klein (14), (15) popularized the use of the Beta distribution to represent cost estimates, which is probably the most used technique today, especially when combined with a Monte Carlo summing procedure.

McNichols PhD Dissertation (18) in 1976 discussed an analytical alternative to Monte Carlo using the moments of probability function. This paper discusses a procedure partially derived from his work. It has evolved over the last ten years and is presently used internally in selected cases of probable high risk.

Though these ideas have slowly gathered strength through the years they have only recently begun to acquire official recognition. The recent revision to DOD Directive 5000.2 states that cost estimates shall be supplied with a confidence band not just as a point estimate using best available means. However, to the authors' knowledge, no service has yet formally implemented this policy.

METHODOLOGY OVERVIEW

Risk is defined as the probability that a project will not be completed within specified cost, time and performance constraints by following a specified course of action (16). Only cost risk is discussed here. However, we often use cost risk as a proxy for performance risk. We have found that it is easier for a designer to express uncertainty in a parameter by an estimate of its range rather than to quantify probabilities of expected performance.

Our results are usually presented in the more conventional sense of implied successfulness (1-risk). We feel that this makes the results easier to explain and causes no mathematical inconsistencies.

The process described here implies:

- a system made up of a set of elements or subsystems - a Work Breakdown Structure (WBS) or set of cost categories
- a Cost Estimating Relationship (CER) for each element - may be complex but can be a simple multiplier, or a direct estimate
- a total system cost found by summing the costs of these elements.

To quantify the results in a probability sense, the following basic assumptions are made:

- some or all of the inputs can be treated as random variables
- there is a greatest lower bound for the resources required for the task to be accomplished with a probability of zero
- there is a least upper bound for the resources required for the task to be accomplished with a probability of one.

Further, we have assumed that the cost elements and CER parameters are independent. This is not necessary in theory, but dependence creates two problems. First, it is more difficult to handle computationally. Second, the degree of dependency must be given or inferred. We have found it very difficult to express this dependency in a meaningful way. This latter problem is basic and if we could solve it, computational algorithms could easily be developed.

An overall block diagram of the procedure is shown as Fig. 1. The major points to be discussed are:

- how to quantify the spread in the input variables
- the analytic techniques used to translate their uncertainties into output uncertainties; a range of program costs
- how to present the output for review and how it can be used to either isolate the major cost drivers or to determine probable program costs.

SELECTION OF INPUT FORMS

On the basis of our experience, we feel that the estimation of the spread in the input variables is the most difficult, but most important, aspect of the problem. Any reasonable analytical technique will provide acceptable results given good input data. No analytical approach, regardless of sophistication, can make up for bad input data. Therefore, much of our efforts have been to find the simplest procedure that can express the designer's or estimator's often intuitive feel for the validity of his cost estimate in terms usable to the cost analyst.

Various approaches have been used to aid the designer to translate his intuitive feelings into hard numbers. Some approaches have

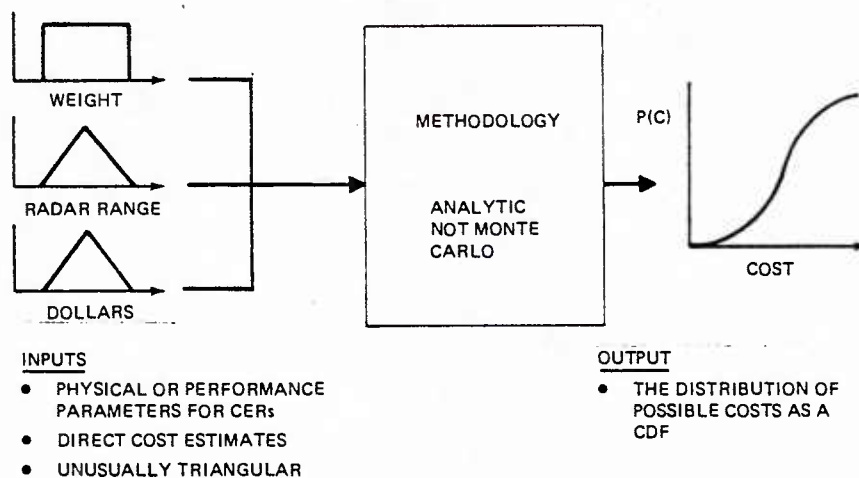


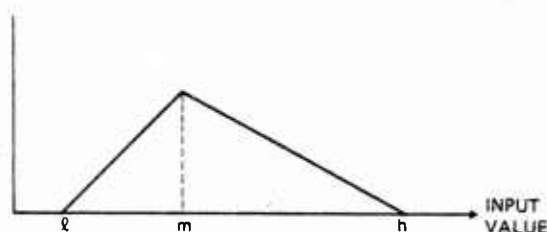
Fig. 1 - Overview of Approach

selected a functional form, usually Beta (13), (14), (15) Gamma, Normal or Weibul. Then, having a generic form they have either selected from among various representations of this form (by selecting the most appropriate picture, etc.), or used some estimate of the data to derive the values of the parameters. A popular method using data has been to select three data values, high, low and mode, as per PERT, etc. Others have attempted to fit functional forms non-parametrically using percentiles or subjective probability rankings (6), (7), (8), (12), (20). The most popular approach in weapon system acquisition literature appears to be to select a representative Beta given an estimate of the range of variability. In practice, we have found that picking a Beta shape can be a difficult and non-repeatable process.

In advance, the true density function is unknown (and probably unknowable). However, we can use some common sense and give our unknown function some characteristics. A reasonable set of characteristics would be:

- finite ends
- not necessarily symmetric
- unimodal
- computationally simple.

The triangular distribution has these properties. It is bounded. It incorporates skewness, an important cost consideration. It can be described by the location of its peak and two end points; the peak corresponding to the most likely cost and the extreme values related to the most optimistic and pessimistic values. A similar view has since been expressed in (2). Further, it appears to be an easy concept to visualize and accept especially for those unfamiliar with statistics. An additional benefit is that it is fairly easy to handle in computation and simulation. Figure 2 illustrates our requirements using this distribution.



- WE NEED 3 VALUES FOR EACH INPUT PARAMETER
- THE MOST LIKELY VALUE - m
- THE LOWEST VALUE THAT THIS PARAMETER CAN HAVE - l
- THE HIGHEST VALUE THAT THIS PARAMETER CAN HAVE - h

Fig. 2 - Standard Input Data

To the best of our knowledge, not many rigorous analyses have been performed comparing the

error resulting from using this function to Beta's or others, other than (17), which concluded that for PERT networks, the triangle was as good as the Beta. Also Ref (18) reviewed and catalogued PERT and PERT derivatives, as well as several other functions, and discussed error magnitudes. In those cases where we have been able to compare to Beta variables, the results have been similar.

Sometimes, even less is known about the variables shape. Then we suggest the use of the uniform distribution, where any value is equally likely within the range (Fig. 3).

However, if the form of the input distribution is known and the parameters can be estimated, then the analytical approach described here can still be used. We presently have computer codes to handle Normal, Log Normal, Beta, uniform and triangular inputs or mixtures of any or all of the above.

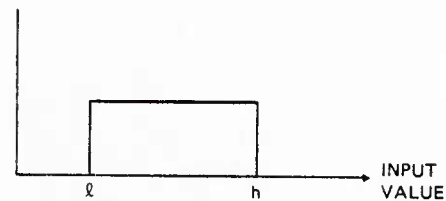


Fig. 3 - Input (All Data Equally Likely)

MATH MODEL

We have proposed an analytical approach to the problem of transforming the input to a final output, rather than the more popular Monte Carlo (3), (11), (23). It uses the moments of the probability distributions, rather than the random variations and is more accurate while using less computer time. This is especially true when a large number of inputs must be included and/or the estimating equations are very complex. Further, it can be used with a small computer, or even a hand calculator, if the problem is not too large.

It allows all input parameters to be entered at their applicable level in the Work Breakdown Structure (WBS). If entered directly, the moments are summed to the appropriate level. If entered via CERs, the moments of the transformed variable are summed at the appropriate level. All moments are summed at the final output level and converted to a Beta function representing the total cost distribution. If desired, a non-parametric method is available to compute the final cost distribution using a Tchebycheff Markoff approximation and the moments. The mechanics of the various processes are handled in a set of modular sub-routines coded for several different computers.

We represent each function by some form of its first four moments. We realize that this is not a complete representation, but an approximation. It has been our experience that using only the mean and variance are not enough; some representation of non-symmetry and shape must be included.

This procedure was first developed in (18) and expanded in (22). The following is a brief expository account and the details and analytic derivations are to be found in the referenced works.

Three moment forms are required; central, origin (multiplicative), and additive. For brevity, the latter two are called "M" and "A" moments, respectively, in the remainder of this paper. The i^{th} central moment has the standard textbook definition of

$$E[(X-E(X))^i] = \int_{-\infty}^{\infty} (X-E(X))^i f(X) dx = u^{(i)}$$

It is shown in (10) that the first four A moments of the density functions of a random variable X are as shown below, and that the A moments of the density function of the sum of independent variables is the sum of these A moments.

$$\begin{aligned} A_1 &= E(X) = u \\ A_2 &= E(X^2) - u^2 = u^{(2)} \\ A_3 &= E(X^3) - 3E(X^2)u + 2u^3 = u^{(3)} \\ A_4 &= E(X^4) - 4E(X^3)u - 3E^2(X^2) + 12E(X^2)u^2 - 6u^4 \end{aligned}$$

where

$$\begin{aligned} A_i &= i^{\text{th}} \text{ additive moment} = i^{\text{th}} \text{ A moment} \\ u &= \text{mean (first origin moment)} \\ u^{(i)} &= i^{\text{th}} \text{ central moment} \end{aligned}$$

It is seen that the first three A moments are exactly the same as the first origin moment and second and third central moments.

Now, by definition,

$$\begin{aligned} u^{(4)} &= E(X-u)^4 = E(X^4) - 4E(X^3)u + 6E(X^2)u^2 - 3u^4 \\ 3u^{(2)^2} &= 3E^2(X^2) - 6E(X^2)u^2 + 3u^4 \\ u^{(4)} - 3u^{(2)^2} &= E(X^4) - 4E(X^3)u - 3E^2(X^2) + 12E(X^2)u^2 - 6u^4 = A_4 \end{aligned}$$

Thus, given a random variable X with known mean and central moments, the A moments may be found.

In the case of a product of independent variables (21) shows that the origin moments of the independent variables may be multiplied to get the origin moments of the product, then A moments determined from the following relationships: Where $M_i(X)$ is the i^{th} origin moment, $M_i(X) = E(X^i)$ and, as before, A_i is the i^{th} additive moment.

$$\begin{aligned} M_1 &= A_1 \\ M_2 &= A_2 + A_1^2 \\ M_3 &= A_3 + 3A_1 A_2 + A_1^3 \\ M_4 &= A_4 + 3A_2^2 + 4A_1 A_3 + 6A_1^2 A_2 + A_1^4 \end{aligned}$$

and

$$\begin{aligned} A_1 &= M_1 \\ A_2 &= M_2 - M_1^2 \\ A_3 &= M_3 - 3M_1 M_2 + 2M_1^3 \\ A_4 &= M_4 - 3M_2^2 - 4M_1 M_3 + 12M_1^2 M_2 - 6M_1^4 \end{aligned}$$

These relationships make the determination of moments for such expressions as

$$C = x_1(x_2 + x_3 + \dots)$$

easy since A moments may be used inside the parentheses, the M moments found, multiplied by the M moments of X_1 , then A moments of C found (Fig. 4).

In a computer routine, we would sum each of the four moments of the variables X_2, X_3 , etc., and convert the sum to M moments (ATOM subroutine). These would be multiplied by the appropriate M moments of X_1 , and the products converted to A moments (MTOA subroutine) of the cost function. Many simple costing problems, such as summing WBS elements with multipliers can be solved in this manner. For complex CERs more complex procedures must be used.

In many instances, it is possible to determine the CER output density function, and hence the moments directly by transformation of variables. X is a random variable with density

function $f(x)$, and $Y = h(X)$, where $y = h(x)$ defines a one-one transformation. The inverse of $y = h(x)$ is designated by $x = w(y)$, and the derivative dx/dy is designated by $w'(y)$. The density function of $Y = h(X)$ is given by

$$g(y) = f(w(y)) |w'(y)|$$

where

$|w'(y)|$ is the absolute value of $w'(y)$

For a CER of the form $y = a + bx^n$, the above technique applies, since the mapping of x into y is one-one, and the inverse is differentiable. A practical requirement is that x have a density function such that $f(w(y))$ is readily solved.

In particular, setting $a = 0$, $b = 1$, $n = 1$ we have $y = x$ and inputting the values of x into our subroutine we output the A and M moments. For example, for the triangular distribution defined as follows:

$$f(x) = \frac{2}{(h-1)(m-1)} (x-1) \quad 1 \leq x \leq m$$

$$f(x) = \frac{2}{(h-1)(h-m)} (h-x) \quad m \leq x \leq h$$

$$f(x) = 0 \text{ elsewhere}$$

for

$$y = a + bx^n$$

$$g(y) = \frac{2}{nb(h-1)(m-1)} (x-1)^{1-n} \quad 1 \leq x \leq m$$

$$g(y) = \frac{2}{nb(h-1)(h-1)} (h-x)^{1-n} \quad m \leq x \leq h$$

$$g(y) = 0 \text{ elsewhere}$$

where

$$m = \text{modal value of } x$$

Since we know $g(y)$ we may find

$$E(y^i) = \int_{-\infty}^{\infty} y^i g(y) dy,$$

and

$$F(y) = \int_{-\infty}^y g(y) dy,$$

so A and M moments, as well as a distribution function and confidence limits may be found directly.

We have found this form almost universally applicable. Figure 5 provides some examples of useful transformations that often appear in cost CERs. Likewise a more general CER of the

form

$$Y = bX^n \star Z^m$$

can be separated into bX^n and Z^m transformed via TRIMO (our subroutine that handles triangular inputs), the two sets of M moments found, multiplied together, converted to A moments and then to the CDF of the cost function.

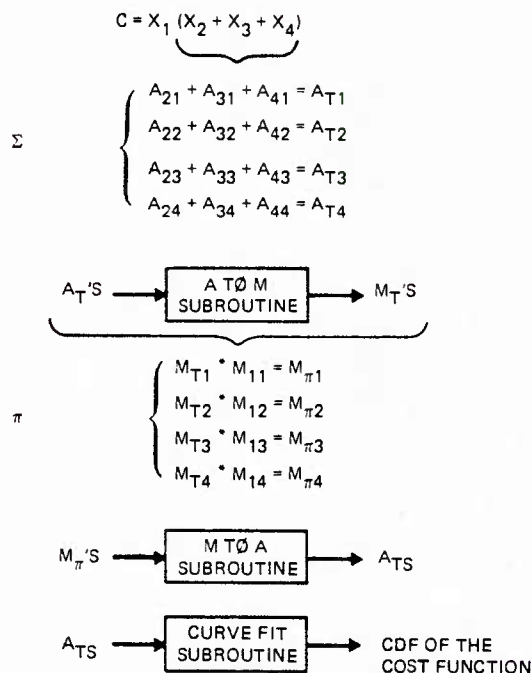


Fig. 4 - Simple Cost Function

$$Y = a + bx^\eta$$

FOR • $a = 0$ $y = x$
 $b = 1$
 $\eta = 1$

• $a = 0$ $y = x^\eta$
 $b = 1$

• $a = 0$ $y = \frac{1}{x}$
 $b = .1$

• $a = 0$ $y = \sqrt{x}$
 $b = 1/2$

Fig. 5 - Almost Universal CER Transformation

The general form of the computer routine we use to solve most problems is shown in Fig. 6. It is a simple repetitive procedure using only a few subroutines and the addition and multiplication of sets of moments.

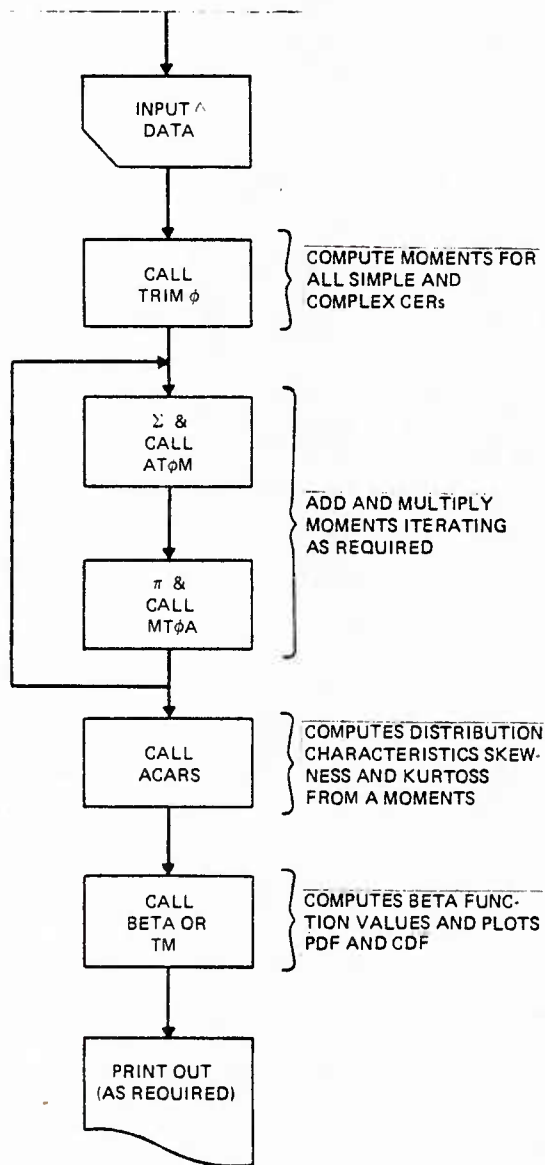


Fig. 6 - Generalized Computer Routine

However, it is possible to find CERs that can not be handled as independent elements in the power form. For example:

$$C = \sqrt{X_1^2 + 2X_1X_2}$$

$$C = aX_1^{bX_2} + dX_3^f$$

Following (18) by first taking a first or second order Taylor Series expansion of C and calculating the first four A moments for this approximate C.

Expand $Y = C(X)$ by the Taylor series around u :

$$Y = C(u) + (X-u) C'(u) + R$$

disregarding the remainder term, and taking expectations of both sides yields

$$E(Y) = C(u) + 0 = u_Y$$

Now square the expansion:

$$Y^2 = C^2(u) + 2(X-u) C'(u) C(u) + (X-u)^2 C'^2(u)$$

then

$$Y^2 - C^2(u) = (X-u)^2 C'^2(u) + 2(X-u) C'(u) C(u)$$

again taking expectations on both sides:

$$E(Y^2) - E^2(Y) = \sigma_x^2 C'^2(u) + 0$$

by definition:

$$V(Y) = \sigma_x^2 C'^2(u) = u_Y^{(2)}$$

This may be expanded to a vector $Y = C(X_1, X_2, \dots, X_n)$, and applied to find the A moments (as shown in (18)):

$$A_1 = C(u_1, u_2, \dots, u_n)$$

$$A_2 = \sum \left(\frac{\partial C(X)}{\partial X_i} \right) u_i^2 u_i^{(2)}$$

$$A_3 = \sum \left(\frac{\partial C(X)}{\partial X_i} \right) u_i^3 u_i^{(3)}$$

$$A_4 = \sum \left(\frac{\partial C(X)}{\partial X_i} \right) u_i^4 u_i^{(4)} - 3 u_i^{(2)2}$$

where the partials are evaluated at u_1 .

The second order expansions are more complex (generally adding the second partials terms) adding additional but small corrections to the first order approximations. Considering the noise inherent in the input data and the CERs, our standard practice is to use the first order approximation.

This procedure can not be made a standard subroutine in the sense that the partials must be computed from the CERs for each application. As these CER forms are, by our definition, fairly rare, partials must be computed each time.

OUTPUT COST DISTRIBUTIONS

The most understandable way to present the output appears to be a Cumulative Distribution Function (CDF), even though the Probability Density Function (PDF) is more familiar to most people. The CDF is the integral of the PDF. It shows for any arbitrary value of cost the probability that the cost will be equal to or less than the arbitrary value selected (Fig. 7). Generally, we have had no problem fitting the final output to a Beta distribution, though we have at times used various non-parametric Markoff type moment approximations. When comparisons must be made between similar systems or between high gain high risk versus low gain low risk systems, we have no panacea. We feel that a presentation of the CDFs makes the issue clearer but does not make the decision easier.

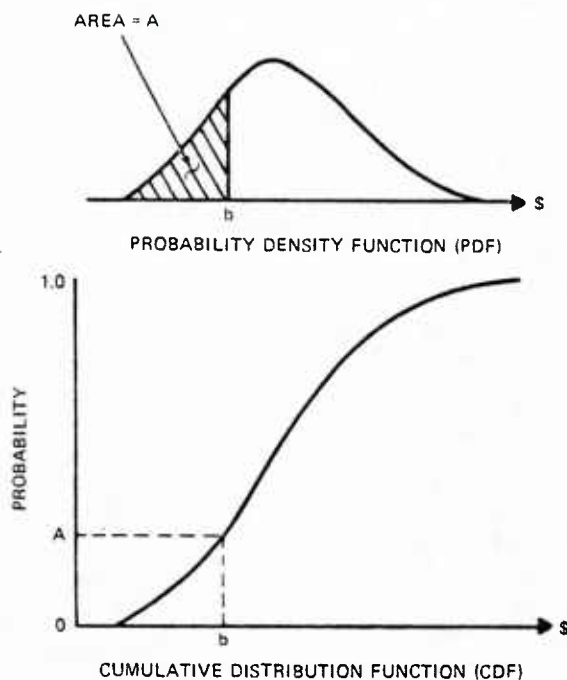


Fig. 7 - Relationship of PDF to CDF

The CDF of the output can be constructed from the four moments either non-parametrically as a Tchebycheff-Markoff four moment fit or as a Beta function. As four moments provide a closer fit for the function than three or two, we compute these upper and lower bounds on the CDF following (24). Then, we rather arbitrarily assumed that the CDF may be approximated by the average of the upper and lower bounds. Figure 8 is a typical CDF constructed from one of our computer graphics routines, comparing the TM approximation of the Normal and triangular distributions to their actuals.

We decided to use the Beta distribution as our choice of an output CDF for two reasons: 1) it has a long history of use in cost uncertainty analysis and 2) it is fairly "general" in the sense that it can satisfy four properties, whereas the exponential satisfies one; Normal, ordinary Gamma, Weibul, two; and so on. This concept is amplified considerably in (19). Other distribution families of the same generality did not appear to be more useful in the parametrics costing field; therefore, we decided to represent our CDF by Beta distributions.

The usual form of the Beta function is

$$f(x) = C Z^{\alpha} (1 - Z)^{\beta}$$

$$0 \leq Z \leq 1$$

Slightly different variations exist, depending on how the interval is defined. For probability functions, C is selected so as to set the area under the curve equal to 1. A more useful form is to define the function as the internal A to A + B with B > 0. Then

$$f(x) = \frac{\Gamma(\alpha + \beta + 2)}{\Gamma(\alpha + 1) \Gamma(\beta + 1) B} \left(\frac{x - A}{B} \right)^{\alpha} \left(1 - \frac{x - A}{B} \right)^{\beta}$$

where $A \leq x \leq A + B$, $\alpha, \beta > -1$ and $\Gamma(y)$ = Gamma function = $\int_0^{\infty} z^{y-1} \exp(-z) dz$

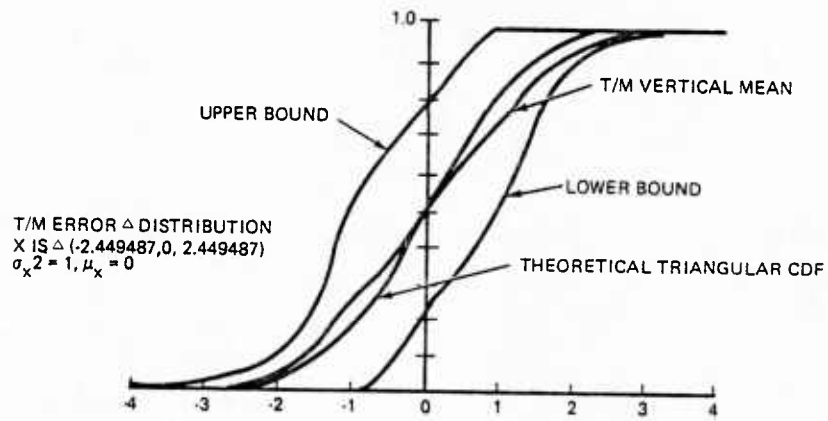
As we knew that the Beta distribution was part of the Pearson system of curves, we turned to Elderton (4) and the revised, easier to read revision by Elderton and Johnson (5) to see if their moment fitting approach could be applied to our problem. They defined Beta parameters in terms of the moments and combined the moments into the coefficients of skewness and kurtosis. However, they used some clever algebraic substitutions and were able to solve the non-linear equations. The algebraic details and the computer programs used to determine α and β are described in (1).

APPLICATIONS

We use risk assessment more as part of the preliminary design process than as an aid in deciding which projects to procure or to determine a level of funding for a series of investments. Therefore, our efforts are directed either to presenting a better view of the project cost picture or to finding the cost drivers that cause the most variation in this picture so that further action can be taken.

Although we feel that a CDF presents a good picture of possible costs, it can not be used in isolation to justify a project externally. It is either too wide, meaning "a good chance of an overrun", or too narrow, meaning "add a few bucks and go fixed price" (Fig. 9).

TRIANGULAR DISTRIBUTION



NORMAL DISTRIBUTION

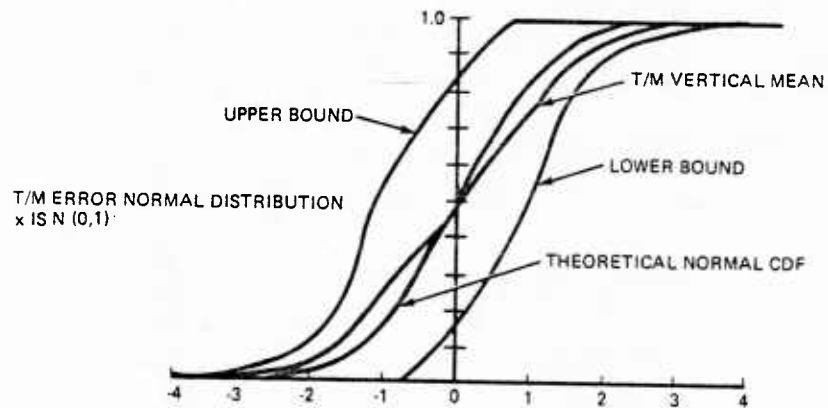


Fig. 8 - TM Approximations for Popular Distributions

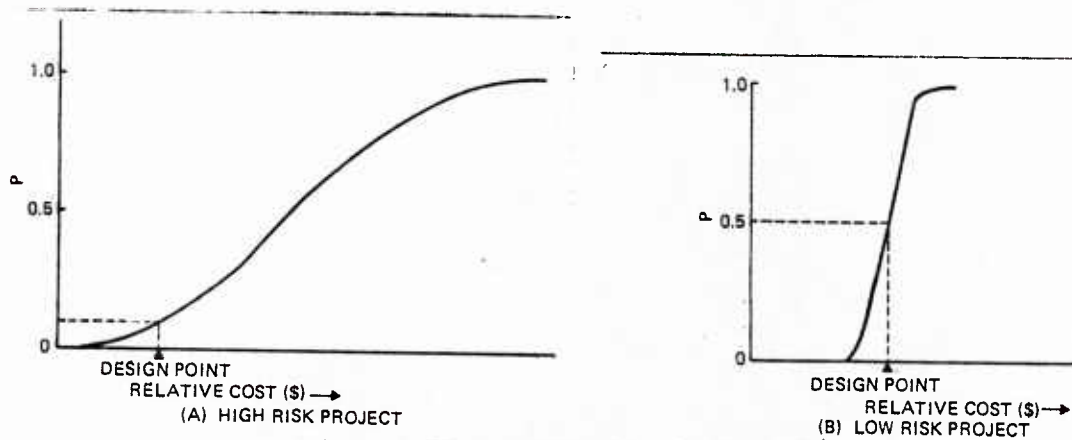


Fig. 9 - Typical Program Cost Curves

Further, when several projects are compared, it is still not easy to quantify risk, especially in a sense of helping decision makers accept one candidate over another or even to accept or reject a single project.

Any situation of clear textbook dominance is so apparent that no manager would have requested a risk analysis.

In a more positive sense, we use the CDF to provide a rough indication of how bad the situation may be (Fig. 10), isolating those features of the design causing the most variance in the CDF. Once isolated, programs are set up to reduce the spread by further analysis, lab tests, experiments, etc. Thus, a program increases some in cost but decreases in risk (Fig. 11). This is an iterative

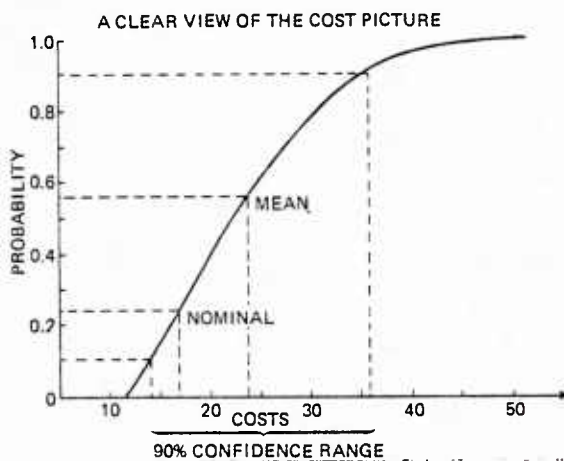


Fig. 10 - A Typical Output

procedure allowing continuous and rational risk reduction during the initial design process.

A more likely situation is shown in Fig. 12 comparing solar powered satellites using three solar cell material. This CDF represents the cumulation of over a 100 inputs processed through about 50 fairly complex CERs. As can be seen, the design values had a very low probability due to the skewness of some of the major causes of variation. Using this approach, it was easy to determine the most significant contributors to the variation in output. Needless to say, they were not readily apparent by initial inspection. Also of significance was the relative shapes of the cadmium versus silicon curves which made cadmium appear more favorably than originally conjectured.

A further application applies to the total uncertainty contained in a CER. We would like to show how the method of moments allows us to take account of both the input uncertainty and the statistical uncertainty of a regression developed CER. This example was taken from a space cost model [25] and is deemed representative of this type of situation.

The CER for first unit cost of the structure of a thermal control and interstage subsystem is given by:

$$y = 91.04 + 9.89 x^{0.75}$$

where

y = 1976 dollars in thousands

x = weight in pounds

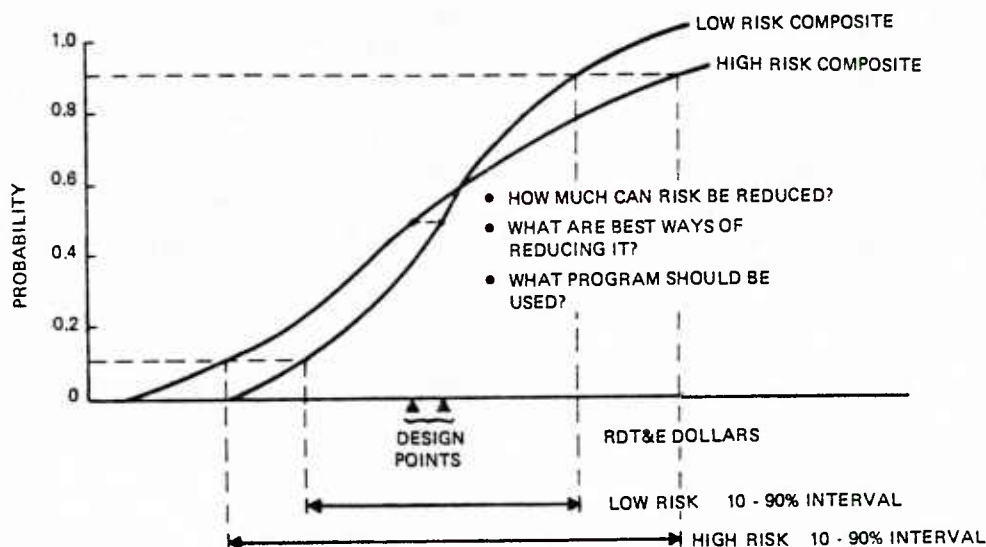


Fig. 11 - Evolving Cost Risk Profile

(MATURE SATELLITE
SMALL CONSTRUCTION
BASE, CONSTRUCTION AT
LEO, VARIOUS SOLAR
CELL MATERIAL)

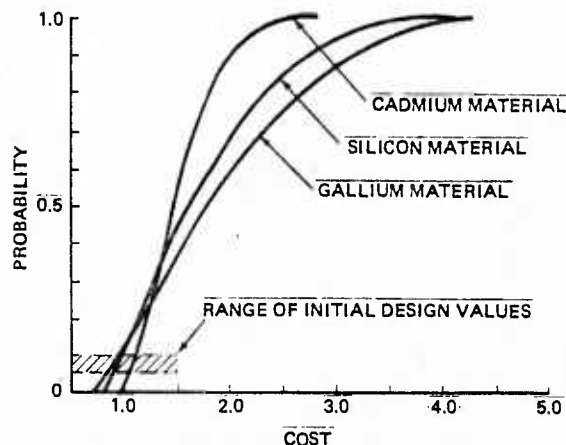


Fig. 12 - Candidate SPS: Cumulative Distributions

The standard error of the estimate is given as 275.4.

For a particular application the point design weight was given as 234.6 and the selected values for the triangular distribution were:

Low = 253.4

Mode = 351.9

High = 480.9

Using the transformation of variables the output moments are shown in Fig. 13.

This standard error is assumed to be normally distributed, with a mean of zero and standard deviation of 275.4. Thus, we have two independent random variables, one with addition moments as given above, and the other normal with moments $A_1 = 0$, $A_2 = 275.4^2$, $A_3 = A_4 = 0$. The convoluted distribution then, has moments as follows:

First = $A_1 = 910.66$

Second = $A_2 = 82119.97$

Third = $A_3 = 31255.08$

Fourth = $A_4 = -23953330$

The Beta parameter of this distribution show α and β in the 800's, and a skewness of 0.0013, kurtosis of 2.996, hence we will use the normal distribution to approximate it.

The PDFs and CDFs are shown in Fig. 14. As is often the case when the CERs are determined by only a few data points the input uncertainty seems to be overwhelmed by the statistical uncertainty. This result should be recognized when statistical CERs are used, and due caution exercised in using point estimates thus based.

MOMENTS FOR $Y=A+B*XTN$, X TRIANGULAR, $L=253.4$
 $U=480.9$, $M=351.9$, $Y=91.04$, $X=0.75$, X TRIANGULAR, $Y=253.4$
 NOMINAL VALUE= 894.585966
 ORIGIN MOMENTS (MULTIPLICATIVE)
 FIRST = 910.658616
 SECOND = 835573.9178
 THIRD = 77336249.2
 FOURTH = 7.19167E+11
 ADDITIVE MOMENTS
 FIRST = 910.658616
 SECOND = 6374.802795
 THIRD = 31255.08
 FOURTH = -23953330
 FOURTH CENTRAL MOMENT = 94166119.97
 COEFFICIENT OF SKEWNESS = 0.062861152
 COEFFICIENT OF KURTOSIS = 2.391632877

Fig. 13 - Computer Output

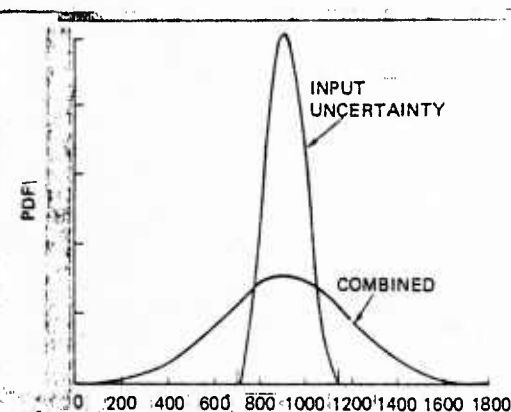
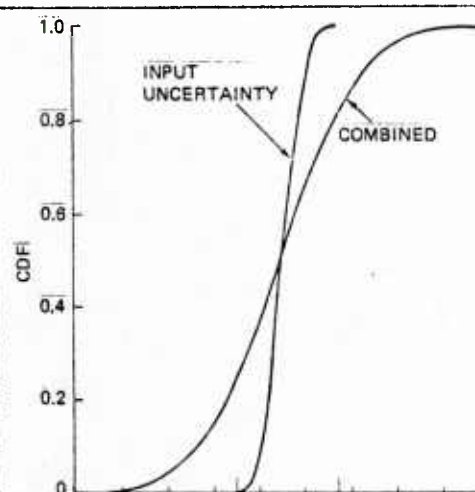


Fig. 14 - Combining Input and Uncertainty

SUMMARY

We feel that the use of the method of moments coupled with the characterization of the inputs by triangular distribution is a viable alternative to the use of Monte Carlo. Generally, it is more accurate and/or requires less computer time. However, it usually requires more analytic effort to implement and is harder to explain to non-specialists in the field.

BIBLIOGRAPHY

- (1) Black, R.; Fitting a Beta Distribution from Moments; Grumman Aerospace Corporation, PDM-OP-79-115, 12 June 1979.
- (2) Brewerton, F.J. and Gober, Wayne R.; Management Science Application of the Triangular Distribution: Some Pros and Cons; Mid West AIDS Conference, Indianapolis, Indiana, 3-5 April 1975.
- (3) Dienemann, P.F.; Estimating Cost Uncertainty using Monte Carlo Techniques; The Rand Corporation, RM-4854PR, January 1966.
- (4) Elderton, William P.; Frequency Curves and Correlation; Hareen Press 4th Edition, 1953.
- (5) Elderton, William P. and Johnson, Norman L.; Systems of Frequency Curves; Cambridge Press, 1969.
- (6) Fallon, Richard; Subjective Assessment of Uncertainty; The Rand Corporation; P-5581, January 1976.
- (7) Fey, Curt F.; Putting Numbers Where Your Hunches Used to Be; IEEE Spectrum, July 1974.
- (8) Fike, Robert Lee; Subject Estimation of Variability; PhD Dissertation; Arizona University, 1977.
- (9) Fisher, G.H.; The Nature of Uncertainty; The Rand Corporation P-5133, November 1973.
- (10) Gnedenko, B.V.; The Theory of Probability; Chelsea Publishing Co., New York, New York.
- (11) Graves, Samuel B.; A Monte Carlo Risk Analysis of Life Cycle Cost Prediction; Air Force Institute of Technology WPAFB, Ohio, September 1975.
- (12) Grayson, A.S. and Lanclos, H.J.; A Methodology for Subjective Assessment of Probability Distribution; AF Institute of Technology, AD A032536, September 1976.
- (13) Haese, Edward J.; Cost Uncertainty/Risk Analysis; USAF System Command, March 1976.
- (14) Klein, Michael R.; Treating Uncertainty in Cost Analysis; The Beta Distribution; U.S. Navy CNO Resources Analysis Group, March 1973.
- (15) Klein, Michael R. and Jordan, Harley R.; An Application of Subjective Probabilities to the Problem of Uncertainty in Cost Analysis; U.S. Navy CNO Resources Group, November 1975.
- (16) Lockory, Robert R., Hensley, R.D., Flammer, Philip, Smith, Donald R., Head, Richard G.; Final Report of the USAF Academy Risk Analysis Study Team; Air Force Academy, 1971.
- (17) MacCrimmon, K.R. and Ryavec, C.A.; An Analytical Study of the Pert Assumptions; The Rand Corporation, RM-3408-PR, December 1962.
- (18) McNichols, G.; On the Treatment of Uncertainty in Parametric Costing; PhD Dissertation The George Washington University Program in Logistics, 2 February 1976.
- (19) Schmeiser, Bruce; Methods for Modeling and Generating Probabilistic Components in Digital Computer Simulation when the Standard Distributions are not Adequate: A Survey; 1977 Winter Simulation Conference, 5-7 December 1977.
- (20) Smith, Lee H.; Ranking Procedures and Subjective Probability Distribution; Management Science, Vol. 14 No. 4, December 1967.
- (21) Sobel, S.; A Computerized Technique to Express Uncertainty in Advanced System Cost Estimates; The Mitre Corporation, Technical Report No. ESD-TR-65-79, November 1965.
- (22) Wilder, J.J.; An Analytical Method for Cost Risk Analysis, Grumman Aerospace Corporation, PDR-OP-T79-12, 27 June 1977.
- (23) Wilder, J.J.; A Simplified Approach to Monte Carlo Cost Risk Evaluation; Grumman Aerospace Corporation; PDR-OP-T73-27, 11 July 1973.
- (24) Zelen, M.; Bounds on a Distribution Function that are Functions of Moments to Order Four; Journal of Research of the National Bureau of Standards, Vol. 53, No. 6, Research Paper 2556, December 1954.
- (25) SAMSO Unmanned Spacecraft Cost Model; 4th Edition SAMSO TR-78-61, February 1978.

A METHODOLOGY FOR MANAGING DELAYS AND DISRUPTIONS
IN THE SYSTEMS ACQUISITION PROCESS

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ABSTRACT

This paper was developed given the assumption that there will inevitably be delays and disruptions in any major systems acquisition. There is little point in citing here a long litany of problems with systems acquisitions for illustration. It (the assumption) is universally recognized as an acquisition "fact of life." What is not nearly as well known is what to do about the effects of delays and disruptions. Specifically, who is responsible and who pays for these effects? The government? The defense contractor?

This paper is designed to review a methodology and illustrate its application as one way of resolving these questions. In the process, another objective is to advance this aspect of program management closer to the science of management as the basis of its art.

The fundamental theme of this paper is that there are methodologies available today that can help program managers manage delays and disruptions during the acquisition process. This paper sets the stage for a discussion of one of these methodologies--a version of simulation called system dynamics--by developing the concept of delays and disruptions in systems acquisition settings.

This commentary is followed by a short survey of some of the past and current folkways of trying to "manage" delays and disruptions. The authors then propose system dynamics as one methodology for monitoring and managing delays and disruptions that works.

A brief discussion of system dynamics follows and a recent successful application of this methodology in systems acquisition is described. The paper concludes with a short discussion of how this approach to delay and disruption management might be implemented and institutionalized in the systems acquisition process for a large project's life cycle.

BACKGROUND

A review of past issues of the Aerospace Daily included a number of items of interest that set the stage for this paper [1]. Among those items cited were:

"...the 60 Minuteman II missiles covered by the Ford Administration supplemental request will not be built and the FY '77 funds will be

used instead for spares."

"...The B-1 program was cut \$280 million in FY '78--from \$2.15 billion to \$1.87 billion--and, as expected, the number of bombers to be procured fell from eight to five."

"...F-15 production was cut back from a rate of 108 a year to 78. The \$334 million resulting saving would be applied to the original \$1.76 billion request to bring it down to \$1.43 billion."

"The Sikorsky CH-53 helicopter for the Navy and Marine Corps was also cut by \$62 million (out of an original \$87 million request) as part of a move to stretch out the program by a year."

"The Army's AAH was cut in half--from \$200 million to \$100 million--reflecting what DOD called a more thorough evaluation of options and what (Secretary of Defense) Brown more specifically identified as a concern over the helicopter's vulnerability."

"In the shipbuilding area, the Aegis-equipped CSGN was knocked out entirely for a \$187 million reduction while another \$43 million was deleted for conversion of an LST to a PHM. The PHM program will be further reviewed."

There are, of course, many more examples that could be quoted, in areas including funding increases, performance upgrading, schedule stretchouts, and the like. Over and over again, events seem to overtake program managers and produce dramatic impacts on system costs, performance, and schedules. Over and over again, delays and disruptions, both planned and unplanned, intended and unintended, seem to haunt program managers. Yet, as has been said before, there is nothing new about this state of affairs.

DELAYS AND DISRUPTIONS

Delays and disruptions hereafter referred to as D&D's, is merely a new concept for a traditional issue. The problems caused by D&D's have existed since man was first confronted with the management of others and his resources in relation to the environment. The Roman Aqueduct had a cost overrun of over 100%. The Suez Canal a cost overrun of 200%. The Panama Canal, built by the French because of their experience at Suez, nevertheless had an overrun of over 70% on cost [9].

In fact, during the first Systems Engineering and Management Seminar recently held in the People's Republic of China (PRC) (in the spring of 1980 in Peking), one of the authors (Sherman) in addressing the officials, faculty, and researchers of the aeronautics and astronautics communities complimented the audience on the fantastic management and engineering feat of the Chinese in building the Great Wall [29]. This wall, according to our astronauts, was the only man-made object on earth clearly visible from outer space. The Great Wall was started in the 4th-5th century and the effort ended in the 15th-16th century. It was over 3,100 miles in length (at one time) and at its peak construction period employed over 300,000 persons for a ten-year period.

However, the audiences' pride was soon tempered when it was noted that there were three basic problems with this feat from the perspective of American program managers: (1) the Great Wall was not completed on time, (2) the cost overrun was fantastic and acceptable only to emperors, and (3) the wall never performed the function for which it was built. In terms of cost, performance, and schedule, the Great Wall was a great disaster.

It seems that delays and disruptions are destined to impact system costs, schedules, and performance. If this is so, we might try to place D&D's in context. Figure 1 shows the linkage between changes, D&D's and impacts on cost, schedules, and performance.

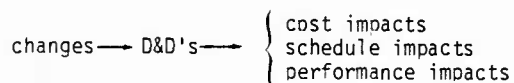


Figure 1. Linkage between Changes, D&D's and System cost, schedule and performance impacts.

Changes produce D&D's. Some changes are beyond the control of either the government or the defense contractor while others may be initiated by either or both. We present here a few examples to illustrate the point.

SOME CAUSES OF DELAYS AND DISRUPTIONS

The causes of delays and disruptions were classified in the pioneering work of E.B. Cochran [8]. This section relies heavily on his work and research into disruptions in major acquisition programs. Figure 2 presents this taxonomy of sources of disruption.

Internal Planning and Management

One cause of D&D's is changes due to internal planning and management; for example, planning or errors in cost estimating. First, cost estimating is at best an art, not a science, especially in the early stages of the systems

acquisition process. It should come as no surprise that unexpectedly high inflation, supply and demand factors, poor resource allocation and managerial inefficiency can cause total estimated program costs at completion to exceed early estimates by 10, 100, or even 300 percent [34].

A more recent addition to the list of inaccurate planning estimates involves the entire man-machine system of a weapons system. There has been a substantial drop in the capabilities of the manpower available to the services in recent years [21]. Consequently, system changes are being forced because either the operators or the maintenance force are incapable of performing at the levels for which the system was initially designed. For example, some equipment in the surface fleet is not used at all because the talents required to operate and maintain it exceed those available in current sailors [21]. And the problem is not unique to the U.S. Navy.

Finally, another example of the management cause is that the defense contractor may simply have "bought in" with the initial bid. In this case the contractor is relying on the usual assortment of changes that are bound to occur to provide the opportunity to make up the effects of the "buy in" or subsequent mismanagement.

External Forces

Secondly, there are external forces. For example, in order to keep the total program costs within some acceptable range for congressional review, initial costs (and often specifications, quantity, and so on) may be underestimated with the tacit understanding that "system growth" can be managed during production with change proposals to bring the system up to the desired capabilities (plussing up!). In effect, this is an intentional end run of the limitations and constraints of the DSARC process called for in DoD Directives 5000.1 and 5000.2. The assumption is that it is easier to get what you want through change proposals once in production than to get what you want in the Milestone I, II, and III decisions. And this assumption is probably correct.

The impacts of newly generated federal, state and local regulations and standards (after award) can be highly cost escalating and cause schedule stretch out. Disposal of toxic wastes, new occupational safety and health rules, and other environmental actions for air and noise pollution are familiar examples that frequently require mandated capital investments [13]. Other examples are major program changes, price escalations and force majeure.

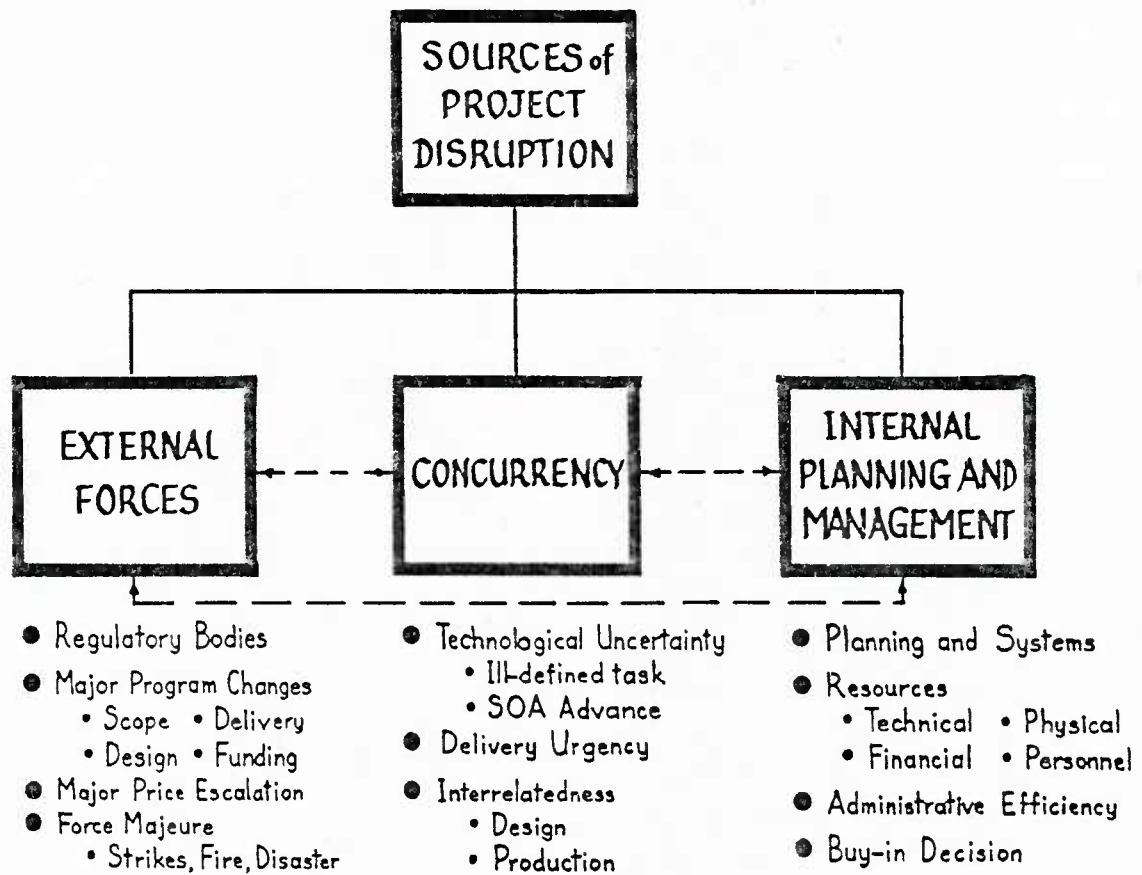


Figure 2 Sources of Project Disruption

Concurrency

Third is the concurrency cause. If a system is the first-of-a-kind as most new hardware or software is, the specific system requirements may not be well defined (technological uncertainty) at the time of contracting. Hence, this will inevitably lead to many changes (some significant) in the system while in development and production. Delivery urgency and interrelatedness are also examples of the concurrency cause.

Concurrency Defined

The author's use of the word concurrency is different and broader from the commonly held DoD and USAF philosophy. The DoD uses the term to describe "planned" concurrency where the stages of the acquisition life cycle intentionally overlap to accelerate delivery. An example is when development overlaps with the initiation of production activities to compress time, as in some early missile programs.

Our use of concurrency includes the case where uncertainty forces unplanned overlap in the stages of the acquisition life cycle. In this case concurrency also occurs. Recognizing and accepting this use of terminology is useful in understanding D&D's.

Factors of Concurrency

The basic factors of concurrency are shown in Figure 3. Delivery urgency (U) is usually market generated by a particular customer, or competitive conditions where a firm commits to an inherently optimistic delivery date. As delivery urgency develops, the initial delivery is usually eased thereby generating unplanned cost increases.

In addition, the firm usually assumes that no serious problems in technology will arise if the effort is state-of-the-art (SOA) or even a modest advance (SOAA). Our definition of SOA (A in Fig. 3) also differs from the general use in DoD. For example, combining existing black boxes (off-the-shelf) is not SOA when used in any new or different combination, package, hardware or system. SOA is, according to the authors, procuring an existing production line/warehouse product for use as is, or as designed, with no other use or application. If not, then what really occurs is some art advance (SOAA).

The normal statements on SOA generally do not reflect the varying degrees of technical uncertainty existing. This technological uncertainty (T) is intensified by the degree of interrelatedness (I) in the design and production process. Where there is a higher interrelatedness, there is increased uncertainty.

If the SOAA is a fundamental driver of technological uncertainty, then the interrelatedness is the major multiplier of the impacts on the costs of development and production.

Other factors compounding the problem and generating additional concurrency are the level of resources (R) and the degree of external control (X) over events.

D&D Process

Concurrency develops and causes D&D's in many ways, often unrelated in advance. In Figure 4, a static model, or flow diagram of concurrency disruption for a broad based program focusing on the process of D&D's and identifying cost impact points is illustrated (shown as dotted line boxes).

A firm normally starts a program that requires the delivery of a specific product within a specified period of time. While judged SOA it is not fully designed, although the product is familiar (as is the process) to the firm. Serious technical problems develop. They require extensive time to resolve. Substantial changes to the original design or tasks are made. In turn this generates a near complete replanning effort including schedules and production procedures. Costs soar as D&D's occur.

Now intensive efforts to minimize the deviation from the original delivery dates interact with the required changes in schedules and production procedures. Costs increase, and confusion is caused by the changes that are now compounded by the compression of time. Time is compressed by the delays and added tasks as new constraints are introduced. The tight delivery schedules create a great deal of the problem.

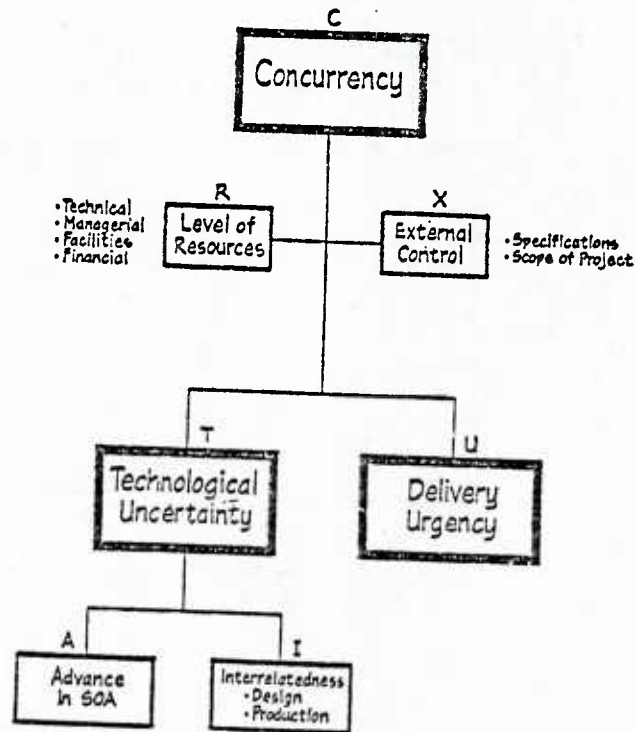
All this intensifies the effects of change on cost. Are these costs normally tracked and accounted for in relation to causality?

Effects of Concurrency

Figure 5 illustrates the effects of concurrency on program costs. The upper life cycle indicates a fairly orderly incremental approach or plan that is generally sequential with little or no overlap. The crosshatching is added costs from false starts, rework and so on.

The life cycle model in the lower half of the figure shows the effects of concurrency caused by overlaps generated by continuing uncertainty. The bulk of the added costs are always in the production stage (or phase).

FACTORS IN CONCURRENCY



$$C = \Phi(A, I, U, R, X)$$

Figure 3 Factors in Concurrency

CONCURRENCY DISRUPTION

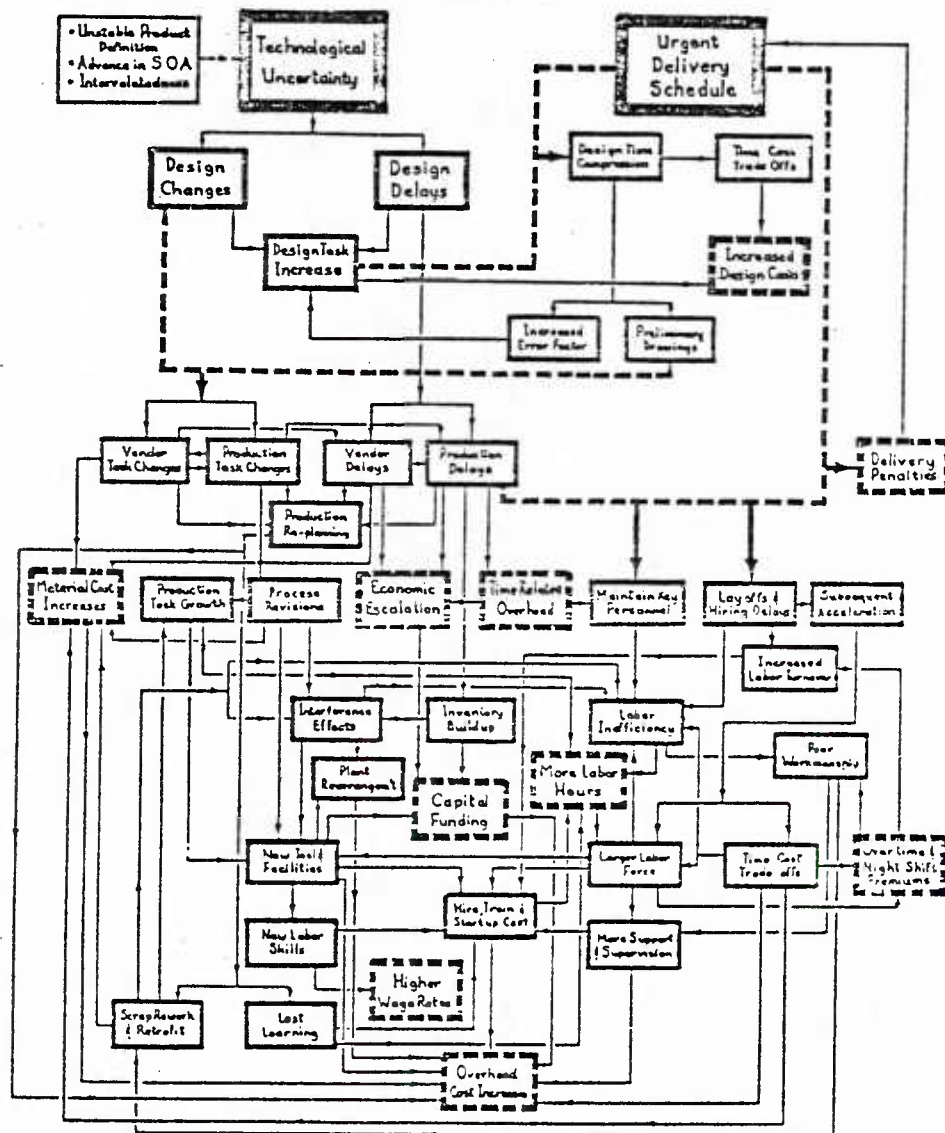


Figure 4 Concurrency Disruption

EFFECT OF CONCURRENCY

On Development Program Costs

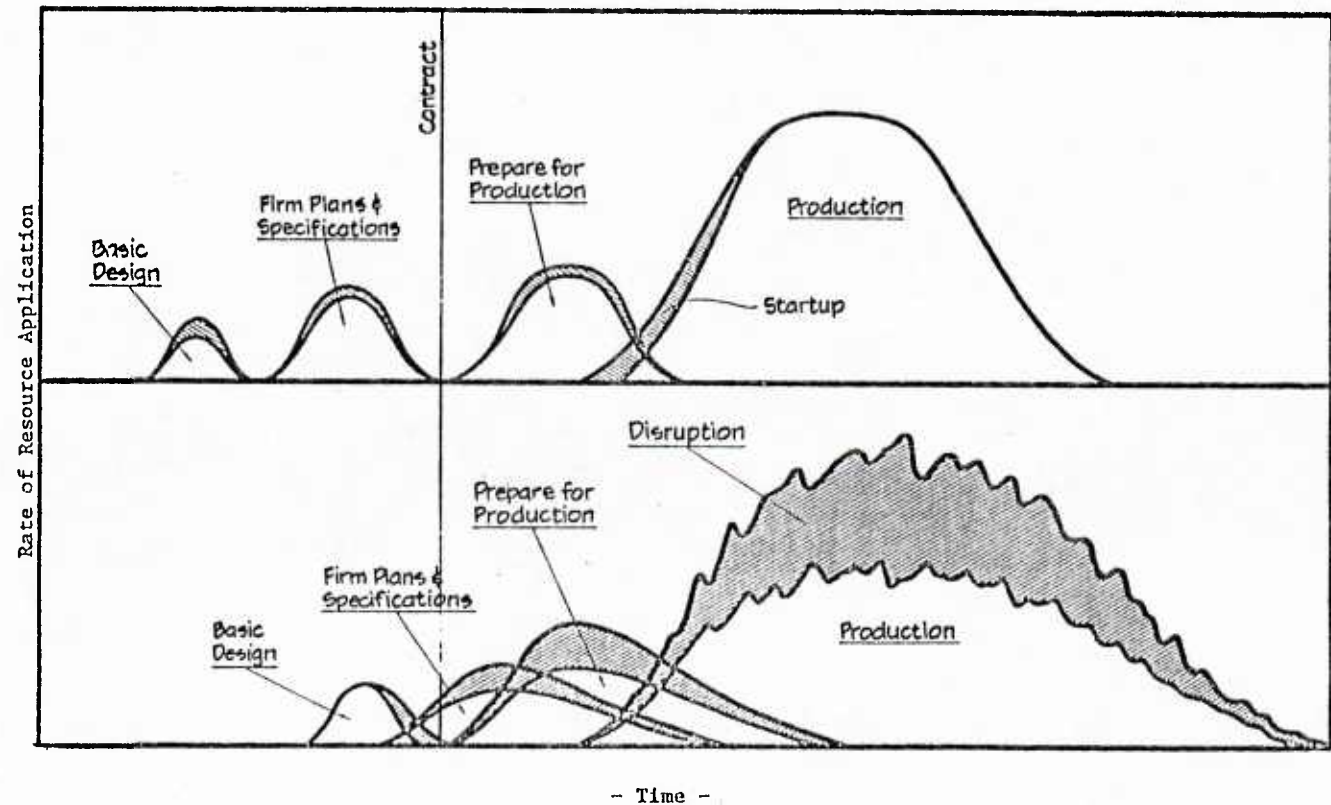


Figure 5 Effects of Concurrency

D&D Model

Finally, to depict the D&D concept the Cochran model of disruption is presented as Figure 6. This was designed as a speculative model to present the impact visually of the disruption factors (or variables) on time and cost. Disruption is shown on a curved surface with the values increasing along lines U and T. One cost surface is defined for each given ratio of resources to tasks. As the resource ratio raises, the cost surface rotates downward. While the model was not developed from general functional characteristics, there is an opportunity for research to continue this effort.

D&D Summary

There are a number of additional categories of changes within the three major causes that produce D&Ds. In the Rowe and Somers paper a fourth major cause, customer uncertainty, has been treated separately [27]. That is not the point. The point is that program managers and defense contractors must face at one time or another D&D's in the form of program change proposals (PCPs), engineering change proposals (ECPs) and contract supplemental agreements.

One naval shipyard experienced 35,000 changes in the process of constructing one aircraft carrier. And each change can produce D&Ds that have the potential to influence cost, performance and schedule. And if D&D's in any of their various forms do impact costs, performance and schedule, who absorbs the cost or who pays the bill?

Who pays the bill is not too much of a problem if: (1) the D&Ds can be traced back to changes either under the control of the government or under the control of the defense contractor, and (2) the exact magnitude of the cost, performance and/or schedule impact can be allocated to each D&D. Since, traditionally, this tracing and identification has been difficult to accomplish (or not attempted at all), many disputes have occurred and program managers (and their sponsors) have attempted a number of methods and ways to squirm out of resolving this continuing program management issue.

SOME FOLKWAYS OF COPING WITH DELAYS AND DISRUPTIONS

Ignorance is Bliss

One way to deal with D&D's is to pretend they don't exist. Then if they do occur and their impacts can no longer be ignored, the government simply pays the bill, revises schedules, and/or adjusts system performance with or without a fuss where the degree of fuss is proportional to media exposure and congressional complaints.

The Deep Freeze

In this approach there is some recognition that the root of D&D problems is in changes. The solution is to attempt to freeze designs and eliminate ECP's, PCP's and the like after some predetermined point. The failure of this approach is borne out by discussions of the 14th change to the seventh version of the third modification to the sixth final absolute frozen plan.

Competitive Bidding

Our contracting agencies have tried, and continue to try, competitive bidding. The historical results for whatever reasons on major systems in particular have been viewed in the public and the congress as "buying in." This, again, is probably due to an underestimate of the D&D's (or a failure to accept the occurrence of D&D's) likely to be encountered and, once encountered, the attempts to up the price tag accordingly.

Although the history of system acquisition and program management since the Korean War contains many examples of government sponsored innovations in contracting techniques, these have been met by contractor responses designed to either maximize gain or minimize losses. The greatest opportunity for the entire community is thought to lie in recognizing and admitting that we operate under the free enterprise system and that competitive bidding should be the best insurance policy against the effects of D&Ds.

Yet, in an economic sense, the market place is monopsonistic. Essentially, one buyer (federal) and a few qualified sellers exist. Given these conditions, once an award is made, a contractor may act as a monopolist (or quasi-monopolist) [29].

One example illustrates what may be a classic case of good management from a defense contractor (and government program manager) point of view. That is the case of the McDonnell-Douglas F-4 Phantom. The continual modifications and changes, mission expansions, and applications ranging from the Navy to Air Force resulted in many design changes with approved ECPs. This permitted McDonnell-Douglas to maintain a "non-loss" production line for many years while still maintaining state of the art technology. In fact, the product differentiation concept of the consumer goods marketplace was successfully applied on the F-4 for market maintenance.

There are many examples where the results of competitive bidding have, on the other hand, produced less than satisfactory results. In fact, some acquisition specialists have suggested that those qualified defense contrac-

DISRUPTION MODEL

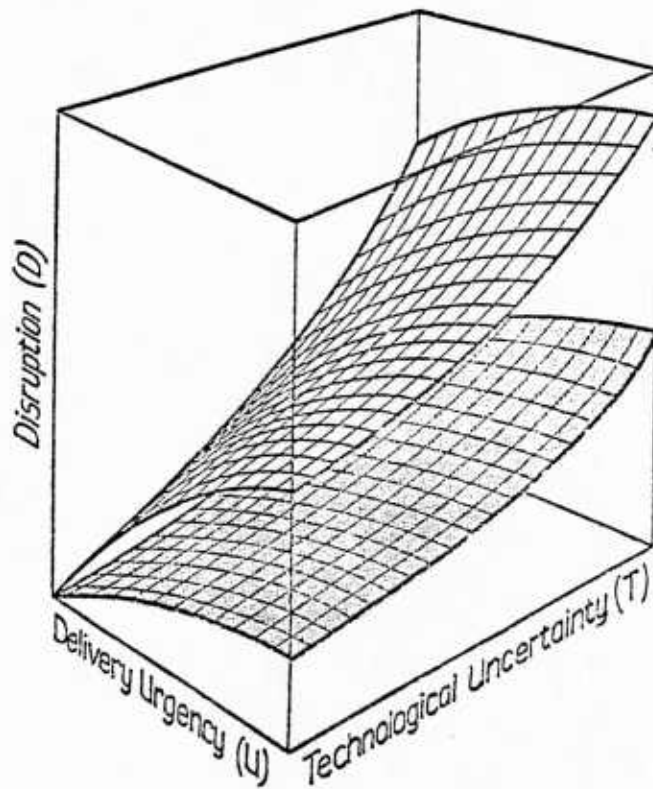


Figure 6 Disruption Model

tors simply be listed alphabetically and each be awarded in turn the next defense contract up in their area of expertise. Others have noted the development of symbiotic relationships to perpetuate traditional contractors [21].

Government Managed Programs

The NASA manned space program that led to landing men on the moon was a competitively bid program. A doctoral dissertation was written on the factors leading to changes in cost estimates by NASA (and active DoD programs) [18]. However, contractors were in effect subcontractors to NASA who maintained system program management responsibility. Strategies varied from extremely close ECP cost-control through a computerized approval and billing system at North American (Downey) to the Grumman approach. Grumman was responsible for the LEM (Lunar Excursion Module) and apparently did not establish such a complete system (partly caused by their long experience and monopoly relationship with a primary customer--the Navy). While Grumman developed a successful product from a performance standpoint, the cost of the system may not have provided for a complete or adequate financial recovery by the firm.

Contracting new systems and programs other than by the federal government is not without overrun problems. For example, the BART system in San Francisco had a three year schedule delay, a \$584 million cost overrun (60%), and a performance efficiency noted at one time at less than 50% [4].

Multiple Incentive Contracting Approach

In the 1960's multiple incentive contracting was the DoD program response to D&D's as the TFX (F-111) was contracted for a multi-service buy and operation [35]. The contractor strategy after award was to optimize incentive dollars by concentrating on Time and Cost incentives to meet scheduled deliveries and budgeted program costs, and by failing to deliver on performance. The strategy was not difficult for decision-makers when it became apparent that the engine subcontractor could not meet performance criteria, and the Navy had required changes in structure and thus weight. These D&D's would not permit attainment of the incentive fee for meeting the contract performance criteria. Thus management emphasis shifted to time and cost controls.

Fly Before Buy Approach

The concept of "fly before buy" was another Pentagon solution (although tried until 1957) [21] to the D&D-induced cost overrun problem [36]. It was thought that a "flying" version before a production decision could reduce the

need for post production changes and, hence, reduce D&D's. The contractor strategy was to gain support wherever possible (including the purchaser) and try to influence the criteria for the decision making model in the test and evaluation phase (fly off). The result appears to have been successful in the case of YA-10 versus A-7 fly-off but, did the Air Force really buy the best tactical fighter given the real world missions?

This may not have been as apparent with ALCM but, it was discouraging to many that the "favored" contractor experienced more initial failures in the ten (10) vehicle tests [6]. And if this system performance was lacking, could this be corrected by ECP's, PCP's, etc? Would not this lead right back to D&D's?

Consortia Approach

Consortia of firms have been formed as a strategy for managing the D&D's of new large scale systems. Complete new organizations have been created but, they, also, have been ineffective in meeting schedules, costs, and performance goals. For example, with the Alaska pipeline, the oil companies involved (and the Fluor Corp) formed the Aleyska Corp. They experienced a time or schedule overrun of five (5) years, a cost overrun of 6.8 billion dollars from the original cost estimate (900 million dollars). While the original overrun was about 800% (on cost), the figure usually quoted is the revised cost estimated after the environmental settlements or a cost overrun of "only 126% (adjusted also for inflation) [26].

The consortia of HBH (Hughes-Bendix-Holmes/Narver) for the SNAP program, while initiated only in 1979, is already experiencing D&D's. The human resources are not available to recruit and/or train in-country for the crews to man the navy under construction for a Middle East country [19].

Private Development

In the private sector the marketplace is not without its examples of corporate overruns caused by D&D. The Lockheed L-1011 with the problems of Rolls Royce on the RB-211 engine resulted in the bankruptcy of RR and the near bankruptcy of Lockheed Corporation. The Lockheed strategy was to engineer a federally insured bail-out [28]. We have yet to see whether this is successful, although the technique has since been applied to the city of New York and the Chrysler Corporation.

Total Program Package Approach

The DoD moved to a new contracting concept or approach, TPP (Total Procurement Package). The Air Force applied TPP to the SCRAM (ATG-69A)

program, and this resulted in a cost overrun of \$297 million or 200% [32]. This was another case where TPP was applied, yet the program was not a major improvement in philosophy, but in reality an attempt to advance the state of the art significantly in solid state rocket motors. In addition to other technological breakthroughs necessary, the missile was also to be deployed with the FB-111 (concurrently under development) and with later versions of the B-52, and become a critical component of the Air Force arsenal.

Lockheed experienced substantial dollar losses on the engine development for this program and the CSA [7].

The TPP concept using a FFF (Firm Fixed Price) contract was also applied on the Ingalls Shipbuilding division of Litton Industries, Inc. contract for the LHA (amphibious assault ships) in 1969 and the DD-963 (Spruance-class destroyers) [12].

The LHA program experienced a complex combination of D&D's, resulting in a \$2.7 billion cost overrun. The contractors strategy was to try to maintain schedule and performance while continuing cost negotiations. This strategy resulted finally in legal action with claims of several billion dollars.

This lawsuit involved cost determinations that were complex and defied simplistic solution. It was ultimately resolved with the development of a production model. The D&D's were traced back and the identifying causes and related costs generated.

Using this production model the dispute was finally settled with a financial settlement to the contractor of \$447 million. It is this last approach that we will examine in the remaining portions of this paper since it represents --to us-- a significant potential to shift emphasis in dealing with D&D's in program management.

MANAGING DELAYS AND DISRUPTIONS

In the context of the foregoing discussions, the central theme of this paper can now be stated. We are proposing that program managers shift from either trying to ignore or prevent (by freezing designs or by contracting devices) D&D's to simply accepting D&D's and learn how to manage them.

In fact, rather than suggest that D&D's are all bad, it may well be that some of them are highly desirable.

For each D&D produced by an ECP, for example, someone must have performed some kind of a trade-off analysis on the benefits of the ECP compared to the impacts, if any, on costs, schedules, and system performance. While these

trade-off studies may at that moment be primarily seat-of-the-pants oriented and rely on the savvy of the proponent of the change and the program manager, they are still probably done. If the perceived benefits outweigh any estimated adverse impacts, the ECP goes forward. And it should. The only question is: Who pays for it?

The only problem with answering this question is that true impacts of change-induced D&D's are hard to trace through the system acquisition process; let alone to link them explicitly and numerically to cost, schedule and performance impacts. And there is the rub. Who is going to determine which impacts or portion of impacts are linked to which changes (D&D's) and how? Once that is done and agreed upon, we assume it becomes fairly straight forward to figure out who is going to pay for them.

We are proposing a new way to manage D&D's that is designed to answer those questions and others like them. What we are proposing is an emphasis on managing D&D's through simulation technology currently available.

Through this methodological approach changes that cannot be controlled can still be managed. Controllable changes can be explicitly examined before their implementation to examine their D&D's with their resulting impacts on program costs, schedules and performance. And for any change-induced D&D, the impacts can be determined explicitly and numerically so that who pays for what can be determined.

The approach we are advocating is a specific version of simulation called system dynamics.

SIMULATION AND SYSTEM DYNAMICS

Our approach in this paper is that of simulation and, more specifically, a version of simulation called system dynamics. Simulation has been around a long time, and modelers who use simulation have generally followed a two-step process. First, they construct a model of some system of interest to them in order to imitate the system's behavior. If the model can successfully imitate the system's behavior under a wide range of circumstances, the modeler will feel confident enough to move on to the second step: running policy experiments. In this step the modeler alters particular inputs to the model that correspond to real world policy options. For example, the Congress could cut the budget of a program by 20%. By interpreting the model's responses to the changes, the modeler hopes to understand how the real system would respond to the same policy changes. Once a model has been developed and confidence has been gained in its utility, the modeler can make his model available to interested users (for

example, a program manager, if the model is one of a system for which the manager has responsibility). The user then can test out real system reactions to changes using his model of the real system as a surrogate for it [10, 31].

In physical systems, simulations are relatively common and run the gamut from simple hand simulations with tabletop models and physical mock-ups to more recent and exotic mathematical models and computer simulations such as those used to control space flights.

In biological systems, experts are now routinely at work constructing computer based simulation models of kidneys, cardiovascular systems, etc., to test new medical policies. In social systems (and the weapon procurement system is a social system), especially over the past decade, there has been a great increase in the resources allocated to building interdisciplinary computer simulation models of complex social systems. In each area of application the process is the same. A model is constructed and then "tweaked" to see what kinds of responses are produced.

With the advent of large digital computers, modelers have turned increasingly to developing models of complex systems that are programmable on digital computers. In fact, most current simulation efforts depend heavily upon the use of a computer to assist in manipulating the otherwise unwieldy mass of data and interrelationships that have to be considered.

We should stress that using a computer does not, per se, lend any particular authority or correctness to an analysis. The computer is merely a very fast, very accurate, electrical idiot that manipulates data according to the framework and ground rules established by the model. Should the computer output fail to accurately initiate the behavior of the real system, the model and the modeler (not the computer) are to blame.

While the advent of bigger and faster computers has helped the modeler to manipulate larger bodies of information, better computers are not the main reason for the growing use of simulation models. Rather, the growth in the complexity of the systems we are called upon to manage and the increasing need for an inexpensive means to test out policies prior to implementation have been the main stimulants. No engineer would dream of trying to analyze and predict the behavior of complex physical systems (such as those used in space flight control) by inspection, thinking a lot, debate, compromise, and seat-of-the-pants intuition. Instead, engineers turn to laboratory prototypes and computer simulation to test policies out before the very expensive rocket is launched. Yet we expect program managers to manage weapon system procurement involving systems that are at least an order of magnitude more

complex than purely physical systems, and to make their judgements by the more accustomed art of debate, compromise, etc. The results are clear.

It is, of course, unfair to say that program managers, like managers of most social systems, do not make use of models. Every time a program manager looks at a PERT chart, a scale model of a new weapon system, or a blueprint of a new system component, he is using a substitute for the real system. These physical and pictorial models are similar to the mathematical models used in computer simulations in that they provide explicit substitutes for the real system. Yet, these models represent physical subsystems and they are static. Most of the interesting (and least understood) aspects of weapon procurement systems come from the dynamic interactions over time of its physical and social components. PERT charts, blueprints, and scale models cannot help managers (or anyone else) project the system behavior over time in normal circumstances, let alone under the influence of D&D's. So they turn to two other kinds of models. In most instances managers are forced to turn to fuzzy, qualitative, chameleon-like mental models to serve as substitutes for the real system. In a growing number of instances, however, managers are trying to turn to explicit, quantitative, mathematical models. These models span the fields of econometrics, operations research, management science, and applied mathematics, and have been used to study physical, biological, and social systems. Our comments that follow report on one specific application, that of system dynamics. We believe this approach to be general and that it can be applied to any system acquisition.

System Dynamics

System dynamics was developed during the 1950's by Jay W. Forrester and his colleagues at the Massachusetts Institute of Technology to help in their study of industrial systems [15]. Over the past decade, the technique has been widely applied to simulate a variety of social systems: the world copper market [3], natural resource use [5], planning and control for community hospitals [22], decay of urban systems [16], the U.S. energy system [25], regulation of electric utilities [14], and logistics systems [33]. The technique is most widely known for its use in the study of The Limits to Growth in population and industrial activity in a finite world [24].

The heart of the system dynamics paradigm is the view that social systems belong to a general class of nonlinear feedback systems. To facilitate the representation of such systems of nonlinear relationships, the system dynamics technique allows for easy representation of nonlinear relationships and chains of relationships

that close on themselves to form feedback loops. It is the interlocking structure of multiple feedback loops that the system dynamics practitioner seeks to find the explanation of the dynamic behavior of complex social systems:

It is in the positive feedback form of system structure that one finds the forces of growth. It is the negative feedback, or goal-seeking, structure of systems that one finds the causes of fluctuation and instability [15].

To build a system dynamics model, one follows a series of steps described in the preface to Dynamics of Growth in a Finite World [23] or those discussed in Introduction to Urban Dynamics [2]. Generally, the following steps are required:

State the Problem

At the very beginning the modeler should specify

the issues the model is to address. Usually, this involves a description of a particular system that is behaving "poorly" and a question of which proposals should be adopted to make the system behave "better" in the future. In this case D&D's are the issues and, for example, the setting could be the post-Milestone III (production) phase of the systems acquisition process.

Determine the Key Factors and Their Causal Interrelationships.

In this step the modeler lists the key factors that are believed to cause the behavior of concern. The interrelationships among these

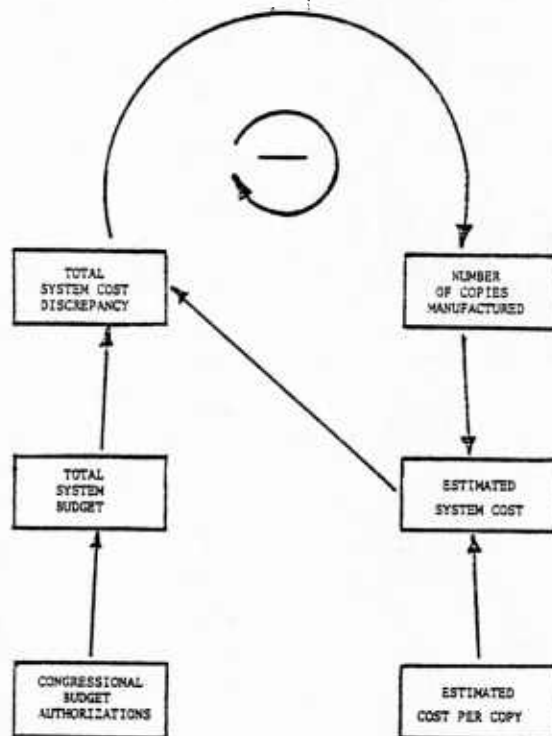


Figure 7 AN ILLUSTRATION OF A (NEGATIVE) FEEDBACK LOOP IN THE WEAPON SYSTEM ACQUISITION CONTROL PROCESS

factors are identified and portrayed in the form of causal diagrams. An example of a causal diagram in the weapon acquisition system is given in Figure 7. As the numerous interrelationships in any system are identified, some series of relationships form a closed chain or feedback loop. In Figure 7, such a loop is noted by a $\odot$. It is in the interaction of these loops that the modelers seek to explain the behavior of the system under study.

Formulate Model in Flow Diagram

In this step the representation of the system is reformulated in the form of a flow diagram which facilitates the eventual representation in the form of a set of difference equations. The flow diagram is especially helpful in distinguishing between flows of material and flows of information. Moreover, the flow diagram forces the modeler to indicate explicitly any delays or nonlinear relationships included in the model.

The use of causal loop diagrams and flow diagrams not only helps the modeler to keep track of his progress, but it helps communicate the important features of the model to potential users as well. The use of meaningful variable names--names that can be seen, "felt", or talked about--together with the diagramming aids, gives properly constructed system dynamics models a good chance of bridging the communication barrier between the model builder and the model user. This barrier has been described by Goldie as follows:

When we attempt to use the new techniques that management scientists advocate, we suddenly find that we are out of the loop. A bright young man takes my problem away and translates it from managerese to computerese [17].

In speaking about this opportunity for bridging the communication barrier, users often refer to the system dynamics approach as "common sense quantified," whereas more elaborate techniques are described as "common sense made difficult."

Estimate the Parameters of the Model

In this step the parameter values must be estimated. Each of the parameters of a system dynamics model is estimated individually from the best information available. This information can take the form of highly accurate physical measurements and make use of volumes of hard statistical data (at one end of the spectrum) or expert opinion and individual intuition (at the other). The use of expert opinion in the absence of more formal data to help parameter identification

tends to make some data purists squirm. Yet, to rule out subjective inputs if they are the only source of information available ignores the fact that most of the relevant data in any real social system is contained in the heads of people and is not easily recorded in the form of time series or cross sectional data.

Practitioners of other modeling techniques prefer to ignore relationships for which hard statistical data is not available. Leaving such relationships out, however, results in assigning them the parameter value that most people would agree is wrong--zero.

By incorporating subjective judgments in estimating parameter values, the system dynamics practitioner can determine through sensitivity testing those areas where further debate and data collection is warranted. If a model's behavior is generally insensitive to certain parameter values, scarce resources should not be wasted in collecting data to estimate them.

Generate Initial Output and Increase Confidence in the Model

Once parameter values have been estimated, DYNAMO equations of a system dynamics model can be easily constructed. (DYNAMO is a software package usually used to construct and test system dynamics models.) If the initial output generated by the model fails to imitate the real system's behavior well enough, the modeler returns to Step 2 and begins an interactive process. We should emphasize that system dynamics models do not automatically reproduce historical trends since model parameters are estimated individually. This procedure is quite different from modeling approaches wherein model parameters are estimated "all at once" to give the best fit to historical trends over a certain period of time. Thus, it should come as no surprise that such models are capable of providing extremely close fits to historical trends over the time period used in the parameter estimation. They are designed to!

Generating a reasonable pattern of behavior - both over some historical period and into the future - is but one of several tests that should be performed to increase confidence in a model. Sensitivity testing should be performed to ensure that the model does not respond unrealistically to changes in particular input values. The response of a model to disturbances in exogenous inputs should be examined for plausibility. These and other confidence tests are described in Forrester's Industrial Dynamics [15].

Simulate the Effects of Proposed Changes

In this final step the modeler simulates the effects of pending or actual changes and observes change-induced D&D's to determine the explicit effect on the system schedules, costs, and performance.

For example, there are at least two kinds of well-known D&D's that can effect system behavior. First, there are changes that are under the control of the program manager. For example, a program manager may be considering the merits of giving a go-ahead on stretching the production schedule vis-a-vis- simply slipping the entire schedule by a uniform amount. A second kind of change is one imposed on the system from the outside. For example, a large cost of living wage increase for production workers, a rise in the cost of material used in construction, or congressional changes in the authorized budget for the program. In these instances there are two questions to be asked: (1) What is the effect of the change on the system if the program manager does nothing? and (2) What action can the program manager take in the face of this change to improve system response to it? In Step 6 each kind of change, as well as combinations of changes, can be and have been examined.

THE INGALLS SHIPBUILDING MODEL: A CASE STUDY

A recent study performed by Pugh-Roberts Associates involved the application of system dynamics to a dispute between the United States Navy and Ingalls Shipbuilding in Pascagoula, Mississippi, a division of Litton Industries, Inc. [11, 12]. This study is reported in detail by Cooper (1980). The dispute focused on issues of delays and design changes and the long-range higher-order impacts of design changes. In 1969 Ingalls was awarded a firm-fixed-price contract by the Navy to design and build nine (subsequently reduced to five) amphibious assault ships (LHA's). As reported by Cooper, the LHA is "20 stories high and the length of three football fields." It is, according to the Navy, "the largest, fastest, and most versatile vessel in the history of American amphibious war fare." The Navy contracted with Ingalls for the LHA program as one of the two Navy shipbuilding programs using a Total Package Procurement approach. This meant that Ingalls was provided only with performance specifications and was thereafter "solely responsible for all system design, detailed design; material procurement, planning, testing, and construction." The other program was the 30-ship Destroyer DD963 program, also awarded to Ingalls in mid 1970.

Cooper sets the stage for an inevitable D&D problem as follows:

The design and construction of the new, complex LHA's and the DD963 Spruance-class destroyers (twice the size of destroyers of the prior generation) dominated the operations at Ingalls throughout the 1970's. Either of the LHA or DD963 programs would have required a significant facilities and manpower expansion for any shipyard - Ingalls more than doubled its workforce for the two programs. During this time there were periodic nationwide material shortages and a critical scarcity of skilled shipbuilding labor. A new form of organization for ship design was being used by Ingalls and the Navy. Formal requirements were instituted for integrating with the usual design effort the consideration of vessel maintainability, reliability, logistics support, manning, and more.

It was in this setting that thousands of design changes on the LHA were received by Ingalls from the Navy [11].

In January 1976 Ingalls approached Pugh-Roberts Associates, convinced that the major contributing factor to overruns of some \$500 million was the disruptions that had been present in every phase of the LHA program. Ingalls further felt that "... Navy-responsible delays and design changes had contributed to the disruption and had affected many areas which otherwise would not have experienced difficulties." (Of course, the counter to placing all the blame for cost overruns on the Navy are charges that the contractor "bought-in" or contractor mismanagement.) Cooper points out that:

Claims against the Navy have evolved to a form in which two major segments can be identified. First, the direct impact, or the "hard-core" costs, of a design change or delay are estimated. While there are always legal questions of entitlement, these costs are not difficult to understand and can be quantified--for example, the number of man-hours required to effect the change in a design drawing and the man-hours needed to implement the immediate change in the construction of the ship. The second segment of the claims consists of "delay and disruption" costs--the second and third-order "ripple effects" of dealing with the direct changes. (These are traditionally the most difficult issues to quantify and justify.) In concept, they are the "snowballing" effects

within a work phase, among work phases, and between work programs, such as altered work sequence, conflicting facilities and manpower requirements, skill dilution, undetected work errors, and more. The ultimate consequences for program performance include the additional cost and time required to accommodate the full range of effects of the direct changes [11].

As pointed out by Cooper, changed designs produce a need to "rip out and rework," which means increased manpower and material costs, and manpower diverted from other programs causing schedule changes, reduced productivity, and so on. All these "ripple" effects work together and "feed upon one another in vicious circles that continue to exaggerate the cost and schedule impacts of design changes far beyond the time and stage of work directly affected. This is the essence of 'delay and disruption.'" [11]

The methodology used to tackle these D&D-induced claims by Ingalls was system dynamics. It was a methodology that would "(a) correctly quantify Navy-responsible delay and disruption costs in the design, procurement, planning, and production stages of the programs, and (b) demonstrate the cause-effect relation of the costs to the items cited in the 'hard-core' segment of the claim." Since a model was developed and presented by Cooper, only essential parts are repeated here. The model developed by Cooper was "... a replica of the management decisions and operations of the company. The single, important, intended use was qualification of the comprehensive impacts of customer changes and delays." [11] The quantification of impacts was accomplished by running the simulation model twice.

In one run, the model calculated the number and timing of man-years expended in each program phase from the beginning of the programs to completion and all of the Navy-responsible changes cited in the hard-core claim items were included. This run re-created and forecast the actual work schedules and expenditure of man-years on the LHA and DD programs, including all the "ripple, D&D, effects."

The second run was identical to the first except all inputs that represented the Navy-responsible changes cited in the hard-core claims were removed. The results of this simulation run were the estimated schedules and man-hours which would have occurred had the Navy not intervened in the LHA program.

The differences between the two runs were the quantification and diagnosis of the cost

impacts caused by the Navy changes and submitted to the government in October 1977. It was the sole technical basis for the majority of the claim.

In the settlement reached in June 1978, Ingalls received \$447 million from the Navy. It was the first time that the Navy had given such a substantial consideration to a delay and disruption claim. The managers and lawyers' estimates place the model's dollar contribution to the settlement between \$170 and \$350 million. The model also eliminated the adversary relationship between Ingalls and its best customer--the Navy. Since the avoidance of contractor claims against the government was cited as a high-priority objective in the procurement process study prepared under the Secretary of the Navy, and since change-induced D&D's seem to be inevitable in complex defense systems acquisition, it would seem that system dynamics provides a methodology and a technique for comprehensive analysis and a mechanism for managing D&D's on the part of both the defense contractor(s) and the defense program managers. The question remains one of implementing and institutionalizing such a management technique.

IMPLEMENTING AND INSTITUTIONALIZING D&D MANAGEMENT

Although the D&D concept developed in this paper is somewhat broader than in the specific Navy-related case study presented, the message is the same. Once a contract is awarded, a basic tool for the management of the acquisition should be a model that can be used to determine causes, effects (including costs), and who pays for the impacts of change-induced D&D's.

The model would be developed to specifically link changes to their D&D's and D&D's to their impacts on cost, performance, and schedule. As such, it would become the primary management mechanism to determine the cost-benefits (or cost-effectiveness) of proposed design changes (for example). It would be the primary management mechanism to provide for dollar adjustments in funding levels or to provide for schedule revisions in the light of changes.

Implementing and institutionalizing such a methodology for management use and philosophical acceptance will not be easy. And here we make a distinction between implementation and institutionalization.

It is relatively easy to implement a change in procedures, policies, or management

approach. To see that the new approach remains implemented over some lengthy time horizon (institutionalization) is quite another matter. There are many examples within D&D of approaches (see Folkways section) that have been implemented, but that have failed to become institutionalized.

It seems to the authors that a key ingredient to both implementation and institutionalization is the active interest and support of both the top management and working management levels in both the D D and Industry. Such support is typically earned in many ways, but there are three necessary (if not sufficient) prerequisites: (1) The approach proposed must be "effective." It must work and yield tangible and readily recognizable results and, (2) it must also be "efficient" and not cost more than its measurable worth at a minimum and, (3) it must be understood by those who are to support and use it.

The Ingalls case study seems to go a long way toward meeting the first two prerequisites. We are not as optimistic that the third has as yet been tackled on any significant scale. We suggest that education (special training programs, short courses, intensive seminars such as this one, master's degrees, etc.), can help provide the conceptual understanding and develop skill through practice, and familiarity to meet the third prerequisite.

The authors are not aware of any large scale effort to provide such educational or training opportunities. Where simulation is formally taught at all (and even then the scale and number of trainees is relatively small), the techniques of simulation seem to dominate if not get in the way of applications.

System dynamics, which we feel is particularly well suited to promote understanding among users with even modest technical skills in computers and simulation, is taught at relatively few institutions around the country. We are not aware of any major effort to train or develop program managers engaged in the systems acquisition process on techniques such as this.

Implementation could occur in the form of DOD directives and/or MIL Standards. The directives or standards would define, at least to some degree, the appropriate ingredients of a model to be developed for managing D&D's for any given acquisition. They might, but probably should not, specify the detailed variables and causal loop diagrams to be flow diagramed and parameterized. They might, and perhaps should, specify the boundaries beyond which no model

should extend.

The main initial activity and function of a program manager within the DOD would be to specify measurement methods for each variable, parameter, table function, or other quantifiable component of the simulation model. They would then spend enormous amounts of time and effort working with the defense contractor, refining and validating the model so that both agree that it is a fair representation of the real world with respect to the D&D issues. Then, as design changes and subsequent other D&D occur, their impacts would be traced through their logical impacts on costs, schedules, and system performance.

For those impacts that can be traced to government-generated D&D's, the government would pay (as with an approved ECP). For those D&D's that are contractor related, the contractor should absorb them.

For D&D's that share a common responsibility or are the result of "mother nature," suitable compensation or settlement rules could be devised. Trade-offs could be made, using the model, with the government's program manager to report on impacts and the cost-effectiveness of proposed changes.

The defense contractor could use the same model to allocate resources in an "optimal" way in the light of D&D's or claims could be reviewed or investigated and resolved without the time consuming and expensive (both in costs and attitudes) process of litigation.

Once agreed-on models had been hammered out, most case-by-case D&D's could "automatically" be managed. Only in response to changed circumstances in the real world would the model be altered to conform once again with the real world. The model would, within the acquisition circle relevant to the acquisition, be public knowledge. This methodology for dealing with risk and uncertainty could be used as an on-going management tool and not only for D&D management.

In short, this approach to D&D management allows D&D conflicts to be objectively discussed, reviewed, and resolved at the systems level rather than on a case-by-case basis for each D&D in the press, the Congress, or in the courts. Such a model, once specified, should define and remove nearly all ambiguity without impairing the program manager or the defense contractor's ability to manage.

Potential saving in financial and social costs, delays, frustrations, etc., while believed to be significant, may be fully

incalculable. We consider the idea of managing D&D's at the system level by a system dynamics simulation model to have the potential of revolutionary impact on program management.

Any broad application of a new conceptual approach is bound to be full of unexpected consequences, booby traps, and surprises for the untrained. For a while, therefore, the wise implementor-to-be would want to run some tests (develop three or four small program models) to fully develop the approach before implementing it DoD-wide.

We therefore suggest that an experimental test of this approach be developed and implemented using carefully selected acquisitions (program) as test beds for the methodology. The results of such tests could provide the necessary insight and feedback to permit a determination of the cost-effectiveness of such a management tool in the management of D&D's.

We know of no such test setting in which even limited experimentation with the method we advocate is occurring at government request. But we have hopes.

LIST OF LITERATURE CITED

1. Aerospace Daily, Ziff-Davis Publishing Company, Inc. Washington, D.C., 1976-1980.
2. Alfeld, Louis and Graham, Alan K. Introduction to Urban Dynamics. Cambridge, Mass.: Wright-Allen Press, Inc., 1976.
3. Ballmer, Ray W. "Copper Market Fluctuations: An Industrial Dynamics Study." Unpublished Systems Dynamics thesis, Cambridge, Mass.: Massachusetts Institute of Technology, 1960.
4. "Bart: A Study of Problems of Rail Transit," transcript of Proceeding of Public Hearings by the California Assembly Committee on Transportation, Sacramento, CA., October 9, 1973.
5. Behrens, William W. III. "The Dynamics of Natural Resource Utilization," in Dennis L. Meadows and Donella H. Meadows (eds.) Toward Global Equilibrium, Cambridge, Mass.: Wright-Allen Press, Inc., 1973.
6. Cameron, Juan. "The Cruise Missile Can Do It All--Almost." Fortune, May 8, 1978, pp. 174-80. "Competing Cruise Missile Test Ends." Los Angeles Times, Part 1, February 9, 1980, p. 27. Aviation Week and Space Technology, July 30, 1979, pp. 14-15; Oct. 15, 1979, pp. 22-3; March 3, 1980, pp. 220-1; March 31, 1980, pp. 18-19, 21-22.
7. Citations critical of the TPP on the F-111 and C5A include: Merrill, Crayson. Managing a Defense Company for Growth and Profit. New York: Exposition Press, 1972, p. 23. Drucker, Peter. Adventures of a Bystander. New York: Harper & Row, 1978, pp. 202-3.
8. Cochran, E.B. Articles on Modeling and Disruption. Tiburon, California, June 13, 1980.
9. Cochran, E.B. and Rowe, A.J. "The Sources of Disruption to Project Cost and Delivery Performance." Proceedings of DOD Sixth Annual Procurement Research Symposium, West Point, New York, June 1977, p. 4.
10. Concentration of modeling has centered primarily on COSTS and LIFE CYCLE COSTING. For a review of available cost models the following sources are recommended: Blanchard, Benjamin S. Design and Manage to Life Cycle Cost. Portland, Oregon: M/A Press, 1978. Collins, D. E. "Analysis of Available Life Cycle Cost Models and Their Applications." Joint AFSC/AFLC Commander's Working Group on Life Cycle Cost, ASD/ACL, Wright-Patterson AFB, Ohio, June 1976. McClure, L. "Life Cycle Costing--A Selected Bibliography." RB 330-1, Orlando, Florida: Martin Marietta Aerospace Corp., October 1976. Srofe, A. "Life Cycle Cost Reference Library Bibliography." Joint AFSC/AFLC Commander's Working Group on Life Cycle Cost, Wright-Patterson AFB, Ohio, March 1976.
11. Cooper, Kenneth G. "Naval Ship Production: A Claim Settled and a Framework Built." Interfaces, Vol. 10, No. 6, December 1980, p. 22.
12. Cooper, Kenneth G. "The Ingalls Shipbuilding Model as a Technique for Cost Management and Negotiation." Cambridge, Mass: Pugh-Roberts Associates, Inc., February 1980.
13. Dunigan, Peter and Rabushka, Alvin (eds.) The United States in the 1980's. California: Hoover Institution, Stanford University, Hoover Press, 1980. See Chapter II "Economic Policy" by Alan Greenspan and Chapter VIII "Government Power and Business Performance" by Murray L. Weidenbaum.
14. Ford, Andrew. "Is Growth Really Necessary?" Electric Light and Power, July 1976.
15. Forrester, Jay W. Industrial Dynamics. Cambridge, Mass: The MIT Press, 1961.

16. Forrester, Jay W. Urban Dynamics. Cambridge, Mass: The MIT Press, 1969.
17. Coldie, J. Harry. "Simulation and Irritation," in Schrieber, A. N. (ed.) Corporate Simulation Models. Seattle, Wash: College on Simulation and Gaming, TMS and Graduate School of Business Administration at the University of Washington, 1970.
18. In addition to the dissertation, an excellent work on the political aspects and impacts on a program, change factors affecting costs and overrun problems of other countries are: Trainor, R. T. "Factors Leading to Changes in Cost Estimates on Selected DoD and NASA Development." Doctoral Dissertation, George Washington University, 1977. Logsdon, John M. The Decision to Go to the Moon: Project Apollo and the National Interest. Cambridge, Mass: The MIT Press, 1970. Melville, Frank, "The Concorde's Disastrous Economics." Fortune, Jan. 30, 1978, pp. 67-70. Gillette, Robert. "Decade After 747: Jumbo Jet Comes to Russia--With Flaws." Los Angeles Times, CC Part IV, February 2, 1981, p. 1, 3.
19. Interview with HBH President, Pete Carroll, by H. A. Sherman, Spring, 1980.
20. Kucera, Randolph P. The Aerospace Industry and the Military: Structural and Political Relationships. Series/No. 03-023, Beverly Hills, California: Sage Publications, 1974, pp. 9-10.
21. Laird, Melvin R. People Not Hardware: The Highest Defense Priority. American Enterprise Institute, 1980, p. 4. (A pamphlet).
22. Masson, Phillippe; Moody, Thomas and Stubbs, John. "Planning and Control for Community Hospitals: A Case Study of the Cambridge Hospital." Unpublished System Dynamics thesis, Cambridge, Mass: The MIT Press, 1972.
23. Meadows, Dennis, et. al. Dynamics of Growth in a Finite World. Cambridge, Mass: Wright-Allen Press, Inc., 1974.
24. Meadows, Dennis L., Meadows, Donella H., Randers, Jorgen and Behrens, William W. III. The Limits to Growth. New York: Potomac Associates, Universe Books, 1972.
25. Naill, Roger F., Meadows, Dennis L. and Stanley-Miller, John. "The Transition to Coal." Technology Review, October/November, 1975.
26. "One Final Squabble." Forbes, April 15, 1977, p. 140.
27. Rowe, A. and Somers, I. "Methods to Evaluate, Measure and Predict Cost Overruns." Risk and Uncertainty Workshop held at U.S. Air Force Academy, Colorado Springs, Colorado, February 9, 1981.
28. Sampson, Anthony. The Arms Bazaar. New York: The Viking Press, 1977, pp. 220-21.
29. Sherman, Herold A. An Analysis of Marketing Structure and Operations in Selected Defense/Space Firms. Los Angeles, California: University of Southern California, the Graduate School of Business Administration, 1966, pp. 456-58.
30. Sherman, Herold A. "Systems Engineering and Management Seminar." Beijing Institute of Aeronautics and Aeronautics. Beijing, People's Republic of China (PRC), Spring, 1980.
31. Shubik, M., Brewer, C., and Savage, E. "The Literature of Gaming, Simulation, and Model-Building: Index and Critical Abstracts." R-620-ARPA, Santa Monica, California: The Rand Corporation, June 1972.
32. SRAM articles in Aviation Week on: January 27, 1969, p. 16; December 1, 1969, p. 47; June 21, 1971, p. 22; June 26, 1972, p. 136; August 14, 1972, p. 15; November 13, 1972, p. 16; April 16, 1973, p. 21; May 14, 1973, p. 20.
33. Stanhagen, John F. and Gardiner, Peter C. "Dynamic Simulation in the Logistics Environment: An Evaluation of Engineered Versus Informal Job Standards in the Maintenance and Overhaul Arena." Proceedings of the 11th Annual International Symposium of the Society of Logistics Engineers. Valley Forge, Pennsylvania, August 1976.
34. The following references present many cases of D&D's and all three basic causes: Cochran, E.B. Patz, A.L. and Rowe, A.J. "Concurrency and Disruption in New Product Innovation." California Management Review, Vol. XXI, No. 1, 1978, p. 28. Loomis, Carol J. "Who Wants General Dynamics? Henry Crown, That's Who." Fortune, June 1970, pp. 76-9, 185-6, 191-3. Kraar, Louis. "Electronic Boat's Whale of a Mess: The Trident Sub." Fortune, July 31, 1978, pp. 104-8. Kraar, Louis. "Pratt and Whitney's Problem Engine." Fortune, November 6, 1978, pp. 57-66. Council on Economic Priorities. Newsletter, CEP Publication, No. 7, New York, November 1980, p. 1.

35. U.S. Congress. Senate Committee on Government Operations. TFX Contract Investigation Hearings. Eighty-eighth Congress, first session. Washington, D.C.: U.S. Government Printing Office, 1963.
36. U.S. Department of Defense, Department of Defense Directive 5000. 1. Major System Acquisition, March 19, 1980. USDRE.

METHODOLOGIES PANELS SUMMARY

This session of the workshop concentrated on the area of "Risk and Uncertainty Methodologies." The papers delivered by the speakers and the intense interaction of panelists, achieved the purposes outlined for this section.

The panel members described a number of methodologies and techniques which, in spite of the problems of definition and the need for more refinements, are considered of practical importance and should be applied. The range and thrust of the recommendations from these panels are an indication of the momentum that was attained. The seriousness regarding research was also evident from the recommendations for future activities.

The first objective was to identify and clarify existing methodologies for a large project's life cycle. One methodology was presented using entropy, a concept to develop a model that would assist project managers in predicting the final program cost when uncertainty is present. The methodology was used in two projects to validate the approach. The model, although static in nature, showed mixed results. The methodology illustrated that formal links between entropic models and methods for determining information requirements from limited data can be established.

Another report reviewed research on network models for project management under conditions of risk. There were several other techniques for assessing subjective probabilities discussed. These included the: Choice-Between-Gambles, Standard Lottery, Churchman-Ackoff, Delphi, DeGood Consensus, and Direct Estimation.

Possibilistic uncertainty was the subject of another presentation and panel discussion. The mathematical development of "fuzzy sets" theory was presented as a methodology for the analyst and decision maker to provide results which more closely represent the actual meaning of the criteria that are to be satisfied.

The major approach of another panel was to discuss the use of moments in cost risk analysis (Wilder and Black). The presentation described a methodology and procedure for assessing, and by implication, to some degree managing, cost risk during the preliminary product design stage in the life cycle. Expert judgments were used to obtain most likely values. These in turn were treated as nodes, with upper and lower bounds, and used to form a triangular distribution.

The process of aggregating uncertainties

for each element, which is the heart of the procedure, uses the method of moments. Appropriate adaptations of this closed-form procedure exist for various rules for combining elements into the aggregate system. The output is expressed by "fitting" the final moment outputs to a beta (or occasionally other) distribution. The properties of that beta distribution are then expressed in the form of a cumulative distribution function showing the probability that the system will be completed at each of a range of possible costs.

System dynamics was the methodology presented and reviewed in another panel (Sherman and Gardiner). The methodology presented covered a computerized simulation model (System Dynamics) used to reconstruct a major ship-building program that attempted to resolve a major litigation between a contractor and the government. The model achieved the objectives of quantifying the amount of delay and disruption costs in the design, procurement, planning, and production stages of the program. The model also demonstrated the cause-effect relationship of costs and identified responsibility for the delays and disruptions that generated the time/cost overruns. Risk and uncertainty were reviewed in the context of disruption in systems acquisition. The assumption was that risk and uncertainty are inherent in any new project and therefore disruption will occur. The emphasis should be placed on the predication of disruption and the use by management of this information.

Another task of the panel was to assess the strengths and application of the various methodologies. A summary of comments follows:

1. Entropy can potentially be used as an indication of disorder in information related to key variables in a program.
2. Six techniques were reviewed for assessing subjective probabilities. While no one best way surfaced, the Delphi approach emerged as the one most acceptable.
3. Fuzzy sets are useful in multicriterion decision theory. They permit trade-offs, and analysis of alternative approaches with multiple objectives.
4. Fuzzy sets permit the use of soft versus hard constraints and are useful for visualizing imprecise (impossibilistic) uncertainty representations.
5. Fuzzy sets theory is presently used in artificial intelligence models, building multiattribute models, and for forecasting.
6. The use of moments in cost risk analysis,

shows ways of relaxing the assumption of additivity of costs. The method may be used, for example, to deal with time risks which may well not be additive.

7. The advantage of using the method of moments over such alternatives as Monte Carlo sampling is that it requires less computer time and is easier to understand the results. The method also produces a clearer picture of which elements of the total system development process will in fact be the cost drivers, both for the mean cost and for its variance. This approach helps to focus attention on the most important issues.
8. Simulation and system dynamics, in particular, facilitate modeling of complex systems and permit "what if" analysis. A significant advantage of simulation is its predictive value to project managers.
9. A system dynamics model can predict the impacts of disruption throughout the phases of a project's life cycle.
10. Because system dynamics is a dynamic methodology, it can contribute more than a typical static analysis to understanding changes over time.
11. Fuzzy sets allow a robust representation because of the ability to "grade" the characteristics. For example, there are gradations of acceptability ranging to unacceptable rather than the simple threshold used in crisp sets.
12. Fuzzy sets formulation allows the normal "goodness" words to be readily converted into mathematical expressions.
13. A probabilistic network model which permits branching at nodes, can consider the three variables of time, cost and performance. It also includes a wider choice of built-in probability functions (constant, uniform, triangular, normal, lognormal, Poisson, Erlang, gamma, beta, and tabulated distributions).
14. The interactive version of the RISCA model features fullyprompted initialization and modification of the networks from keyboard to system printer.

Some of the weaknesses noted in the application of methodologies discussed were:

1. The entropic model (Martin) needs further validation.
2. The use of the method of moments does not examine ways of relaxing the assumption of independence among elements.

4. A methodological problem that was discussed concerned the use of moments and the interaction between estimation of cost relationships, errors, and for costs assessed by techniques such as regression analysis. This was seen as a subtle but not unmanageable issue.
5. Another issue concerning the use of moments was the problem produced by the combination of the Central Limit Theorem and the independence assumptions. If the number of probability distributions convolved to obtain total system cost distributions, is large, regardless of the form and character of the input distributions, the output distribution will be relatively normal, with relatively small variance and little or no skewness. While no solution is suggested, most panelists agreed that outputs with small variance and no skewness are unrealistic descriptions of the results expected.
6. A discussion of sensitivity analyses led to the conclusion that, while indispensable to analysts, they were probably confusing to decision makers, and should usually be held in reserve unless they led to very clear conclusions not visible in the original analysis.
7. A weakness of the use of system dynamics is inherent in any large computerized simulation, namely the development of an accurate model including the time and cost functions involved.
8. Emphasis should be placed on the importance of attaching caveats of various kinds to estimates, especially when those estimates depend in any important way on independence assumptions.

The panels were asked to summarize the state-of-the-art on methodologies for risk and uncertainty analysis. The advances have been dramatic. They range from increased mathematical applications, such as fuzzy sets, to a greatly expanded use of the computer, not only for analysis, but for complex system model building. Most participants agreed that currently there were inadequate ways to communicate these state-of-the-art advances in risk and uncertainty analysis to the parties and organizations (stakeholders) concerned. This perceived problem led to the final objective presented to the panelists.

RECOMMENDATIONS

The panel members were asked to suggest ways of integrating the use of methodological approaches into the DoD project acquisition process. The recommendations included (not in order of importance) the following:

1. Develop formal means for relating the entropic model to the methods for determining

maximum information from limited data.

2. Identify the hierarchy of activities, and number of activities with potential impact on uncertainty.
3. Extend the validation of the Martin model (and possibly develop an improved model) and test the model in the following areas: (a) psychology, (b) construction, (c) portfolio management.
4. Develop a revised, validated Martin model so that it can become a useful managerial tool.
5. Expand the application of the fuzzy set theory to allow greater use of expert, algorithms and questionnaires for building evolutionary systems, and querying data bases.
6. A pilot application of fuzzy sets theory should be performed to evaluate a preferred technical approach in the development of an acquisition strategy. The results of that study be presented at the next conference.
7. Use the method of moments in cost analysis to compare two DoD programs, one staffed with trained cost analysts, the other not.
8. Conduct research on the concept of organizational slack.
9. Develop a real world application of system dynamics on a new project or system for predicting disruption and assigning responsibility (using an ECP type arrangement), as a technique for the management of disruption.
10. Select a new system or project and run a parallel development (systems model at milestone 0), working with a contractor and the project manager on the model. This would serve as an example to validate the use of system dynamics. The purpose would be to test and validate the methodology in a real application.
11. Expand the Cochran disruption model and conduct research to verify the theoretical concepts.
12. Generate a glossary of terminology to be added to the taxonomy.
13. Develop training programs targeted specifically at project managers using system dynamics.
14. Consider renaming our area of interest from risk and uncertainty analysis to the management of disruption or the

management of risk and uncertainty.

15. Establish a national center for the study of disruption and elicit DoD or service support for the establishment of a designated national data bank for the retention of information on the study of risk and uncertainty methodology.
16. Create a central repository of methodologies (from above) catalogued using the taxonomy developed for ready reference with explanations, working examples and an assessment of usefulness the methodologies.
17. Conduct research on the relationship between management behavior and contract type.
18. Concentrate on the management of disruption rather than trying to solve overrun problems by devising new types of procurement contracts.
19. Use dynamic, nonlinear, time indexed, simultaneous equations for simulation analysis.
20. Conduct a survey of academia, industry, project managers, military service and OSD staff offices to ascertain what methodologies are being utilized for managing risk and uncertainty.
21. Determine the most appropriate methodologies for the front-end analysis in a program and identify areas for further research.
22. Identify methodologies to analyze risk and uncertainty in human factors and recommend areas for further research.
23. Special emphasis needs to be placed on determining risk and uncertainty related to the variable of "performance" since it is a much more complex methodology. Initiate research on selected trial applications for projects having specific requirements.
24. Develop methods to transfer the state-of-the-art in risk and uncertainty analysis management to the system acquisition practitioners. This education would include the ideas, structures and tools (application, definitions, interrelationships, methodologies and assessments).
25. Network models like the VERT and RISCA developed for the U.S. Army can assist a manager in dealing with the risks associated with complex acquisition programs in other DoD areas.
26. DoD program sponsors, project managers.

directors (RDT&E), should have cost analysts to ensure that the requirements for the identification areas of risk and uncertainty under USDRE 5000.2 and the DCP's for milestone reviews are adequately treated in planning and properly reviewed.

A SUCCESSFUL QUANTITATIVE RISK ASSESSMENT TECHNIQUE

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ABSTRACT

In today's competitive environment, industry and the Government have become increasingly aware of the need to assess risk as part of the decision-making process. The probability of achieving the estimate, range of probable deviation, and enumeration of possible causes for overrun must be evaluated before a knowledgeable decision can be made (1, 3, 5, 8).

This paper presents the cost-schedule-technical risk assessment technology being used by Boeing Vertol for the past eight years to evaluate proposed program estimates and the estimates to complete of on-going programs. The complete risk assessment process is described and several useful applications are discussed.

INTRODUCTION

Boeing Vertol is a major manufacturer of helicopters. We are a high technology company, as are most companies within the aerospace industry. The risk assessment methodology presented herein evolved from a need to understand the risk associated with major technical development programs. It has since proved applicable to production programs, smaller research and development contracts, special analyses of technical trade-offs, proposed product warranties, and incentive fee arrangements.

The methodology has been successfully applied to major aircraft programs of other Boeing Companies. At the Boeing Military Aircraft Company in Wichita, Kansas, major B-52 program cost proposals were evaluated, including the Weapons System Trainer development and later the proposed production program; the Offensive Avionics System (OAS) and the Cruise Missile Integration (CMI) Full Scale Development programs; and the initial production programs for OAS/CMI. The C-14 Program cost estimate was thoroughly evaluated for the Boeing Aerospace Company in Seattle, Washington.

It should be noted that many different personnel at both Vertol and other Boeing locations have been able to provide meaningful risk data for these assessments. Thereby

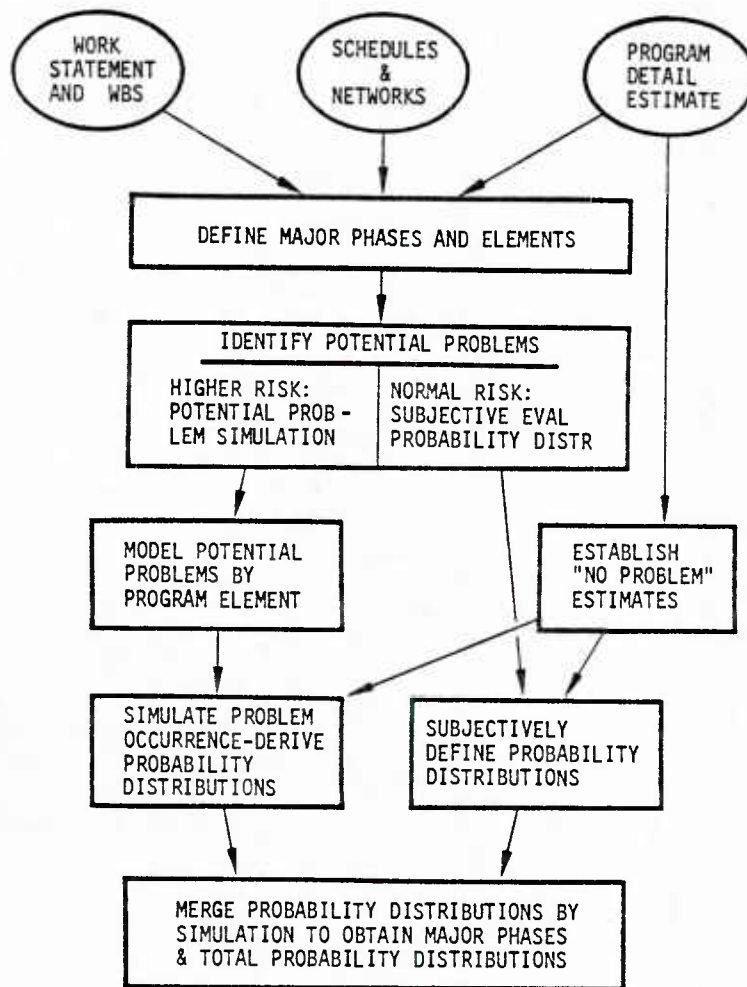
providing some measure of proof regarding the universal application of the Boeing Vertol risk assessment technique. The methodology combines a realistic approach for obtaining relatively unbiased personal judgement data with an innovative computer model that simulates the proposed program expenditures. This methodology is unique because it does not utilize a decision tree or network approach, which in other methods becomes complicated and unrealistic when applied in sufficient detail to obtain a comprehensive analysis.

A basic concept of the methodology is that inherent program risk is primarily attributable to the occurrence of unforeseen problems which are usually technical in nature (1, 8, 11). Cost and probabilistic data, regarding potential problems, are obtained from persons with the appropriate expertise. The computer model simulates the occurrence of these problems to derive probability distributions. These distributions, when combined by simulation with other subjectively defined probability distributions, provide a quantification of program risk. The results of the analysis include risk information regarding potential problems and cumulative probability curves that provide valuable data for company and customer management decision-making. In addition, it serves as the basis for risk reduction activities during the period of contract performance.

METHODOLOGY

Risk assessment is usually performed after the proposed program has been defined. Work statements, work breakdown structure, schedules or networks, and an initial estimate are generally available at this stage of proposal preparation. This program planning and estimating data appears at the top of the Risk Assessment Flow Diagram (Figure 1) for a typical prototype aircraft program. The diagram illustrates the complete assessment process including both the gathering of risk data and utilization of the computer simulation model.

Initially, the proposed program is divided into major phases. These are again subdivided into no more than 20 to 30 program elements to accomplish the analysis in sufficient detail without being "bogged down" by



RISK ASSESSMENT FLOW DIAGRAM

FIGURE 1

over complexity. This permits determination of risk information with the personnel most knowledgeable of the particular elements of the program. Figure 2 provides an example of the major phases and elements for the prototype aircraft program.

Two alternate approaches are utilized to assess the risk in each program element. The first, shown on the left side of Figure 1, employs simulation to evaluate the impact of potential technical problems. This technique is used for analysis of program elements considered to have high risk. The other approach (on the right side of Figure 1) consists of a subjective assessment of probability distributions (9). It is used for

elements with lower risk or when the modeling of potential problems is not feasible. The probability distributions for each program element, developed by either approach, are merged or summed by Monte Carlo simulation (6, 7, 10). The two approaches and the summation process are more fully described in the following paragraphs.

SIMULATION OF POTENTIAL PROBLEMS

This technique is used to assess the higher risk elements of the program (as noted by asterisks in Figure 2). Generally, the risk

PROTOTYPE AIRCRAFT PROGRAM
COST ESTIMATE
(DOLLARS IN MILLIONS)

<u>PHASE I - AIR VEHICLE DESIGN</u>	<u>\$4.0</u>
1. Airframe & Landing Gear	
2. Propulsion & Drive System	
3. Vehicle Subsystems	
4. SAS, Flight Control System	
5. Other Design & Support	
*6. Design Support Tests	
<u>PHASE II - MAJOR SUBCONTRACTOR</u>	<u>\$5.0</u>
7. Wing and Nacelle	
<u>PHASE III - A/C MANUFACTURING</u>	<u>\$9.0</u>
8. Manufacturing/Final Assembly	
9. Tooling	
10. Material	
11. Engineering Liaison	
<u>PHASE IV - SUBSYSTEM TEST</u>	<u>\$3.0</u>
*12. Component Test	
*13. Propulsion System Test	
<u>PHASE V - GROUND & WIND TUNNEL TEST</u>	<u>\$2.0</u>
*14. Ground Tie-Down Test	
*15. Wind Tunnel Test	
<u>PHASE VI - AIRCRAFT FLIGHT TEST</u>	<u>\$3.0</u>
16. Preparation/Instrumentation	
*17. Boeing Flight Test	
18. Customer Flight Test	
<u>PHASE VII - PROJECT MGT. & OTHER</u>	<u>\$2.0</u>
19. Project Management	
20. Data & Documentation	
21. Spares & Miscellaneous	

Total Program Cost \$28.0

*Simulate Impact of Potential Problems

MAJOR PHASES AND ELEMENTS

FIGURE 2

or technical problems surface in the testing elements such as Tool Proving, Bench Test or Operational Test, although the cause of the problems may be attributable to a prior design, analytical, or fabrication element.

The risk analyst asks the engineers and line supervisors to first identify potential technical problems that could occur in these higher

risk elements as shown in Figure 3, Technical Risk Identification. Other data provided includes a judgmental evaluation of the problem probability of occurrence and its average cost/schedule impact. The problem listing is usually organized by subsystem and indicates the program elements where each problem could occur (Source of Discovery). This list gives to program management, a

PROTOTYPE AIRCRAFT PROGRAM DRIVE SYSTEM					
POTENTIAL PROBLEM	SOURCE OF DISCOVERY	PROB'LY OF OCCUR	CONSEQUENCE	IMPACT COST & SCHEDULE	RECOVERY ACTION
TRANSMISSION COOLING IS INADEQUATE	PROPULSION TEST	2%	TRANSMISSION OVERHEAT LIMITS OPERATION	\$48K 2 WKS	CHANGE TO OIL PUMP WITH INCREASED CAPACITY
GEAR CONDITION UNSATISFACTORY AT TEARDOWN INSPECTION	PROPULSION TEST	5%	GEARTOOTH SURFACE DAMAGE (SCUFFING)	\$50K 2 WKS	REVISE LUBE SYSTEM, REGRIND GEARS, AND RETEST
	GROUND TEST	5%		\$75K 8 WKS	
CROSS-SHAFT SUPPORT FAILURE	PROPULSION TEST	2%	LOSS OF CROSS-SHAFT CONTINUITY, LIFT UNBALANCE & CONTROL	\$80K 3 WKS	DESIGN MOD FOR INCREASED STRENGTH, REPAIR & REPLACE COMPONENTS IF REQ'D.
	GROUND TEST	1%		\$200K 8 WKS	
LOW BEARING LIFE	PROPULSION TEST	5%	LOW TRANSMISSION OVERHAUL TOUR	\$20K -	PURCHASE ADD'L SPARES. REVISE INSTALLATION PROCEDURES, LOCK BRG. RACE.
CLUTCH FAILURE	PROPULSION TEST	5%	LOSS OF DRIVE FROM ONE ENGINE	\$28K 1 WK	LUBE SYSTEM REVISIONS
	GROUND TEST	2%		\$75K 3 WKS	
TRANSMISSION MOUNTING LUGS FAILURE	GROUND TEST	1%	INADEQUATE FATIGUE LIFE	\$400K 9 WKS	REDESIGN FOR ADD'L STRENGTH. LAB RETEST & GROUND TEST PARTIAL REPEAT.

TECHNICAL RISK IDENTIFICATION

FIGURE 3

preview of the risk envisioned by line supervision. A thorough review at this point in time can result in redefining some aspects of the program to reduce the risk.

Next, the analyst conducts a potential problem modeling session with the person who identified the problem, to obtain more data. A small (optimistic) and large (pessimistic) cost/schedule impact are determined. This requires a brief one sentence description and basic estimate information for each impact so that a valid cost estimate, including engineering, manufacturing, retest, etc. can be prepared. Also, a relative probability is assigned to each of the three problem impacts, including the previously defined average impact. This data gathering can be accomplished rapidly once the person has experienced an initial modeling session. The work sheet resulting from a typical problem modeling session is provided in Figure 4.

After the problems have been modeled, they are regrouped by source of occurrence and reviewed with the manager of the particular element involved. For example, the Wind Tunnel manager would review the potential problems that could occur during Wind Tunnel Test. He ranks the problems relative to his opinion of their probability of occurrence by sorting the modeling data work sheets.

He then reviews and revises the previously identified probabilities of occurrence, as required. This step is a further check to minimize any bias of the individuals who initially assigned a probability of occurrence to each problem during the identification process. Next, he provides additional risk data by determining the probability that if a problem occurs, it was previously identified. This probability generally ranges from 60% to 85%. An unidentified problem with associated cost/schedule impacts and probabilities is also modeled with the help of the risk analyst.

The last step, in the modeling process, is an evaluation of one of the more important parameters. The supervisor is asked to estimate the most likely number of problems expected to occur during the schedule span of the program element. In making this estimate, he considers the problems encountered on past programs and problems modeled for this particular program and their probability of occurrence. This risk parameter is relatively easy to obtain since the supervisor can relate to "the number of problems that may occur" and therefore, he can feel comfortable in making such a decision. Also, the parameter can be readily reviewed by program management, later, when the analysis results are presented. An example of the Potential Problem Modeling Data for a program element

PROTOTYPE AIRCRAFT PROGRAM

PROBLEM NO. 10 ESTIMATE WORK SHEET PROB'LY OF OCCUR 2%

DESCRIPTION	OPTIMISTIC	AVERAGE	PESSIMISTIC
Drive System Transmission cooling is inadequate.	Inadequate airflow at maximum fan RPM. Change to fan with greater CFM capacity.	Oil delivery rate to cooler precludes optimum cooler performance. Change to pump w/increased capacity. 2 week retest req'd.	Total cooler capacity is inadequate. Req. new cooler and assoc. equipment. 4 week retest req'd.
PROPULSION SYSTEM TEST		(Program continues with operating restrictions)	
Schedule impact to resolve. Relative probability.	1 Week 20%	2 Weeks 40%	5 Weeks 40%
COST IMPACTS			
Engineering	650 HRS \$13,000	1000 HRS \$20,000	1300 HRS \$26,000
Manufacturing	550 HRS \$11,000	900 HRS \$18,000	1400 HRS \$28,000
Material	\$ 5,000	\$10,000	\$40,000
Total Dollars	\$29,000	\$48,000	\$94,000

PROBLEM MODELING WORK SHEET

FIGURE 4

is provided in Figure 5. Note that a "No Problem" estimate prepared by the risk analyst is shown on the third line, right side of the form. To calculate this estimate, the program element estimate is reduced, to "scrub out" the cost attributable to problems inherent in the statistical data which served as the basis for its determination. This is necessary, otherwise the simulation model would add the cost increase due to problem occurrence on top of an estimate which already contains the cost of significant problems.

The Simulation of Potential Problems Flow Diagram presented in Figure 6 depicts the simulation process for a program element. The simulation method employed uses a computer generated random probability, to pick a corresponding value or action from discrete probability distributions formed from the problem modeling data. First, a Poisson probability distribution, based on the most likely number of problems expected to occur over the element schedule span, is tested to see if a problem has occurred. If not, the computer proceeds to the next month and tests again. Assuming a problem is found to have occurred, a choice is made as to whether it is an identified or unidentified problem. If it is "identified", one of the particular identified problems is selected and also one of three possible impacts. If an unidentified problem is selected, one of five possible impacts is chosen. The problem cost impact is added to the "No Problem" Baseline Estimate. The schedule remaining is tested for sufficient time to resolve the problem and

extended as necessary. Finally, the probability of the selected problem impact occurring again is reduced and the computer proceeds to the next month. The model continues to simulate the "real life" of a program element starting with the first month and proceeding month by month to the end of the schedule span. The result is a sample case of cost and schedule information. The probability distributions, required later in the model, are computed by simulating several hundred sample cases for each program element (6, 10).

Of special interest is the initial problem occurrence determination which is accomplished by sampling a Poisson probability distribution (2, 7) to make this monthly selection. The "most likely number of problems expected to occur" during the schedule span is used as the basic parameter to calculate the probability of 0, 1, 2 or 3 problems occurring in any month. Generally, the probability of zero or no problems occurring is quite high and one problem occurring relatively small. Two and three problems occurring generally have very small probabilities. Note that the probability of "3 problems occurring" include the residual probability of 4, 5, ... problems occurring. If the element schedule span lengthens due to simulated problem occurrence, the model "winds down" because the Poisson distribution is recalculated based on the longer span. The probability of no problems occurring becomes even larger and the probability of 1, 2 or 3 problems occurring becomes correspondingly smaller. These features enable

Program: PROTOTYPE AIRCRAFT PROGRAM Phase: PROPULSION SYSTEM TEST
 Expected Problems: 4.0 Schedule in Weeks: 12 Prob'ly Identified Problem: .60
 (Identified: 2.4 & Unidentified: 1.6) "No Problem" Estimate: \$1100.00

No	Problem Description	Prob'ly of Occur	Potential Problem Impact			
			Descr.	Prob'ly	Estimate*	Sched
1	Actuator - False Failure Signals	.20	Opt. Avg. Pess.	.30 .50 .20	50.0 70.0 100.0	1 2 3
2	Engine Overtemp (External)	.10	Opt. Avg. Pess.	.20 .60 .20	20.0 20.0 40.0	1 1 2
3	Engine Fire Extinguisher Inadequate	.10	Opt. Avg. Pess.	.30 .50 .20	20.0 25.0 40.0	1 1 2
4	Nacelle Hinge - Excessive Wear	.05	Opt. Avg. Pess.	.40 .50 .10	49.0 69.0 88.0	2 3 4
5	Engine Inlet Flow Distortion	.05	Opt. Avg. Pess.	.30 .50 .20	25.0 38.0 63.0	2 3 5
6	Gear Condition Unsatisfactory at Teardown Inspection	.05	Opt. Avg. Pess.	.60 .30 .10	36.0 50.0 80.0	1 2 3
7	Low Bearing Life (Drive System)	.05	Opt. Avg. Pess.	.50 .40 .10	10.0 20.0 78.0	0 0 3
8	Clutch Failure	.05	Opt. Avg. Pess.	.30 .60 .10	23.0 28.0 45.0	1 1 1
9	Control System Actuator Chatter	.02	Opt. Avg. Pess.	.20 .60 .20	28.0 33.0 58.0	1 1 1
10	Transmission Cooling Is Inadequate	.02	Opt. Avg. Pess.	.20 .40 .40	29.0 48.0 94.0	1 2 5
Unidentified Problem		Optimistic		.05	30.0	1
		Less Optimistic		.20	60.0	2
		Average		.60	100.0	3
		Less Pess.		.10	250.0	4
		Pessimistic		.05	600.0	6
*Dollars in Thousands						

POTENTIAL PROBLEM MODELING DATA

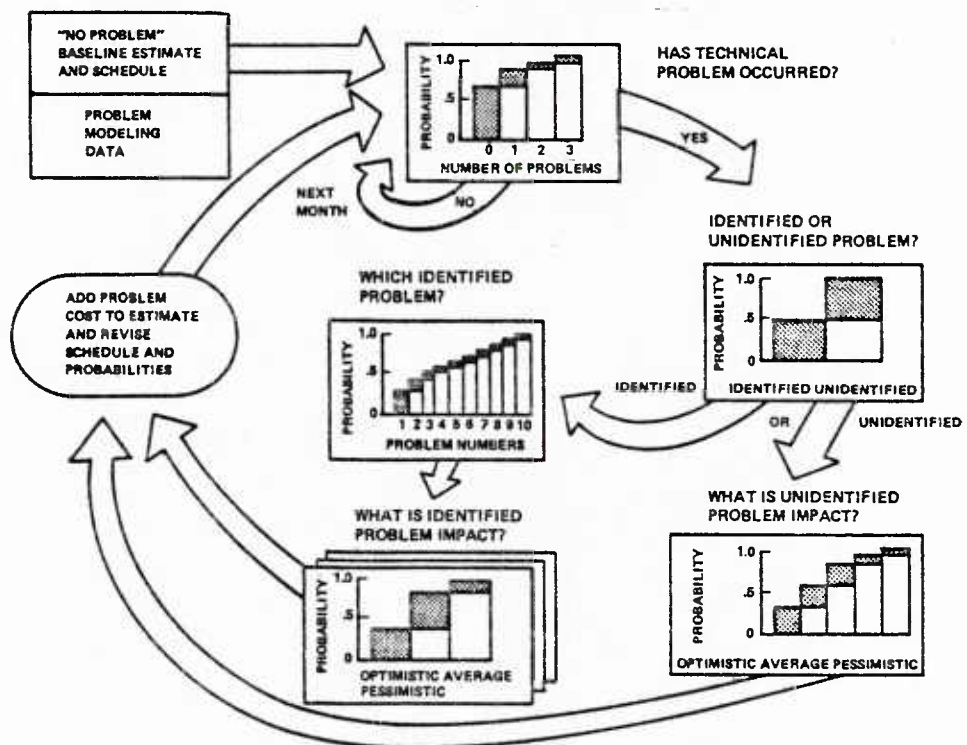
FIGURE 5

the potential problem simulation to essentially duplicate the occurrence of actual problems similar to experience on past programs.

SUBJECTIVE PROBABILITY EVALUATION

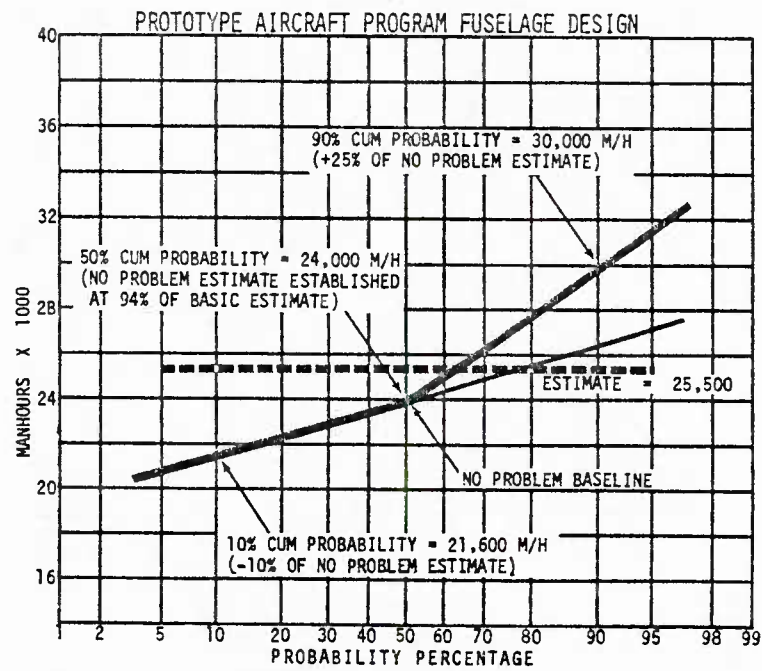
This approach consists of a subjective assessment of probability distributions (9) using Normal probability graph paper as "talking paper" during the information gathering process. It is applied to program elements considered to have moderate risk or where potential problem modeling is not feasible, such as Program Management. Opti-

mistic, most likely, and pessimistic estimates of program elements and associated probabilities are used to construct a probability curve connecting three or more points. These are reviewed for reasonableness by checking such factors as the variation of slope, probability of achieving the estimate, and relationship to past experience. Figure 7 is a probability curve derived by this subjective process. When applicable, an adjustment should be made to the curve to "scrub out" the historical cost impact of problems simulated in other program elements. For example, Manufacturing and Final Assembly (Element No. 8) should be reduced to delete the cost attributable to refabrication of test parts on past programs.



SIMULATION OF POTENTIAL PROBLEMS FLOW DIAGRAM

FIGURE 6



SUBJECTIVE PROBABILITY CURVE

FIGURE 7

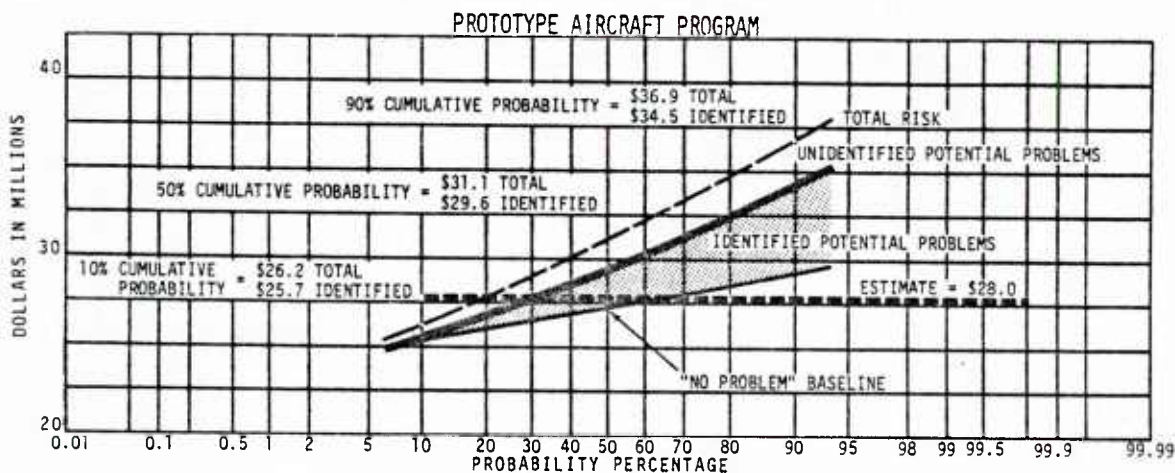
SUMMATION OF PROBABILITY DISTRIBUTIONS

Probability distributions for each program element are derived by either simulating the impact of potential problems or subjectively evaluating probability curves. These distributions are summed by a simulation technique that randomly selects a cost estimate from each element probability curve to form a typical program. Several hundred sample cases are computed to determine a statistically valid probability distribution for each phase and the total program (6, 10). A unique feature of this summation process is the application of a computer generated correction factor to negate the statistical convergence which occurs in accordance with Sampling Theory and the Central Limit Theorem (2, 12). The personnel using their judgement to "model" problems and to determine subjective probability curves do not think in terms of their estimate being a small sample, with the potential for large cost deviations. This is easily demonstrated by dividing a program into twice the number of elements and modeling problems and subjective curves. The summation results will show a considerable reduction in the standard deviation which is not valid. The correction factor restores this loss in risk deviation while still retaining the arithmetic average of the distribution.

EVALUATION OF RISK CURVES

Fundamental to the utilization of risk assessment in the decision process is the evaluation of the resultant cumulative probability distribution curves. An example of these curves for the Prototype Aircraft Program is shown in Figure 8. The three probability curves on the graph show the cumulative impact of potential problems as follows:

- 1) The "no problem" baseline estimate provides a reference for evaluating the cost impact of potential problems.
- 2) The identified risk area defines the range of anticipated cost attributable to the occurrence of the potential problems identified in the information gathering process. It also includes the variation above 50% probability of the subjective distributions relative to a "straight line" cumulative Normal probability distribution.
- 3) The additional impact of the unidentified potential problems is shown by the upper line. This "total risk" probability curve is more subjective than the identified problem curve, due to the lack of precise definition. However, it provides an upward boundary reference of potential program cost if unforeseen problems occur.



PROGRAM RISK PROBABILITY DISTRIBUTION

Interpretation of probability curves is a subjective evaluation based on personal experience. Where one manager considers a 50% probability of achieving the estimate as acceptable, another manager may look at a 75% probability as the lowest to which he can agree. The risk analyst must deal with these personal opinions on an individual basis. Any interpretation should recognize that assuming the program could actually happen several hundred times, the curves provide a picture of the final cost versus cumulative probability of occurrence. The point where the horizontal cost estimate line intersects the curve provides the probability of not overrunning the estimate. Therefore, this probability should be viewed in relation to the slope of the curve. For example, if a high probability, such as the 90% confidence level, indicates a relatively small increase in cost, then the probability of achieving the estimate has less significance. The interpretation being that even if an overrun occurred, it would be very small.

Most cost estimating is based on statistics derived from past programs. The estimates prepared from this statistical data base include an average cost impact of problems that occurred on those programs. The risk analysis, on the other hand, requires a hypothetical "no problem" baseline which was obtained by subjectively "scrubbing out" an average cost for background problems. The risk model then simulates the cost impact of specifically identified problems for a particular program to determine a probability distribution that portrays the cost risk associated with its statement of work. Thus, if the program being estimated is typical of the past programs, with similar expected problems, there should be a 50% probability of achieving the estimate. However, for a program which is not typical of the past history, the probability of achieving the estimated cost may vary significantly from the 50% point.

MANAGEMENT REVIEW AND ACTION

Management review of a risk assessment includes an evaluation of the essential data used in the analysis and probability curves for the total program and major phases. The data evaluated consists of:

- o Definition of program phases, elements and associated cost estimates (Figure 2). Presents how the analysis was organized and provides the base estimates.
- o Listing of potential problems identified and modeled for the analysis (Figure 3). Provides visibility as to what is causing

the risk and where risk reduction activities could be effectively applied.

- o Cumulative probability curves (Figure 8) which display the probability of achieving the estimated cost and the range of probable deviation. Enables management to understand the extent of possible overruns for the total program and specific phases.

This review can result in follow-up actions. For example, if a later phase such as Flight Test indicates an excessively high risk, then consideration is given to performing additional laboratory and wind tunnel tests earlier in the program to surface problems in sufficient time to resolve them at a lower cost and with minimum schedule delay. Another example is high risk in a phase primarily derived from subjectively defined probability curves, such as Manufacturing. This could be an indication that the base estimate is too low and should be revised.

The total program probability curve can be used in determining the final cost estimate for a Government contract. This decision must be made within the context of the competitive situation, type of contract (e.g., cost vs. fixed price), and compliance with Government regulations. If the probability of achieving the estimate was only 40%, the 90% confidence estimate was not excessively high, and the proposed contract will be an incentive fee cost type, then the estimate could be considered as an acceptable risk in a highly competitive environment. On the other hand, for fixed price quotations and commercial proposals, the cost estimate is normally expected to have a higher than 50% confidence of being achieved. Thus, risk assessment makes a significant contribution to pricing strategy and the ultimate bid price decision.

INCENTIVE FEE STRATEGY

Risk analysis probability curves can provide substantiation for proposing incentive fee arrangements (13). Figure 9 is an example of how the Prototype Aircraft Program probability curve (Figure 8) can be used to establish the target cost, and the cost values at minimum/maximum fee limits. Assume it was decided to propose a cost of \$30 million and a fee of 11% (\$3.3 million) for the target cost. The 10%/90% cumulative probability values of the Total Risk Curve in Figure 8 which are \$26 million and \$37 million respectively, are used to define the fee sharing limits. The maximum fee of 15% and minimum fee of 4% relative to these corresponding cost values determine an incentive

PROTOTYPE AIRCRAFT PROGRAM (DOLLARS IN MILLIONS)

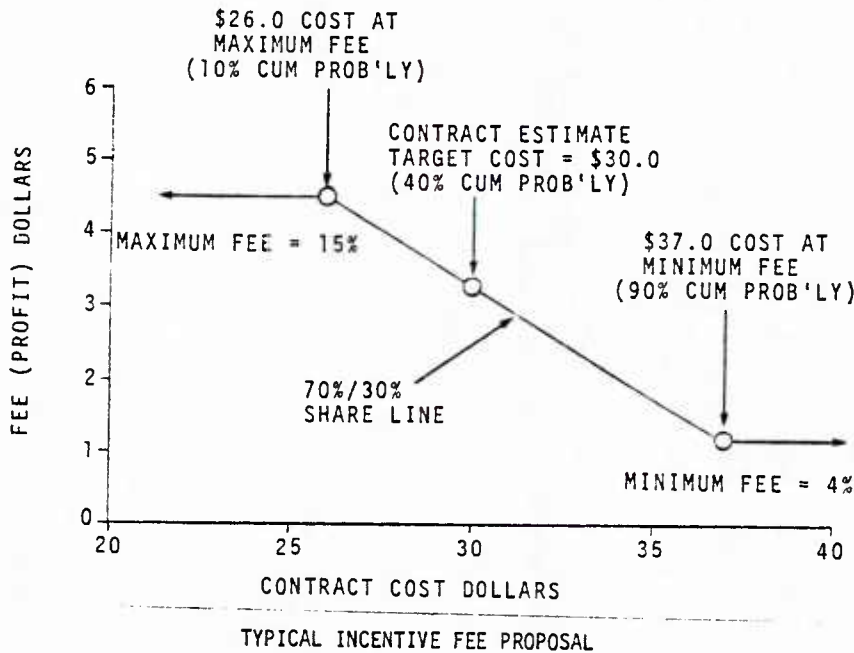


FIGURE 9

share line of 70%/30% (customer/contractor). For example, if the actual contract cost turns out to be \$29 million, then the customer saved \$1 million in cost and pays \$3 million of this saving to the contractor as incentive fee for underrunning the contract cost. The important feature of relating the incentive fee share line to the risk probability distribution is that the probability of earning various fee (profit) dollars can be readily determined. Thus, the program risk assessment curve provides assistance in establishing the strategy for the proposed incentive fee arrangement and subsequent negotiations.

described, yields the required cost probability distributions. This risk data aids in developing the final company position.

Another use of risk analysis is to augment the decision data for technical trade-off analysis of alternative configurations and designs. This is usually limited to major "trade-offs", such as choosing between alternative rotor blade designs. In these evaluations, technical considerations are very important. However, risk analysis gives insight into the technical problems that could occur and provides another dimension to evaluating the cost estimates.

SPECIAL USE ANALYSES

Risk assessment is useful in establishing product warranties for high value and/or safety of flight components. These warranties usually relate to the reliability and maintainability of dynamic components (e.g., rotor blades, transmissions, actuators, etc.). Since the occurrence of technical problems is the cause of failing to meet a warrantee, the simulation of these potential problems using the methodology previously

RISK REDUCTION

Risk reduction is a continuing activity. The problems identified during the preparation of a proposal risk analysis enables management to revise program requirements and schedules to reduce potential risk. Fallback positions are formulated to minimize the impact of the problems. The probability data and curves are used to compare the cost of added testing to the resultant reduction in risk.

POTENTIAL PROBLEM	PROB'LY OF OCCURRENCE	AVERAGE IMPACT		
		DESCRIPTION	SCHEDULE	COST
CAR BODY INADEQUATE CAR BODY STIFFNESS	5% 3%	CAR BODY NATURAL MODES IN AN UNDESIRABLE FREQUENCY RANGE, EXCESSIVE DEFLEC- TION UNDER LOAD OR UNACCEPTABLE VIBRATION LEVELS	2 MONTHS	\$250K

RISK AVOIDANCE ACTIVITIES:

- o CAR BODY SUBCONTRACTOR WILL TEST DESIGN ON "PRE-PRODUCTION" SHELL. THEY'RE DOING DETAIL DESIGN. BOEING VERTOL TECHNICAL EXPERTISE IS HIGH IN THIS AREA. PROJECT ENGINEER IS A DYNAMICIST. JUNE
- o HAVE HIRED ENGINEER WHO IS NOW IN RESIDENCE AT CAR BODY SUBCONTRACTOR. JULY
- o INITIAL TESTS ON "A" SECTION (SEPT.) PRE-PRODUCTION CAR SHELL VERY SUCCESSFUL WITH ONLY SLIGHT BUCKLING; EASILY REINFORCED. CONFIDENCE MUCH HIGHER FOR SUCCESSFUL PRODUCTION TESTS. (TESTS WERE TO 90% LOAD) SEPTEMBER
- o BASED UPON CAR "A" SECTION INITIAL TESTS, PROBABILITY OF OCCURRENCE REDUCED TO 3% BY JOE BLANK. OCTOBER
- o PRODUCTION SQUEEZE TESTS SET FOR FEBRUARY IN NEW FIXTURE DECEMBER

RISK AVOIDANCE ACTION

FIGURE 10

Once the contract has been received, the potential problems can be monitored periodically. Figure 10 presents a typical format used on a previous program for this purpose. Note that as the risk avoidance actions were recorded chronologically, the probability of occurrence was subsequently reduced. As the program progresses, cost estimates for the remaining work are prepared. The risk analysis is updated when these estimates indicate a significant increase in cost or after a phase of the program has been completed (e.g., Design Completion). Problems that occurred and were resolved are eliminated. Problems that did not occur in already completed program phases are also deleted. The probability of problem occurrence might be revised. New problems may be identified. These "estimate to complete" risk analyses provide much greater visibility into program status than "single point" estimates.

The most important aspect of risk analysis and avoidance activities is the attitude of risk awareness that is created. Although too intangible to evaluate quantitatively, risk awareness soon permeates throughout the organization. The result is threefold; it reduces the time to conduct an analysis, it improves accuracy and more importantly, it has a definite benefit in actions to reduce risk.

RISK ASSESSMENT VALIDATION

Validation of risk assessments can be determined by comparative evaluation, although precise measurement is difficult since a single program "at completion" cost is being compared to a probability distribution with a continuum of cost values. Certainly if the "at completion" cost exceeds the 100% probability value, which is hardly ever the case, it was a poor risk assessment. In addition, pricing strategy, contract terms, success (or failure) in negotiating cost targets for the initial contract and/or contract changes, and excessive inflation impact, are some of the factors that must be considered in the evaluation. Further, the number of programs to be studied is limited to completed contracts and therefore excludes unsuccessful proposals and incomplete contracts. However, because eight years have elapsed since the Vertol risk assessment technique was first applied, sufficient programs are now available for a comparative evaluation.

Seven programs were studied, including major development, research, and modification programs; aerospace and non-aerospace diversification programs; and a new technical concept research and development program. The comparison was made relative to number, type, and severity of actual problems versus

potential problems identified in the risk assessment, and final "at completion" cost versus the predicted probability distribution. Results of this comparison, except for the non-aerospace diversification, indicated a consistent relationship of incurred program cost to the risk described in the original assessment as portrayed by potential problem identification and cost probability distributions. The non-aerospace diversification analysis proved that to achieve desired risk assessment results, the personnel providing the risk data must have sufficient experience and expertise in the product industry. An example of the aerospace applications was the first major program evaluated, which had an excellent correlation with the risk assessment. The actual number of problems was within 14% of the number projected. The ratio of identified versus unidentified problems that occurred, varied by only 5% from the prediction. The completion cost was equivalent to 50% probability on the risk curve. These program comparisons have provided reasonable substantiation that the Boeing Vertol risk assessment technique has been successful in quantitatively predicting program risk.

CONCLUSIONS

Successful utilization of risk assessment at Boeing-Vertol is attributable to the method by which the three essential elements of the technology are accomplished.

- 1) Risk Input Data - A minimum of easily obtainable and reliable risk information is required for the model. The primary data is formulated using potential technical problems that are relevant to the engineers and line supervisors. This

enables them to provide reliable probabilistic data. The most important parameter is couched in non-probabilistic terms (most likely number of problems to occur) to make it more meaningful. The problem risk data is first reviewed in detail by the element supervisor and later by management. Therefore, the subjective information is not only reasonable to obtain but is relatively unbiased.

- 2) Computer Model - The model realistically simulates the occurrence of risk for the proposed program. The problem simulation portion of the computer model duplicates the "real life" of the high risk program elements by increasing the cost and allowing the schedule to slip as problems occur, while still completing the program within a realistic time period. The correction factor applied by the model during the summation of probability curves, properly retains total program risk by negating statistical convergence.
- 3) Management Acceptance - The assessment results are readily amenable to review by company and customer management. The risk assessment provides comprehensive visibility relative to the probability of achieving the cost estimate, the range of possible deviation, and insight into the causes of increased risk. This assessment data has been proven accurate by eight years of experience. Therefore the risk information is accepted by management and utilized with confidence.

The Boeing Vertol quantitative risk assessment technique has proven to be a uniquely successful predictor of problem risk.

BIBLIOGRAPHY

1. N.R. Augustine, Assistant Secretary of the Army (Research and Development), RDT&E Cost Realism - Future Development Programs, Memorandum for the Director of the Army Staff, July 12, 1974.
2. R.C. Clelland, J.S. de Cani, F.E. Brown, J.P. Bursk, D.S. Murray, Business Statistics With Business Applications, New York, 1966, John Wiley & Sons.
3. J.M. Cockerham, Army RDTE Funding, Planning & Management "Total Risk Assessing Cost Estimate (TRACE)" Concept, Army Research, Development & Acquisition Magazine, July - August 1979, 24-26.
4. J.D. Cooper, The Art of Decision - Making, Garden City, N.Y., 1961, Doubleday & Company Inc.
5. Department of Defense Directive 5000.1, Acquisition of Major Defense Systems, DDR&E, July 13, 1971.
6. G.S. Fishman, Concepts and Methods in Discrete Event Digital Simulation, New York, 1973, John Wiley & Sons.
7. G.J. Hahn, S.S. Shapiro, Statistical Methods in Engineering, New York, 1967, John Wiley & Sons.
8. Col. R.R. Lockry, Lt. Col. R.D. Hensley, Lt. Col. P. Flammer, Lt. Col. D.R. Smith, Maj. R.G. Head, Maj. E.M. Henry, Maj. W.R. Hodson III, Maj. E.B. Nelson, Capt. G.G. Carson, Capt. J.F. Guilmartin, Final Report of the USAF Academy Risk Analysis Study Team, United States Air Force Academy, August 1, 1971.
9. W.T. Morris, Engineering Economy, The Analysis of Management Decisions, Homewood, Ill. 1960, R.D. Irwin Co.
10. T.H. Naylor, J. L. Balintfy, D.S. Burdick, K. Chu, Computer Simulation Techniques, New York, John Wiley & Sons.
11. J. Peck, F.M. Scherer, The Weapons Acquisition Process: An Economic Analysis, Boston, 1962, Division of Research, School of Business Administration, Harvard University.
12. K. Sasaki, Statistics for Modern Business Decision Making, Belmont, Cal. 1968, Wadsworth Publishing Co.
13. F.M. Scherer, The Weapons Acquisition Process: Economic Incentives, Boston 1964, Division of Research, School of Business Administration, Harvard University.
14. R. Schlaifer, Probability and Statistics for Business Decisions; An Introduction to Managerial Economics Under Uncertainty, New York, 1959, McGraw-Hill Book Co.

IMPROVING CONDITIONAL PROBABILITY ASSESSMENT FOR FORECASTING AND
DECISION MAKING IN WEAPONS SYSTEMS ACQUISITION

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ABSTRACT

The assessment of the conditional probabilities of events is useful and needed for forecasting, planning, and decision making, as for example, in the weapons system acquisition process. The difficulties associated with the assessment of these conditional probabilities are examined. The necessary and sufficient conditions that the elicited information on conditional probabilities must satisfy are evaluated against actual assessments in several different controlled settings. A high frequency of implicit violations of the probability calculus was observed. The consistency of the assessments are affected by the causal/diagnostic and positive/negative relationship of the events. Use of a judgmental aid in the form of a joint probability table reduces the number of inconsistent responses significantly. Using the probability axioms, it is also shown that only first order conditional probabilities need be assessed, as such higher order probabilities are robust to the unconditional and first order conditional assessments.

INTRODUCTION

Conditional probabilities are basic input to many important decision models that are used to analyze decisions under uncertainty in both the private and public sectors. These models include decision analysis (e.g., [9], [15]), cross-impact analysis (e.g., [3], [4], [10]), long term probabilistic forecasting [1], [7] fault tree analysis [2], [6], and several other applications of statistical decision theory. Often, if not usually, the conditional probability of an event A given that some other event B is known to have occurred, $p(A|B)$, can only be assessed subjectively by an "expert". The assessment of $p(A|B)$ is intricate and subtle. While there are numerous experimental and field studies concerned with the assessment of marginal event probabilities (e.g., [1], [8], [9]), there has been little attention paid to the elicitation of conditional probabilities.

The elicitation of conditional probabilities poses additional problems that are not encountered in the assessment of marginal probabilities alone. We demonstrate some of the resulting difficulties that are likely to be encountered in the elicitation of conditional probability assessments and suggest ways to improve the assessment procedure. The difficulties involve the implicit violation of the probability calculus and unmeaningfulness of the assessments manifested in terms of their informativeness. These difficulties are shown to be affected by the causal versus diagnostic, and positive versus negative relationship of the events assessed. We also show that employment of a joint probability table (JPT) as a judgmental aid in policing assessments improves their consistency and meaningfulness and mitigates the influence of the causal/diagnostic nature of the events on the assessments. Moreover, the bounding of second and higher order conditional probabilities (e.g., $p(A|B \cap C)$, $p(A|B \cap C \cap D)$) reduces considerably the number and complexity of the conditional assessments to be made to only first order conditional assessments, $p(A|B)$. The implications of the results reported should be useful to the decision analyst, policy analyst, and planner in obtaining valid and meaningful probabilistic input from experts for development and implementation of forecasting and decision models, such as in weapon system acquisition.

Our principal thesis is that experts' responses on first order conditional probabilities alone, $p(A|B)$ (the simplest kind of conditional probability assessment), are often inconsistent with the simple axioms of probability. These violations are not simply ϵ -level errors that are expected in any subjective elicitation, but are errors of considerable magnitude that result from systematic perceptual and cognitive biases in experts' responses. Moreover, even statistically mature experts are highly susceptible to these errors. The interested reader should note that this study has a somewhat different objective than the widely debated phenomena that the subjects do not revise their prior probabilities according to Bayes' rule (e.g., [5], [18], [15 pp. 20-21]). In our work

conditional probability is a basic measurement that cannot be computed and has to be elicited from the subject. In order to convince the reader about the seriousness of these violations and provide motivation for our detailed experimental investigations, in the following section we report some representative difficulties that were encountered in assessing conditional probabilities in an actual policy setting. We then report on several controlled experiments involving management students and business executives to (1) further illuminate the difficulties experienced in assessing conditional probabilities, (2) better understand the assessment process and several factors which affect it, and (3) evaluate the value of the JPT as a judgment aid.

PROTOTYPICAL EXAMPLES OF INCONSISTENT ASSESSMENTS

In a study to determine market penetration of solar electric energy by the year 2000 several experts from governmental agencies, research laboratories, and utility companies were interviewed to assess the likelihoods of future scenarios [17]. Several events that comprise a future energy scenario, such as restrictions on oil-fired capacity, nuclear slowdown, tighter air quality standards, commercial acceptance, etc., were identified. Since these events are interdependent, the marginal and the conditional probabilities of occurrence of these events were required as an input to the computation of the scenario probabilities. Below we provide some of the responses of some experts. It should be noted that for expositional simplicity we are using the abbreviated description of each event. In the actual application these events were precisely defined.

Response Set 1:

$p(\text{restrictions on oil fired capacity}) = .9$
 $p(\text{conservation}) = .5$
 $p(\text{conservation} | \text{restrictions on oil fired capacity}) = .7?$

Response Set 2:

$p(\text{nuclear slowdown}) = .3$
 $p(\text{restrictions on oil fired capacity}) = .9$
 $p(\text{restrictions on oil fired capacity} | \text{nuclear slowdown}) = .6?$

Response Set 3:

$p(\text{incentives to solar energy}) = .6$
 $p(\text{commercial acceptance of solar energy}) = .2$
 $p(\text{commercial acceptance} | \text{incentives}) = .3$
 $p(\text{incentives} | \text{commercial acceptance}) = .5?$

Each of the conditional probability responses (question mark above) is inconsistent with some probability axioms as will be shown later. However, even many decision analysts, management scientists, and statisticians agree that the above responses seem reasonable. It is only after careful analysis and introspection that the implicit inconsistencies become obvious.

In the next section the necessary and sufficient conditions that the elicited conditional probability must satisfy are given.

NECESSARY AND SUFFICIENT CONDITIONS

Suppose A and B are two events of interest and the marginal probabilities $p(A)$ and $p(B)$ have been assessed. The necessary and sufficient conditions that a conditional probability, such as $p(B|A)$, must satisfy in order to be consistent with the probability axioms are as follows:

$$p(B|A) \leq 1 \quad (1)$$

$$p(B|A) \leq \frac{p(B)}{p(A)} \quad (2)$$

$$p(B|A) \geq \frac{p(B) + p(A) - 1}{p(A)} \quad (3)$$

$$p(B|A) \geq 0 \quad (4)$$

If in addition to $p(B|A)$, the conditional probability $p(A|B)$ is also assessed then these two must be related.

$$\frac{p(B|A)}{p(B)} = \frac{p(A|B)}{p(A)} \quad (5)$$

Thus, if $p(B|A) > p(B)$, then $p(A|B) > p(A)$. This directional consistency is obviously necessary to satisfy condition (5).

Consider the prototypical responses of the experts given in section 2. In response 1 condition (2) is violated. An implication of this violation is that $p(\text{restrictions on oil fired capacity} | \text{conservation})$ would be greater than 1. In response 2 condition (3) is violated. In response 3 conditions (1) - (4) are satisfied but condition (5) is violated. Although it is reasonable to expect that the equality in condition (5) may not be exactly satisfied in a subjective assessment, response 3 represents a more serious violation since even the direction of probability revision is inconsistent.

In order to explore the nature and causes of these violations several detailed controlled experimental studies were undertaken, some of which are described below. These studies dealt only with the assessment of pairwise (first order) conditional probabilities $p(A|B)$. The problems associated with the more complex assessment of higher ordered conditional probabilities, e.g., $p(A|B \cap C)$ is reserved for a later section of the paper.

EMPIRICAL INVESTIGATION

4.1 Experiment I: Credit Scoring of Loan Applications

This experiment had the following three objectives: (1) to examine the difficulties in assessing conditional probabilities in terms of the frequency of consistency violations

of the probability calculus; (2) to attempt to understand the effect of the causal/diagnostic and positive/negative relationships of the events on the conditional probability assessments and the frequency of violations; (3) to evaluate the use of the JPT as a judgmental aid to assist the assessor in policing his conditional judgments for consistency and meaningfulness.

4.11 Instrument and Task

The experimental instrument involved a case study in which each subject assumed the role of a bank lending officer. Given the base rate probabilities of delinquency, $p(D)$, and the probability of having either a bad or good credit rating, $p(B)$ or $p(G)$ respectively, individuals assessed the conditional probabilities $p(D|B)$, $p(B|D)$, and $p(D|G)$. The sets of specific values for $p(D)$, $p(B)$, and $p(G)$ provided to subject are given in Table 1. The instrument and task have been shown to possess a variety of properties that make it well suited for systematically investigating human probabilistic information processing behavior, while providing a high degree of subject interest and involvement [1], [12], [13].

Table 1

Subjects were undergraduate upper division general management students enrolled in a course in managerial statistics at the Krannert School of Management at Purdue University. The subjects had knowledge of probability and the concept of a joint probability table at the time they participated in the experiment.

After reading the situational scenario, subjects first specified their perceptions of the strength of the relationships between a credit rating and delinquency on a 5-point scale from very weak to very strong. Then, given $p(D)$ and either $p(B)$ or $p(G)$, they intuitively assessed conditional probabilities such as $p(D|B)$, $p(B|D)$, and $p(D|G)$ for 15 questions partitioned into five groupings. They next specified how they arrived at their assessments. Then given a JPT with the marginal event probabilities included, they reassessed several of the previous questions. Finally, they rated the JPT as an assessment aid on a 7-point scale from not very helpful to very helpful, described how the JPT helped, and indicated in what way the table aided them in revising their responses.

4.12 Consistency Violations

Group 1 and Group 4 questions were designed to test the consistency with respect to conditions (2) and (3) respectively. Out of 118 subjects, 14 assumed that the events delinquency and bad credit rating are statistically independent. The results reported are for 104 subjects who considered credit rating to have some impact on delinquency. In Table 2, the consistency bounds using conditions (1) - (4) are given and the number of violations observed for each of the six questions in Groups 1 and 4 are reported. It is clear from Table 2 that a large number of violations were observed. Further, 98 subjects out of 104 gave inconsistent responses on at least one out of these six questions.

Table 2

In group 1 questions, the evidence of bad credit rating enhances the likelihood of delinquency. A possible cause of violation of condition (2), may be that the subjects ignore the base rate frequency of the event bad credit rating in revising the probability of delinquency. As the base rate frequency of bad credit rating increases, the revision in the probability of delinquency should be smaller.

In group 4 questions, the evidence of good credit rating diminishes the probability of delinquency. Here again, the subjects seem to ignore base rate frequencies of $p(D)$ and $p(G)$ in a downward revision of the probability of delinquency.

The questions in group 2 involved specification of $p(B|D)$. A comparison of the responses for group 2 and group 1 questions revealed that the subjects violated directional consistency. To satisfy directional consistency, $p(B|D)$ should be greater than $p(B)$ since $p(D|B)$ is greater than $p(D)$. The number of violations are given below:

	$p(D B) > p(D)$		
	Q1	Q2	Q3
$p(B D) < p(B)$	Q4	33	
	Q5	41	
	Q6		58

Notice that in questions 4 to 6, violation of conditions (1) - (4) cannot occur since the bounds are 0-1. It was further observed that a large number of subjects had no consistent pattern for revision as the base rate frequency of bad credit rating was increased. Intuitively, as $p(B)$ increases the informativeness of event B decreases and therefore the relative increase in $p(D|B)$ should be small. In the limiting case when $p(B) = 1$, $p(D|B) = p(D)$. This lack of pattern in the direction of

revision was also observed for group 3 questions in which $p(D) = .5$. This suggests that before an analyst elicits detailed assessments, it would be worthwhile to discuss with the expert the qualitative impact of evidence on the event for which the conditional probability is being assessed.

4.13 Meaningfulness Violations

Assessments that are not meaningful are defined as ones that either imply that two events, say D and B , are statistically independent or uninformative (when they should not be), or whose imputed informativeness is contrary to the data (i.e., in a direction counter to the direction of revision implied by the data, assuming no "gaming", which was verified to be the case in this experiment).

a. Statistical independence. In this experiment, for example, a statistically independent response would imply that there is no relationship between the credit rating and the delinquency or non-delinquency of the loan applicant, i.e., the likelihood ratio

$$L_1 = \frac{p(B|D)}{p(B|ND)} = 1, L_2 = \frac{p(G|ND)}{p(G|D)} = 1;$$

or equivalently, e.g., $p(D|B) = p(D)$, $p(B|D) = p(B)$.

b. Imputed informativeness. In this experiment, responses that are contrary to the data result in assessments which reduce the probability of delinquency given a bad credit rating, and enhance the probability of delinquency given a good credit rating, from the prior probability of delinquency. This is manifested by implied likelihood ratios of $L_1 = p(B|D)/p(B|ND) < 1$ and $L_2 = p(G|ND)/p(G|D) < 1$. Disregarding "gaming" (e.g., disbelieving the data provided), such responses presumably result from the difficulty of making conditional assessments, due to the complex interactions involved as manifested by conditions (1) - (4). More precisely, the conditions for a meaningful response in this sense, can be derived from the following relationship, which is the odds representation of Bayes' Theorem; e.g.,

$$\frac{p(D|G)}{p(ND|B)} = \frac{p(D)}{p(ND)} \cdot \frac{p(B|D)}{p(B|ND)}.$$

Hence, if $\frac{p(D|B)}{p(ND|B)} > \frac{p(D)}{p(ND)}$ (or, more simply, if

$$\frac{p(D|B)}{p(B|D)} > \frac{p(D)}{p(B)}, \text{ then the likelihood ratio } \frac{p(B|D)}{p(B|ND)} > 1.$$

Out of 118 responses per question (including the 14 discarded subjects who responded statistically independent to most questions), the mean number of statistically independent responses per question was 29.4 (= 25%)

(Table 3a). In terms of imputed informativeness the probability of a consistent and meaningful response is about 0.4 (Table 3b). Alternately stated, the average number of such responses per question was only 35.6 (= $.4 \times 535 \div 6$) or 30% (= $.4 \times 535 \div 708$) for questions 1 - 3 and 7 - 9; 38.1 (= $.44 \times 260 \div 3$) or 32.0% (= $.44 \times 260 \div 354$) for questions 4 - 6; and 34.7 (= $.39 \times 534 \div 6$) or 0.29% (= $.39 \times 534 \div 708$) for questions 10 - 15.

Table 3

4.14 Factors Influencing Assessments

The conditional probability $p(D|B)$, can be interpreted as a revision in $p(D)$ given the evidence on the occurrence of the event B . If the relationship between D and B is perceived to be strong, a greater revision is expected. Two factors which may effect the perceived strength of the relationship between D and B are the causal versus diagnostic and the positive (confirming) versus negative (disconfirming) relationship of these events.

Causal versus diagnostic. Tversky and Kahneman [20] call the relationship between D and B causal if, in assessing $p(D|B)$, B is perceived as a cause of the occurrence or non-occurrence of D . For example, in our experimental setting, where the event of interest is delinquency D , if the event B is a bad credit rating then the event B is a causal datum. Conversely, the event B is called a diagnostic datum if, D is perceived as the cause of B .

Tversky and Kahneman [20] found that individuals perceive a causal relation as more informative than a diagnostic relation. In the context of our experiment this, for example, implies that

If $B \rightarrow D$ and $p(D) = C p(B)$, then $p(D|B) > C p(B|D)$;

where " $\rightarrow$ " denotes the direction of causality, C is a constant, and $p(D|B)$ and $p(B|D)$ are assessed directly. The setting of our case study clearly implies that the event B is a causal datum. If a causal relation is perceived more informative then, for example, if in question 1 a subject responds $p(D|B) = .2$ then he should respond $p(B|D) < .6$. In other words the value of $p(D|B)$ computed from $p(B|D)$ should be smaller than the assessed value. This indeed was the case in our experiment as 255 out of 312 responses showed that a causal relation caused a greater revision in conditional probability than a diagnostic relation.

Q.	$p(D B) > C p(B D)$	$p(D B) < C p(B D)$
Q1 V/S Q4	84	8
Q2 V/S Q5	91	2
Q3 V/S Q6	80	7

Q.	$p(D B)=C$	$p(B D)$
Q1 V/S Q4	12	
Q2 V/S Q5	11	
Q3 V/S Q6	17	

The above table shows that the magnitude of the assessed $p(D|B)$ was consistently greater than that imputed from $p(B|D)$. The causal relationship thus led to more substantive revisions, and therefore higher conditional probability assignments than the diagnostic relationship. Theoretically, there should be no difference.

This was further substantiated in a separate experiment in which 36 different management students assessed $p(D|B)$ and $p(B|D)$ on three questions, given the same probabilities of .2, .5, and .8 for $p(D)$ and $p(B)$. In this case, the assessments could be compared directly since $p(D|B)$ should be equal to $p(B|D)$. It was found that more than twice as many of the responses indicated $p(D|B) > p(B|D)$ than $p(D|B) < p(B|D)$.²

A causal relation leads to a more substantive revision in conditional probability. Thus, with a causal relationship, more violations than expected may occur. Individuals, however, find it easier to assess $p(D|B)$ if B is causal and have more confidence in their assessments [20]. This could represent a paradox for an analyst since a more "meaningful" assessment may also give more inconsistencies. This observation further strengthens our argument for the use of an assessment aid such as a JPT.

Positive versus negative. A positive (negative) relationship between events B and D implies that knowledge of B occurring should increase (decrease) the probability of D occurring. Individuals may, however, perceive a positive relation as more informative than a negative relation [11], [12], [13]. In our experiment this, for example, implies that

$$p(D|B) > \frac{p(D) - p(D|G) \cdot p(G)}{p(B)}$$

where G denotes a good credit rating, and $p(D|B)$ and $p(D|G)$ are directly assessed by an individual. Again, this would imply that a positive relation between events would lead to more violations.

As shown in Table 4 the value of $p(D|B)$ was also consistently greater than that imputed from $p(D|G)$. A positive relationship between events thus also appeared to be more informative than a negative relationship. This too was further corroborated in another experiment in which 17 business executives in a forecasting seminar assessed $p(D|B)$ and $p(D|G)$, given probabilities on $p(D)$ of .2, .5, and .8 and a probability of .5 on $p(B)$ and $p(G)$.

Table 4

4.15 JPT as an Assessment Aid

The reduction in consistency violations resulting from using a JPT as an assessment aid are shown in Table 5. There was a marked improvement in consistency. The overall frequency of violations of conditions (1) - (4) was reduced from 62% to 15%. Directional violations were also markedly reduced. Before using the JPT, 58 subjects had specified $p(D|B) > p(D)$ and $p(B|D) < p(B)$. But, after using the JPT only 5 subjects violated directional consistency, almost a 12-fold improvement.

In terms of meaningfulness, the average number of statistically independent responses per question was reduced only slightly from 29 (= 24.6% of all responses) to 24.6 (= 20.8%). In fact, it was just as likely for an individual to switch from an independent to a non-independent response with the use of the JPT, as conversely. Thus, the JPT had little effect on reducing the number of such responses. However, the frequency of meaningful responses in terms of imputed informativeness (which was also consistent with conditions (1) - (4)) was increased from 19.6 (= 11.6% of all responses) to 52.8 (= 44.7%) per question, a 270% improvement. The value of the JPT is further highlighted by about a 7-fold increase in the number of individuals whose responses obeyed all consistency and meaningfulness conditions (e.g., in questions 3 and 6 the increase was from 9 to 66).

The causality/diagnosticity effect was also mitigated significantly by the use of the JPT. To illustrate, before using the JPT, out of 104 responses to questions 3 and 6, 80 responded $p(D|B) > C p(B|D)$, 7 responded $p(D|B) < C p(B|D)$, and 17 responded $p(D|B) = C p(B|D)$. Using the JPT, 14 responded $p(D|B) > C p(B|D)$, 6 responded $p(D|B) < C p(B|D)$, and 84 responded $p(D|B) = C p(B|D)$. A large number of subjects indicated that they found the JPT to be a helpful assessment aid.

Table 5

4.2 Experiment II: Lincoln Securities Analysts, Inc.

This experiment differed from the previous one in the following respect: (1) the context involved an actual problem situation; (2) both marginal as well as conditional probabilities were assessed. The objective was to determine if there were differences in the results between this experiment and the previous one, due to the problem situation and assessing the marginal events as opposed to having them provided.

The task was to predict the following events:

1. The likelihood that the Dow Jones Industrial Index (DJI) as of July 1, 1979 would be in a specified range, i.e., $p(\text{DJI} < 800)$, $p(800 \leq \text{DJI} < 900)$, $p(\text{DJI} \geq 900)$.
2. The likelihood that real GNP growth for the first 6 months of 1979 would have the rate of growth specified, i.e., $p(\text{GNP} < 2\%)$, $p(2\% \leq \text{GNP} < 4\%)$, $p(4\% \leq \text{GNP} < 6\%)$, $p(\text{GNP} \geq 6\%)$.
3. The likelihood that the DJI as of July 1, 1979 would be in a specified range given real GNP growth for the first 6 months of 1979 would have the specified rate of growth.

In certain cases, the likelihood that GNP growth would have the rate of growth specified given the DJI would be in a specified range was also assessed.

Eighty-nine management students participated. Of these, 40 were discarded -- 3 did not have their various event probabilities sum to 1, although instructed to do so; 8 gave probability responses that were > 1 or < 0 ; 29 gave conditional probability responses that were strictly independent.

Results

The frequency of consistency violations was less in this experiment than in the previous one, because the marginal probabilities assessed by subjects often resulted in loose consistency bounds for the conditional probabilities (contrary to the previous experiment, a separate bound existed for each individual based on his marginal probability assessments).

Use of the JPT reduced the frequency of violations in half, from 40 to 20 out of 196 responses examined. Directional violations were also reduced significantly. The frequency of meaningful responses increased from 34% to 51%. The JPT had little effect on altering individuals' marginal probability assessments, as reflected below:

	Changed Marginals		
	Yes	No	
Changed			
Conditionals			
Yes	18%	72%	90%
No	0%	10%	10%
	18%	82%	100%

This table shows that the subjects tend to have more confidence in their assessment of marginal probabilities and are more likely to revise

their conditional probability assessments if an assessment aid such as a JPT is offered.

4.3 Discussion

The results reported in the experiments underscore the complexities and concomitant difficulties associated with assessing simple first order conditional probabilities. These difficulties were manifested by a high frequency of consistency violations of the probability calculus as well as assessments that were unmeaningful. Such factors as the causal/diagnostic and positive/negative relationship between events also affected the nature and quality of the responses.³

The use of a JPT resulted in a dramatic improvement in consistency and meaningfulness of the conditional probability assessments and mitigated the causality/diagnosticity "effect". The results of the post-experimental questionnaires further indicated that the subjects, particularly those who initially violated conditions (1) - (4), found the joint probability table highly useful as an assessment aid. Moreover, many of those who were consistent, in fact, developed their own JPT in making their initial assessments. Most subjects in these experiments were familiar with probability concepts and JPT's and therefore inferences must be limited to such groups.

It may be argued that to avoid the problem of consistency, an analyst could compute the bounds using conditions (1) - (4) and require the decision maker (subject or expert) to supply the estimates of conditional probability within the computed bounds. This would avoid the necessity of an assessment aid such as a JPT. We, however, feel that the violation of consistency is merely a symptom for cognitive biases and lack of understanding of the concept of conditional probability. Thus, even in those cases where consistency violations cannot occur e.g., when bounds are between 0 and 1, an assessment aid could improve the reliability of the assessments. This question of reliability, however, needs to be examined in situations where external observations are available against which subjects' assessments can be evaluated (e.g., [14], [22]).

HIGHER ORDER CONDITIONAL PROBABILITIES

The assessment of higher order conditional probabilities is even more complex a task than the assessment of simple pairwise conditional probabilities. This is because a conditional probability such as $p(A|B \cap C)$ must satisfy a larger number of constraints. For example, if $p(A)$, $p(B)$, $p(D)$, $p(A|B)$, $p(A|C)$, and $p(B|C)$ are assessed, then; the constraints that

$p(A|B \cap C)$ must satisfy are as follows:

$$\begin{aligned} p(A|B \cap C) &\geq 0 \\ p(A|B \cap C) &\geq \frac{p(A|B)p(B) + p(A|C)p(C) - p(A)}{p(B|C)p(C)} \\ p(A|B \cap C) &\geq \frac{p(A|B)p(B) + p(B|C)p(C) - p(B)}{p(B|C)p(C)} \\ p(A|B \cap C) &\geq \frac{p(A|C)p(C) + p(B|C)p(C) - p(C)}{p(B|C)p(C)} \\ p(A|B \cap C) &\leq \frac{p(A|B)p(B)p(B|C)p(C)}{p(A|C)p(C)p(B|C)p(C)} \\ p(A|B \cap C) &\leq \frac{p(A|C)p(C)p(B|C)p(C)}{p(A|C)p(C)p(B|C)p(C)} \\ p(A|B \cap C) &\leq \frac{p(B|C)p(C)p(B|C)p(C)}{p(B|C)p(C)} \\ p(A|B \cap C) &\leq \frac{1 - p(A) - p(B) - p(C) + p(A|B)p(B) + p(A|C)p(C) + p(B|C)p(C)}{p(B|C)p(C)} \end{aligned}$$

Besides, the problem of consistency violation due to a larger number of constraints, subjects find it difficult to consider the interaction between the three events. To lend further support that the mathematical definition of the conditional probability and the psychological notion that people employ in supplying these probabilities are often inconsistent, consider the responses of a group of graduate students in Business Administration (11 students) that were given the following information:

$$p(A|B) > p(A) \text{ and } p(A|C) > p(A).$$

They were then asked to estimate the lowest value of the conditional probability of event A given both B and C occur; i.e., $p(A|B \cap C)$. Many replied it has to be the $\max\{p(A|B), p(A|C)\}$. Some said it could be the $\min\{p(A|B), p(A|C)\}$. None agreed that it could be less than $p(A)$. The reader can easily verify that if $p(A) = p(B) = p(C) = .1$ and $p(A|B) = .2$, $p(A|C) = .3$, $p(B|C) = .1$ then it is possible to have $p(A|B \cap C) = 0$. In the special case when the probability that neither of the events will occur is 0, it is indeed true that $p(A|B \cap C) \geq \min\{p(A|B), p(A|C)\}$. We now show that such higher order conditional probability assessments, which further complicate the assessment task considerably, can be largely circumvented by appropriate bounding. We will discuss the strategy of bounding higher order probabilities in the context of an example. Our results, however, equally apply to other decision contexts.

Consider n binary events, where each one of the events either occurs or does not occur. Then there exist 2^n combinations of occurrence or non-occurrence of these sequences of events. Each combination is defined as a scenario. For example, if $n = 3$, one scenario is that the event 1 occurs and the events 2 and 3 do not occur; yet another scenario is that event 1 does not occur and events 2 and 3 occur, and so on. The assessment of the probabilities of each of the 2^n scenarios would minimally require $2^n - 1$ judgments from the experts. An approach proposed in Sarin [16] is to elicit n marginal probabilities plus $n(n-1)/2$ conditional probabilities of the pairs of events (i.e., first order conditional probabilities). This

information, which is considerably less than $2^n - 1$ probability judgments if n is even moderately large is then used to bound the higher ordered conditional (or joint) probabilities. That is, if there are four events, we need to know $p(E_i)$, $i = 1, \dots, 4$; $p(E_i \cap E_j)$, $i = 1, \dots, 3$; $j > i$; $p(E_i \cap E_j \cap E_k)$, $i = 1, 2$; $k > j > i$; and $p(E_1 \cap E_2 \cap E_3 \cap E_4)$ to completely specify the probability of each of the 16 scenarios. However, using Sarin's approach [16], elicitation of only four marginal probabilities, six first order conditional (or joint) probabilities of the pairs of events need be elicited. These, as it turns out, place tight bounds on the higher ordered joint probabilities.

It can be shown that the theoretical maximum difference between the upper and lower bound of $p(E_1 \cap E_2 \cap E_3 \cap E_4)$ is $1/2^{n-1}$. That is, no matter what values we choose for $p(E_i)$ and $p(E_i \cap E_j)$ in the four event case above, the value of $p(E_1 \cap E_2 \cap E_3 \cap E_4)$ must lie within a range of 0.125. We have conducted a simulation study in which different values of marginal and joint probabilities of the pairs of events were randomly generated from uniform distributions. The random assignments to joint probabilities were made using the consistency bounds. The difference in the upper and lower bounds for the higher ordered joint probabilities was computed. It was found that, for 90% of the problems generated (100 problems were generated for each of the 3 events and 4 events cases), the difference in the upper and lower bounds for $p(E_1 \cap E_2 \cap E_3)$ was $\leq .04$ and for $p(E_1 \cap E_2 \cap E_3 \cap E_4)$ was $\leq .006$. The mean and standard deviation of the difference in the upper and lower bounds for $p(E_1 \cap E_2 \cap E_3)$ were .015 and .017 and that for $p(E_1 \cap E_2 \cap E_3 \cap E_4)$ were .003 and .004. These results indicate that, practically speaking, only the marginal and pairwise conditional (or joint) probabilities need to be elicited. The analyst or the expert can then choose the values for the higher ordered joint (or conditional) probabilities within the specified bound, with apparently little adverse significance.

CONCLUSIONS AND FURTHER RESEARCH SUGGESTIONS

The assessments of conditional probability seem so deceptively simple that the difficulties associated with these assessments are largely ignored in the literature. Conditional probabilities are, however, basic input to many forecasting and decision models. We have shown that a large number of consistency violations of the probability calculus occur in a direct assessment of conditional probabilities. These violations are not due to small random errors that are expected in any subjective elicitation, but are errors of considerable magnitude that result from systematic perceptual and cognitive biases in subjects' responses. We have found

that the conditional probability assignments are considerably larger if the relationship between the events is perceived to be causal rather than diagnostic. Similarly, a positive relationship between events leads to a larger assignment of conditional probability than a negative relationship. Normatively, the assignments of conditional probability should not be influenced by the causal or diagnostic and positive or negative relationships of the events.

Our results clearly show that the use of an assessment aid such as Joint Probability Table results in a dramatic improvement in consistency as well as mitigates the causality/diagnosticity and positive/negative effects. We have also shown that the even more complex task of assessing higher order probabilities can be largely circumvented by appropriate bounding. This simplifies the assessment task considerably in many real forecasting and decision situations by reducing the number and level of difficulty of the assessments.

To further understand how people process information in assigning conditional probability a psychological experiment would be desirable. The merits of eliciting joint as opposed to conditional probabilities, as well as using assessment aids other than a JPT also need to be investigated. Similarly, the question of reliability of assessments remains to be studied. We believe that if an analyst interacts with the expert on a one-to-one basis, as should be the case in a real application, the effectiveness of an assessment aid such as a JPT will further increase. More experimental and field studies are, however, needed to answer these questions. In the interim we propose that an analyst should make the decision maker aware of the consistency conditions and discuss with him qualitatively the impact of evidence on the event for which conditional probability is being assessed. The analyst should also use an assessment aid such as JPT in the elicitation process. The real-life and classroom experiments that we have undertaken over the past few years provide overwhelming evidence that even in relatively simple situations an unaided assessment of conditional probabilities leads to serious errors of considerable magnitude.

FOOTNOTES

¹ In weapons acquisition, such events that would comprise a weapons system acquisition scenario might broadly be, cost of the weapons system, time required for system development, capability of achieving specified performance characteristics, and so forth [7].

² Sometimes it is possible to reduce the discrepancy between causal and diagnostic responses of the probabilities by a careful structuring of the questions. This would be the case, for example, in Response 3 of the solar energy example. We could ask: what is the chance that incentives had been given to solar energy given that commercial acceptance is observed. Now, we can expect $p(I|C) > p(I)$. But, our results still show that the relative magnitude of $p(D|B)$ is higher than $p(B|D)$ even if careful questioning avoids temporal or other consideration.

³ The following standardized regression model was developed to predict the % of individuals responding consistently to conditions (1) - (4) (standard errors in parentheses):

$$\begin{array}{rcccl} \%NV = & -.45P & & -.46T & - & .19C \\ & (-.15) & & (-.44) & & (.16) \end{array}$$

where

NV = % of individuals responding consistently;
P = positive (- 1) or negative (= 0) relation between events;
T = range of tightness of consistency bound (= upper - lower bound);
C = causal (= 1) or diagnostic (- 0) relationship between events.

² turned out to be equal to .50. The %-age of consistency violations increased with a positive relationship between events and tighter bounds. Causality had only a small negative effect on consistency.

REFERENCES

1. Armstrong, J. S., Long-Range Forecasting, Wiley, 1978.
2. Atomic Energy Commission. Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Power Plants, WASH-1400. Washington, D.C.: The Commission, 1974--Draft; 1975--Final.
3. Dalkey, Norma. "An Elementary Cross-Impact Model," Technological Forecasting and Social Change, 1972, 3, pages 341-351.
4. Duval, A., Fontela, E., and Gabus, A. "Cross-Impact Analysis: A Handbook on Concepts and Applications," in Portraits of Complexity: Applications of Systems Methodologies to Societal Problems, M.M. Baldwin, ed. (Columbus, Ohio, Battelle Memorial Institute, June 1975).
5. Edwards, W., and Phillips, L. D., "Man as Transducer for Probabilities in Bayesian Command and Control Systems," in G. L.

- Bryan and M. L. Shelley (Eds.), Human Judgments and Optimality, New York, Wiley, 1964.
6. Fischhoff, B., Slovic, P., and Lichtenstein S. "Fault Trees: Sensitivity of Estimated Failure Probabilities to Problem Representation," Journal of Experimental Psychology: Human Perception and Performance (in press)
 7. Grayson, A. S. and Lanclos, H. J. "A Methodology for Subjective Assessment of Probability Distributions," Master's Thesis: Air Force Institute of Technology, School of Systems and Logistics, Wright-Patterson Air Force Base, Ohio, 1976.
 8. Hogarth, R. B., "Cognitive Processes and the Assessment of Subjective Probability Distributions", JASA, 70, pages 271-289.
 9. Howard, R. A. "Bayesian Decision Models for System Engineering," IEEE Transactions on Systems Science and Cybernetics, Vol. SSC-1, No. 1, Nov. 1965.
 10. Martino, Joseph P., "Technological Forecasting - An Overview," Management Science Vol. 26, No. 1, January, 1980, pages 28-34.
 11. Mason, R. O., and Moskowitz, H. "Conservatism in Information Processing - Implications for Management Information Systems," Decision Sciences, 3(4), Oct. 1972, pages 35-55.
 12. Moskowitz, H. and Mason, R. O. "Accounting for the Man/Information Interface in Management Information Systems," OMEGA (International Journal of Management Science), 1(6), 1973.
 13. Moskowitz, H., Schaefer, R. E., and Borchertding, K. "Irrationality of Managerial Judgments: Implications for Management Information Systems and Operations Research," OMEGA, 1976.
 14. Murphy, A. H., and Winkler, R. L., "Reliability of Subjective Probability Forecasts of Precipitation and Temperature," Journal of the Royal Statistical Society, Series C, 1977, pages 41-47.
 15. Raiffa, H. Decision Analysis - Introductory Lectures on Choices Under Uncertainty. Reading, Mass.: Addison-Wesley, 1968.
 16. Sarin, R. K. "A Sequential Approach to Cross-Impact Analysis," Futures, 10(1), Feb. 1978, pages 53-62.
 17. Sarin, R. K. "An Approach for Long Term Forecasting with an Application to Solar Electric Energy," Management Science, 25(6), June 1979, pages 543-554.
 18. Slovic, P. and Lichtenstein, S., "Comparison of Bayesian and Regression Approaches to the Study of Information Processing in Judgment," Organizational Behavior and Human Performance, 6, 1971, pages 649-744.
 19. Spetzler, C. S. and Staßl von Holstein, "Probability Encoding in Decision Analysis," Management Science, 22, 1975, pages 290-301.
 20. Tversky, A. and Kahneman, D. "Causal Schemata in Judgments Under Uncertainty," In Progress in Social Psychology, M. Fishbein (Ed.), Hillsdale: Lawrence Erlbaum Associates, 1977, in press.
 21. Winkler, R. L., "The Assessment of Prior Distributions in Bayesian Analysis," JASA, 62, 1967, pages 776-880.
 22. Winkler, R. L. and Murphy, A. H. "Experiments in the Laboratory and the Real World," Organizational Behavior and Human Performance, 10, 1973, pages 252-270.

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Table 1

Credit Loan Application Assessments

D = event, delinquent
 B = event, bad credit rating
 G = event, good credit rating
 $p(\cdot)$ = probability of a given event

Group	Questions	$p(D)$	$p(B)$	$p(G)$	Response	Consistency Range Bounds
G 1	Q 1	.1	.3		$p(D B)$	0 - .33
	Q 2	↓	.5		↓	0 - .20
	Q 3*	↓	.9		↓	0 - .11
G 2	Q 4	.1	.3		$p(B D)$	0 - 1.00
	Q 5	↓	.5		↓	0 - 1.00
	Q 6*	↓	.9		↓	0 - 1.00
G 3	Q 7	.5	.3		$p(D B)$	0 - 1.00
	Q 8	↓	.5		↓	0 - 1.00
	Q 9*	↓	.9		↓	.44 - .55
G 4	Q10*	.9		.3	$p(D G)$	.66 - 1.00
	Q11	↓		.5	↓	.80 - 1.00
	Q12	↓		.9	↓	.88 - 1.00
G 5	Q13	.1		.1	$p(D G)$	0 - 1.00
	Q14	↓		.5	↓	0 - 2.20
	Q15*	↓		.7	↓	0 - 0.143

*Responses to these questions were also obtained subsequently using a joint probability table as a decision aid.

Note that the following questions are equivalent:

Q 1 and Q15

Q 2 and Q14

Q 3 and Q13.

Table 2
Frequency of Consistency Violation
(total responses = 104)

Group	Questions	p(D)	p(B)	p(G)	Response	Consistency Bounds	Number of Violations
1	1	.1.	.3		p(D/B)	0 - .33	31
	2	.1.	.5		p(D/B)	0 - .2	70
	3	.1	.9		p(D/B)	0 - .11	69
4	10	.9		.3	p(D/G)	.66 - 1	58
	11	.9		.5	p(D/G)	.80 - 1	87
	12	.9		.9	p(D/G)	.88 - 1	78

Table 3
Meaningfulness of Assessments

a. Number of Statistically Independent Responses (Condition 6)

Question No.	Response (n = 118 responses per question)		
	p(D B)	p(B D)	p(D G)
1	21		
2	18		
3	31		
4		32	
5		27	
6		35	
7	20		
8	59		
9	24		
10			18
11			16
12			33
13			43
14			27
15			37
Total	173	94	174
Mean	28.83	31.33	29.00

n = 118 responses per question, including the 14 who responded as statistically independent to most questions.

(TABLE 3 CON'T)

b. Joint Probability of Consistent/Inconsistent (Conditions (1) - (4)) and Meaningful/Unmeaningful (Condition (7)) Responses

Q 1, 2, 3; and Q 7, 8, 9 (n = 108 x 6 = 708 responses)*

	Inconsistent	Consistent	
Meaningful $p(D B) > p(D)$	.44	.40	.84
Unmeaningful $p(D B) < p(D)$	.02	.14	.16
	.46	.54	1.00

*173 responses were statistically independent; these were not included in the above table, which was thus based on 535 responses.

Q 4, 5, 6 (n = 118 x 3 = 354 responses)*

	Inconsistent	Consistent	
Meaningful $p(D B) > p(D)$	0	.44	.44
Unmeaningful $p(D B) < p(D)$	0	.56	.56
	0	1.00	1.00

*94 responses were statistically independent; these were not included in the above table, which was thus based on 260 responses.

Q 10 - 15 (n = 118 x 6 = 708 responses)*

	Inconsistent	Consistent	
Unmeaningful $p(D G) > p(D)$	.17	.19	.36
Meaningful $p(D G) < p(D)$	.25	.39	.64
	.42	.58	1.00

*174 responses were statistically independent; these were not included in the above table, which was thus based on 534 responses.

Table 4

Positive v/s Negative Causality

Question	$p(D B) > \text{computed value from } p(D G)$	$p(D B) < \text{computed value from } p(D G)$	$p(D B) = \text{computed value from } p(D G)$
Q1 v/s Q15	92	9	3
Q2 v/s Q14	94	5	5
Q3 v/s Q13	82	13	9

Table 5

Effect of Decision Aid (Joint Probability Table)
on Consistency Violations

Question Number	Sample (Size (n))	Frequency of Violations	
		Before	After
3	104	69 (66%)	4 (4%)
6*	104	0	0
9	104	78 (75%)	9 (9%)
10	104	58 (56%)	20 (19%)
15	104	51 (49%)	30 (29%)
Total**	416	256 (62%)	63 (15%)

*In this question, the bounds could not be violated since it ranged over the entire probability space, from 0 to 1.

**Does not include Q6, since bounds could not be violated.

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ABSTRACT

An emerging weapon system concept is typically judged by its military worth. The military worth of a weapon system is often evaluated by several criteria:

- system performance
- life cycle cost
- developmental risk.

Recent revisions to Department of Defense (DOD) Directives and Instructions (e.g. 5000.1, 5000.2, and 5000.39) stress the importance of performing an adequate risk analysis.

This paper briefly describes one key problem of risk assessment. A risk assessment must include not only the likelihood of success, but also the consequences of failure in quantitative, measured terms, such as dollars.

Management Consulting & Research, Inc. (MCR) has been involved in weapon system risk analysis for some time. This particular paper describes a simple procedure for performing a risk analysis and integrating cost consequences into the model. This simple methodology, called "cost-risk assessment" will be described. We will then examine its use in analyzing the effect of competition. The mathematical formulas are not included in this paper, but are available from the author or references (particularly 3).

INTRODUCTION

Within the past year several events have occurred to reinforce the increasing emphasis on risk and resource analysis problems within the Department of Defense. Specifically DoD Directive 5000.1, "Major Systems Acquisition," was updated on March 19, 1980 to fully implement the concepts and provisions of Office of Management and Budget Circular A-109; DoD Instruction 5000.2, "Major System Acquisition Procedures," was also updated on March 19, 1980 to include procedures for acquisition planning; DoD Directive 5000.39, "Acquisition and Management of Integrated Logistic Support for Systems and Equipment," was issued January 17, 1980 to establish policy and responsibilities for Integrated Logistic Support (ILS). In addition untold studies of particular mission areas or weapon systems have examined mid-mix design alternatives, assessment of risks based on sensitivity to uncertainty in key design and logistic parameters, and life cycle cost considerations.

In evaluating contractor proposals for specific responses (under the A-109 philosophy) to DoD Mission Element Needs Statements, we are beginning to observe evaluation criteria of a system's military worth such as:

- system performance
- system life cycle cost
- developmental risk.

Typically the developmental risk evaluation factor assesses the degree to which a contractor's proposed system is likely to achieve its predicted performance within the predicted cost and schedule goals. In evaluating or in conducting any risk analysis, it is essential to consider:

- Risk Assessment: Identify the degree of technical risk with respect to realism, soundness, and credibility (i.e., the technical feasibility as well as the "contractor bias problem). Answer questions such as: Are there low-risk alternatives to high-risk components? How much would performance suffer? What additional cost is incurred for continuing multiple alternatives?
- Risk Management: Develop a plan for managing all types of risk (risk minimization plan) as a function of time (i.e. Acquisition Milestone I, II, and III). The role of quality assurance, hedges against new technology failure, etc. are considered here.
- Risk Demonstration: A test and evaluation demonstration plan should allow early identification of risks and the steps required to reduce high risk program elements to demonstrated acceptable levels as well as the cost of doing so.

A risk assessment includes not only likelihood of success, but also must include the consequences of failure in measured terms, usually dollars, hence the concept of a "cost-risk analysis" becomes of interest.

A recent article by this author (1) described a statistical procedure for treating risk assessments. Additional work by the author for the Naval Air Systems Command (2), and ongoing work for the Air Force's Rome Air Development Center further extend the methodology reported in (3-9). We have developed a simple, yet comprehensive, system for not only performing a risk analysis, but integrating the cost consequences into the model.

The following is a summary of the steps in a typical cost-risk analysis:

Step 1: Identify Key Risks

The key risks or uncertainties relevant to a particular component/system and technology are identified as a first step in assessing risk. A special form was developed for this step called a Cost-Risk Assessment Input Data Sheet.

Step 2: Develop Measurement Standards

The second step in a risk assessment is the definition process of measures of effectiveness (MOEs), often called measurement standards. The standards were defined as far as possible in quantitative terms rather than qualitative terms. Cost is only one of several potential measurement standards.

Step 3: Develop an Analytic Methodology

The methodology used in cost-risk assessment for combining several types of risk is adapted from the cost uncertainty procedures described in Refs. 1 and 3.

The advantages of such a procedure are:

- Consistency across technologies/manufacturers/program phases
- Ease of application and explanation
- Ability to quantify subjective knowledge of technical experts in each key risk area.

The essence of a cost-risk methodology is to:

- Estimate the distribution of cost and risk associated with each key risk variable identified in Step 1, via three basic inputs: a low value, a most likely value, and a high value.
- Apply a set of simple analytical formulas to calculate the likelihood (probability) that any particular value (such as the goal or most likely value) will be exceeded.

The objective is to include in the analysis an uncertainty measure of the costs required to successfully accomplish stated objectives. A larger magnitude of cost (mean or measure of central tendency) implies that multiple design alternatives are being retained which should reduce development risk. A larger uncertainty (variance or measure of dispersion) in cost implies that potentially greater risks are being taken.

Little is usually said about the problem of "composite risk score" but we should point out that:

- Different risks (e.g. technologies) may have to be combined sequentially (in series) if one development depends on other prior developments.
- Competing technologies may be continued in parallel to increase the composite likelihood of success.
- One particular technology may be more crucial than others in the series (weakest-link-in-the-chain approach).

A solution to the composite risk problem is to develop a "composite risk score" from subjective inputs of experts in each technical area. For example, our definition of a "Good" Risk in a recent application was "The technical approach includes mostly proven concepts; some minor modifications to available equipment or technology; risk is reasonable based on the methodology employed." Verbal definitions over a scale from 0 to 100 in increments were used (Good was an 80 on this scale).

COST-RISK ANALYSIS

The purpose of a Cost-Risk System is to provide the acquisition manager with the quantitative cost-risk values associated with alternative acquisition strategies at key program milestones. This concept assumes that there are fixed preliminary design alternatives being developed on a fixed time schedule. Thus, the cost-risk assessment may be proposed either by one, or by multiple contractors. These quantitative cost-risk values provide an additional tool to the acquisition manager for evaluating the many alternative strategies available.

INPUT DATA

For the purpose of this cost-risk assessment we will use cost as the measurement standard and identify key risks by system/subsystem level and life cycle phase.

In examining several alternatives, each contractor would identify hardware elements for which cost-risk estimates would be prepared. The objective is to isolate high design risk items in order to determine the best strategy for ensuring program success recognizing the existence of these elements. Thus, the breakdown of each weapon system should go no lower than is necessary to include hardware elements which are considered to have particularly high design risk. For example, each contractor could consider the following elements:

- Air Vehicle
 - Structure
 - Flight Controls
 - Other

- Critical Mission Systems (e.g., new radar)
- Propulsion and Power
- All Other (needed to add up the total costs by phase)

All cost elements should be assigned to identified hardware elements of each weapon system.

The hardware elements for which cost estimates are made should be identical to the elements for which design evaluations are made. This is essential in order to allow trade-offs which consider back-up hardware elements.

The cost elements can be segregated by the early life cycle phases (Concept Formulation, Validation, and Full Scale Development) in order to consider alternative programs in each phase on a comparable cost basis.

Constant Year (e.g. FY80) costs should be used for consistency. Note: the effects of inflation can be separately handled. Further, treatment of present value is left to the reader.

As an example of the input data collection procedure, assume an analysis will be made of one proposed configuration of V/STOL "B." Further assume:

- The high technical risk elements are the digital flight control system and the thrust deflection portion of the propulsion system.
- The configuration uses existing (proven production configurations are available) core avionics systems.
- With the above assumptions Figure I would be prepared. For all hardware elements which were not available in a production configuration, a code will be entered in each combination of life cycle phase and hardware element. The hardware costs must add up to the total cost. Thus, a column labeled "other" may be needed.
- For each code entered in Figure I a Cost-Risk Assessment Input Data Sheet will be completed. Figure II shows an example of a completed form for the hypothetical example. A form like this would also be required for the "other" costs.

ANALYSIS PROCESS

A procedure is briefly described which can be used to assess cost-risk trade-offs between both alternative system concepts and program alternatives in acquiring a given concept. The methodology described in this section will enable the decision maker to analyze the following:

- The cost-risk uncertainties inherent in alternative design concepts proposed by individual contractors, and
- The cost uncertainties of having alternative combinations of contractors develop their respective design concepts in parallel (i.e., effect of competition).

It is imperative to consider both of the cost characteristics (magnitude and uncertainty), hence a cost-risk system is developed. The effects of competition can be specifically treated in this analysis.

The procedure outlined in this section requires several necessary steps before an assessment of cost-risk trade-offs is possible. These are listed below:

For each contractor's design:

- Develop a Probability Density Function (PDF) of cost (i.e., cost uncertainty) for each element of each weapon system design concept proposed by that contractor. We do this using only the Low, Most Likely, and High estimates of hardware element cost submitted.
- Develop a PDF of cost for each weapon system design concept, i.e., for each contractor.
- Display the cost uncertainties graphically by contractor.

For each competitive phase:

- Develop the composite cost PDFs resulting from the parallel development of alternative concepts (i.e., examine cost-risk of 1 contractor, 2 contractors, etc., continuing the development).
- Display the composite cost-risk uncertainties graphically.
- Relate the resultant cost-risk PDFs to each other so that cost-risk trade-offs can be examined.

Using these ground rules, the methodology accomplishes the following:

- It treats the cost of each hardware element/subsystem as a random variable from a generalized Beta probability distribution.
- It develops, for each hardware element, a cost Probability Density Function (PDF) based on a Low, Most Likely, and High estimate of its cost.
- It statistically combines the hardware element cost PDFs (via an analytical technique known as the "method of moments") to obtain major subsystem cost PDFs.

- It statistically combines each major subsystem cost PDF (via the same technique) to obtain a total system cost PDF for a particular contractor's design.

The cost uncertainty of developing different combinations of design concepts in parallel, i.e., the effect of competition, can be determined by applying the "method of moments" technique again to statistically combine total system cost PDFs.

EXTENDED MCR METHODOLOGY (INDEPENDENT ASSESSMENT OF RISK)

The procedure described above collapses cost and risk into the single measurement standard of "cost." However, in examining the effects of competition, it would be useful to include an evaluation of "probable technical success."

The concept of adding redundancy to achieve greater reliability is certainly understood by the reader. This concept can be extended to the problem of assessing the effect of competition in developing a complex weapon system, such as V/STOL.

Assume that it is possible to derive some measure of "anticipated success" (i.e., the probability of developing a "successful" weapon system) for each design concept. In this case, as before, it could be shown that by developing two design concepts in parallel (i.e., adding competition), the probability of achieving at least one "successful" design is greater than if only one concept were developed.

It can be seen then that the effect of adding redundancy into a system's design is the same as the effect of adding competition to the development of a weapon systems design concept. In both cases, added redundancy (or competition) enhances the chances for success. However, in both cases, this enhanced likelihood of success is achieved at the expense of greater cost.

THE PROBLEM

The intent here is to define alternative methodologies that can be employed by the decision maker to aid in making trade-offs between two criteria:

- The larger cost of having alternative combinations of contractors develop their designs throughout the various stages of program development, and
- The technical risk (or probability of achieving a "successful" design) which can be expected in having each combination of contractors develop that design.

THE SOLUTION

The methodology for deriving cost uncertainty for each design concept can be used. This methodology would enable each contractor to develop an uncertainty distribution around cost, (i.e., a probability density function (PDF) of cost) for their particular design concept. Using the cost PDFs for individual contractors, it was shown that composite cost PDFs for combinations of contractors could be derived via the "method of moments" technique (2).

Since individual contractor cost PDFs do in fact include elements of design risk (i.e., larger cost variance implies greater risk), it is possible to perform cost-risk trade-offs for individual contractors on the basis of their estimated cost PDFs alone. Unfortunately, it is not possible to compare combinations of contractors solely on the basis of cost uncertainty. The reason for this is that cost uncertainty is in direct proportion to the number of contractors, while risk is inversely proportional to this factor. Figure III illustrates this point.

In Figure III cost risk profiles are illustrated using "most likely" system cost estimates. To do this, it is assumed that some measure of anticipated success (probability of technical "success," or TP_s) can be derived for each contractor's design concept. Figure III-a presents the trivial case in which it is assumed that each contractor (and hence, each contractor combination) has a 100% chance of developing a "successful" technical design (i.e., no attempt to assess probability of technical success is made). In this case, the decision maker would never consider contractor combinations, because nothing would be gained for the higher most likely cost this would require.

On the other hand, Figure III-b illustrates the case in which point estimates for probability of technical success are somehow derived for each contractor's design. With this additional information, the decision maker can use the cost PDFs and the cost-risk profiles in trading off the higher expected costs of developing two independent designs simultaneously against greater likelihood of a technically successful design. If A has only a 60% probability of being successful and B has only 75% probability of being successful, the combination of A and B should give us a 90% chance of technical success for this particular acquisition phase.

It is clear that, in order to conduct effective cost-risk trade-offs for combinations of contractors, it is necessary to estimate some measure of the technical risk involved for each contractor's design concept in addition to cost uncertainty. Given that it is possible to assess such a figure, several alternatives for presenting cost-risk trade-offs to the decision maker are possible.

One simple alternative for providing cost-risk trade-offs was discussed briefly in the previous section. The methodology required two pieces of information from each contractor:

- A cost PDF for a particular acquisition phase, and
- An estimate of the probability of technical success (TP_s) for the design concept and program plan for that phase.

Given this information, cost-risk profiles similar to the one illustrated in Figure III-b could be prepared.

The cost-risk profile of Figure III-b does provide useful information to the decision maker, however, it does have one serious shortcoming. That is, for each contractor combination, there is only one point on the cost-risk profile. Presumably, for a given design concept, each contractor will have a set of alternative design strategies. These design strategies will differ for a variety of reasons, among which are the following:

- Some design strategies will rely on established, low-risk technologies and therefore, will have more certain cost estimates.
- Some design strategies will involve more redundancy in the system design, consequently driving system cost up.
- Some design strategies will depend upon technological breakthroughs and hence, will have more uncertain cost estimates.

In brief, each design strategy of a given contractor will have a unique cost uncertainty and technical probability of success (TP_s) combination associated with it. Obviously, Figure III does not capture this cost-risk variation among alternative design strategies for individual or combinations of contractors. Consequently, a methodology to deal with this problem is required.

One is tempted at this point to use the cost PDF developed for each contractor in order to exhibit the cost-risk variation among alternative design strategies for individual (or combinations of) contractors. However, we caution against this! Consider, for instance, Figure IV. This figure illustrates the cost PDF (P_c) and its associated cumulative distribution function (TP_s) for one design strategy of contractor A. On the cost curve, note that the 90th percentile cost (C_A) is marked. The interpretation of this point is the following: "The probability that the total cost for this particular design strategy will be less than or equal to C_A is 0.90." In other words, 0.90 represents a measure of cost uncertainty; it does not represent a "success" probability for the technical design strategy. To use it as such is misleading!

The curve would be generated from data on the Cost-Risk Assessment Input Data Sheets for a particular contractor's design. The individual estimates of Low, Most Likely, and High costs for each cost element/hardware element combination are the absolute low, absolute high, and most likely cost estimates for developing a defined end product. Let's assume the particular end product has a probability of technical success (TP_s) of 0.95, i.e., we think there is a 95% chance it will work. Then the cumulative distribution function of cost we developed above should be labeled "For a 95% chance of technical success" as shown in Figure V-a.

The procedure described for constructing this figure may be repeated for several design alternatives, i.e., other assumed values of probability of technical success. For example, the procedure could be repeated for a 50-50 chance design ($TP_s = 0.5$) and a high risk design ($TP_s = 0.1$). Cost uncertainty curves for each of these designs can then be developed. Figures V-b and V-c can then be constructed.

The data from alternative design programs, Figure V, allow us to compare the probability of achieving technical success (TP_s) with various probabilities of not exceeding a given cost value (TP_c). For example, let's assume it is desired to determine the relationship between probability of technical success for various values of cost (using a cost value having a 90% chance of being achieved, i.e., $TP_c = 0.90$). By drawing a horizontal line at $TP_c = 0.90$ the "cost" at three values of technical success may be obtained for contractor A, contractor B and the combinations of contractors A and B. This data can then be plotted as Figure V-d. It is important to note that although Figure V-d is similar to Figures V-a, -b, and -c, it is not measuring the same physical phenomenon. There is uncertainty associated with both cost and technical success and therefore neither can be determined independent of the other.

The data from the curves of Figure V are tabled below. One might be tempted to use the costs for Cases I, II, and III as the Low, Most Likely, and High costs of a cost uncertainty distribution directly. Hopefully the analysis above has pointed out the fallacy of doing this since Figure V-d is constructed from Figures V-a, -b, and -c.

	$TP_s = .1$ CASE I	$TP_s = .5$ CASE II	$TP_s = .95$ CASE III
C_A	\$40 M	\$ 70 M	\$100 M
C_B	\$80 M	\$100 M	\$110 M
	HIGH TECHNICAL RISK	MODERATE TECHNICAL RISK	LOW TECHNICAL RISK

Given three alternative design concepts, one could construct an Acquisition Strategy composed of, say one Low Technical Risk design; and one High Technical Risk design. In fact, with two firms and three design alternatives, all nine combinations of (A,B) could be considered: (I,I), (I,II), (I,III), (II,I), (II,II), (II,III), (III,I), (III,II), (III,III). Each of these would have a composite technical probability of success given by:

$$TP_{SAB} = 1 - (1 - TP_{SA})(1 - TP_{SB}),$$

where

TP_S is the technical probability of success for a particular case.

Rigorous comparison of multiple alternatives rapidly increases the complexity of this methodology. The use of high speed computers enables the acquisition manager to deal with this complexity.

The composite cost uncertainty distribution for the particular acquisition phase could be obtained using the MCR analytical methodology reference.

CONCLUSIONS

The area of risk analysis is a very complex but increasingly important subject. This paper has briefly examined a simple procedure for integrating both cost and technical risk. The initial cost-risk methodology MGR developed is being used by several hardware contractors in various risk assessments as well as by ourselves.

In the area of cost estimating and risk assessment we believe uncertainty should be treated explicitly. Several complex issues for analysis still remain (such as dependence between subsystems).

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BIBLIOGRAPHY

1. G. R. McNichols, "Treatment of Uncertainty in Life Cycle Gosting," Proc. 1979 Annual Reliability and Maintainability Symposium, IEEE, Norcross, GA.

2. G. R. McNichols, "Cost-Risk Methodology for the V/STOL Acquisition Strategy Study," TR-7924-1, Management Consulting & Research, Inc., Falls Church, VA, March 1980.

3. G. R. McNichols, On the Treatment of Uncertainty in Parametric Gosting, Report T-330, Office of Naval Research Program in Logistics, George Washington University, Institute of Management Science and Engineering, Washington, D.C., 1976.

4. G. R. McNichols, "Macro Models for the Treatment of Uncertainty in Parametric Costing," Proc., Ninth Annual Meeting, Southeastern Chapter of The Institute of Management Sciences (TIMS), Glemson University, College of Industrial Management, Glemson, SG, 1973, pp. 57-66.

5. G. R. McNichols, "Independent Parametric Gosting: What? Why? How?," Proc., 1975 Spring Conference of the American Institute of Industrial Engineers, AIIE, Norcross, GA, 1975, pp. 3-11.

6. G. R. McNichols and R. Moyer, "The Navy's Use of Analytic Procedures for Treating Cost Uncertainty in Parametric Gosting," Proc., 13th Annual Meeting, Southeastern Chapter of The Institute of Management Sciences, Glemson University, College of Industrial Management, Glemson, SC, 1977, pp. 41-66.

7. G. R. McNichols, "Risk Assessment of Selected Fuel Economy Improvement Technologies," TR-1371-SCT, J. Watson Noah Associates, Inc., Falls Church, VA, April 1978.

8. J. Ignizio, with J. N. D. Gupta and G. R. McNichols, Operations Research in Decision Making, Crane-Russak, New York, 1975.

9. G. R. McNichols, "Generation of Parameter Values in Subjective Probability Density Functions," IR-7703, Management Consulting & Research, Inc., Fairfax Station, VA, March 1977.

V/STOL "B" Hardware Breakdown Structure	Flight System						Mission Systems			Other
	Air Vehicle			Core Avionics	Propulsion and Power Systems		Guided Weapon Systems	Armament Systems	All Other Mission Systems	
	Structure	Digital Flight Control System	All Other Air Vehicle Systems		Thrust Deflection System	All Other Propulsion and Power Systems				
1.0 RDT&E				(Uses existing core avionics systems)			BMG	BMA	BMO	BO
1.1 Concept Formulation	BFAA	BFAO	BFAO		BFPT	BFPO				
1.2 Validation	CFAA	CFAD	CFAO		CFPT	CFPO				
1.3 Full Scale Development	DFAA	DFAD	DFAO		DFPT	DFPO	DMG	DMA	DMO	DO

Illustrated on Cost-Risk Assessment Input Data Sheet

Figure I. V/STOL "B" (CONFIGURATION #1) COST MATRIX INDEX CODES

AIAA Acquisition Strategy Study

COST MATRIX CODE CFPT COMPILED BY Maxmillian G. Gartwingle
DATE 3/11/80
AIRCRAFT WEAPON SYSTEM V/STOL "B" Configuration #1
SYSTEM/SUBSYSTEM Thrust Deflection System
LIFE CYCLE PHASE Validation
COST UNCERTAINTY ESTIMATE (\$1,000 Constant FY1980)

1. Low Value: \$620

Rationale: If Phase I full scale tests confirm the internal nozzle configuration successfully demonstrated by the scale model air flow tests completed during the concept formulation phase, the full scale flow tests (\$60,000) may be eliminated from the proposed program. (\$680,000 minus \$60,000 = \$620,000.)

2. Most Likely Value: \$680

Rationale: A similar configuration successfully completed in 1978 similar validation tests to those proposed. (See NO-THRUST Engine Co. Report xxx of March 1979.) The cost of that program (\$515,000) was escalated three years at 9.7% per year. $(\$515,000 \times (1.097)^3 = \$680,000.)$

3. High Value: \$820

Rationale: Durability tests assume the final validation can be demonstrated with only one major redesign. In the event two major redesigns are required, an additional \$140,000 will be required. $(\$680,000 + \$140,000 = \$820,000.)$

Figure II. COST-RISK ASSESSMENT INPUT DATA

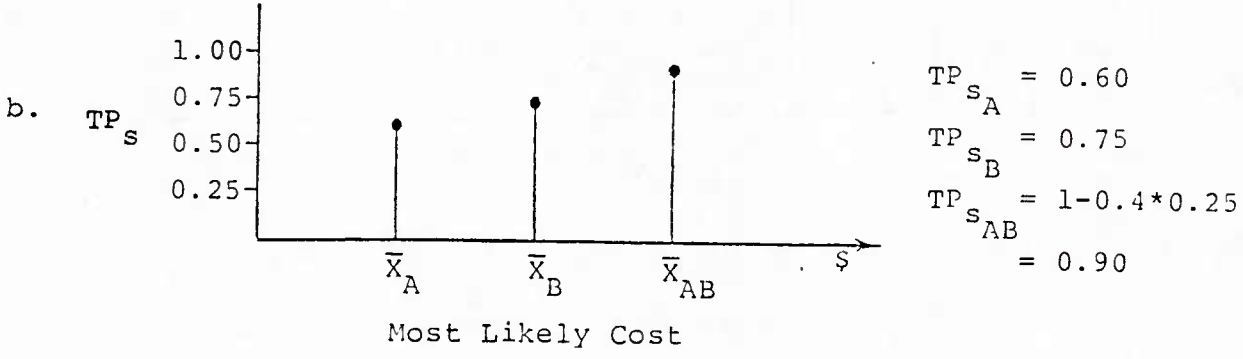
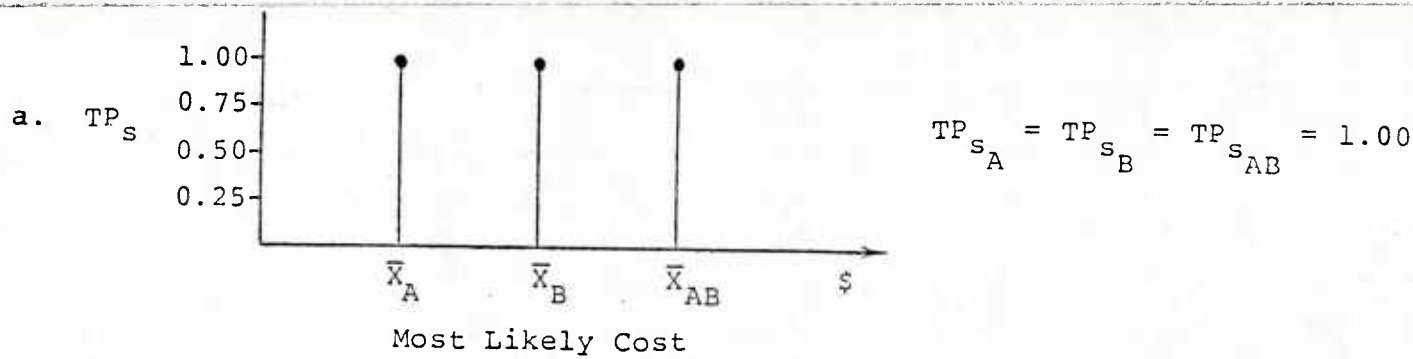


Figure III. COST-RISK PROFILE FOR TWO CONTRACTOR COMPARISON
(TECHNICAL PROBABILITY OF SUCCESS
VS MOST LIKELY COST)

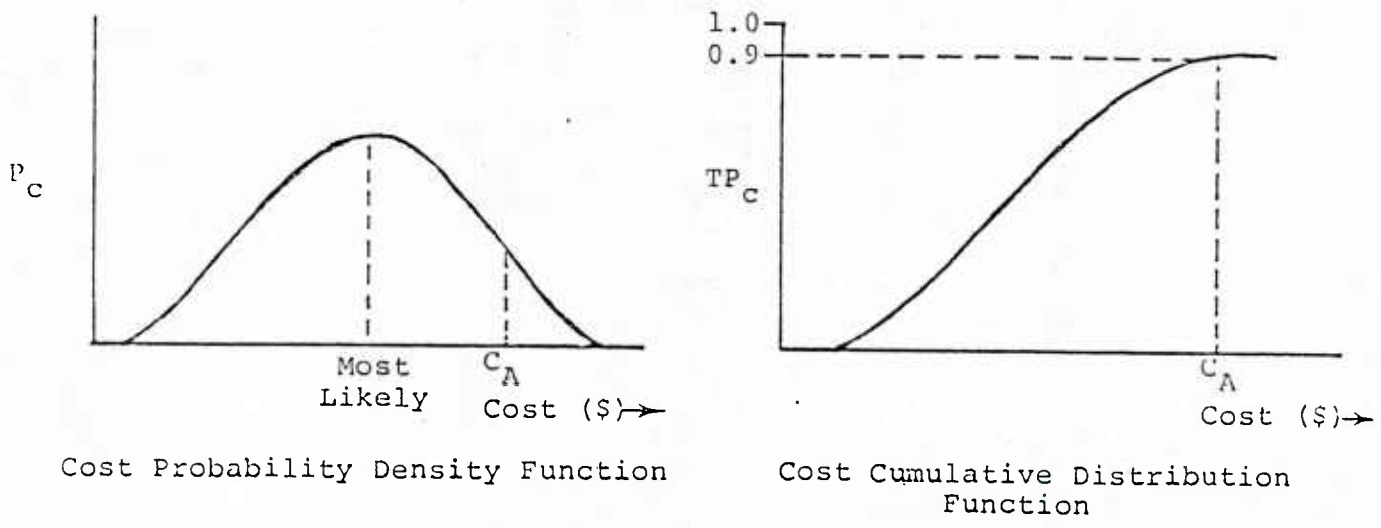


Figure IV. COST UNCERTAINTY FUNCTIONS FOR DESIGN A

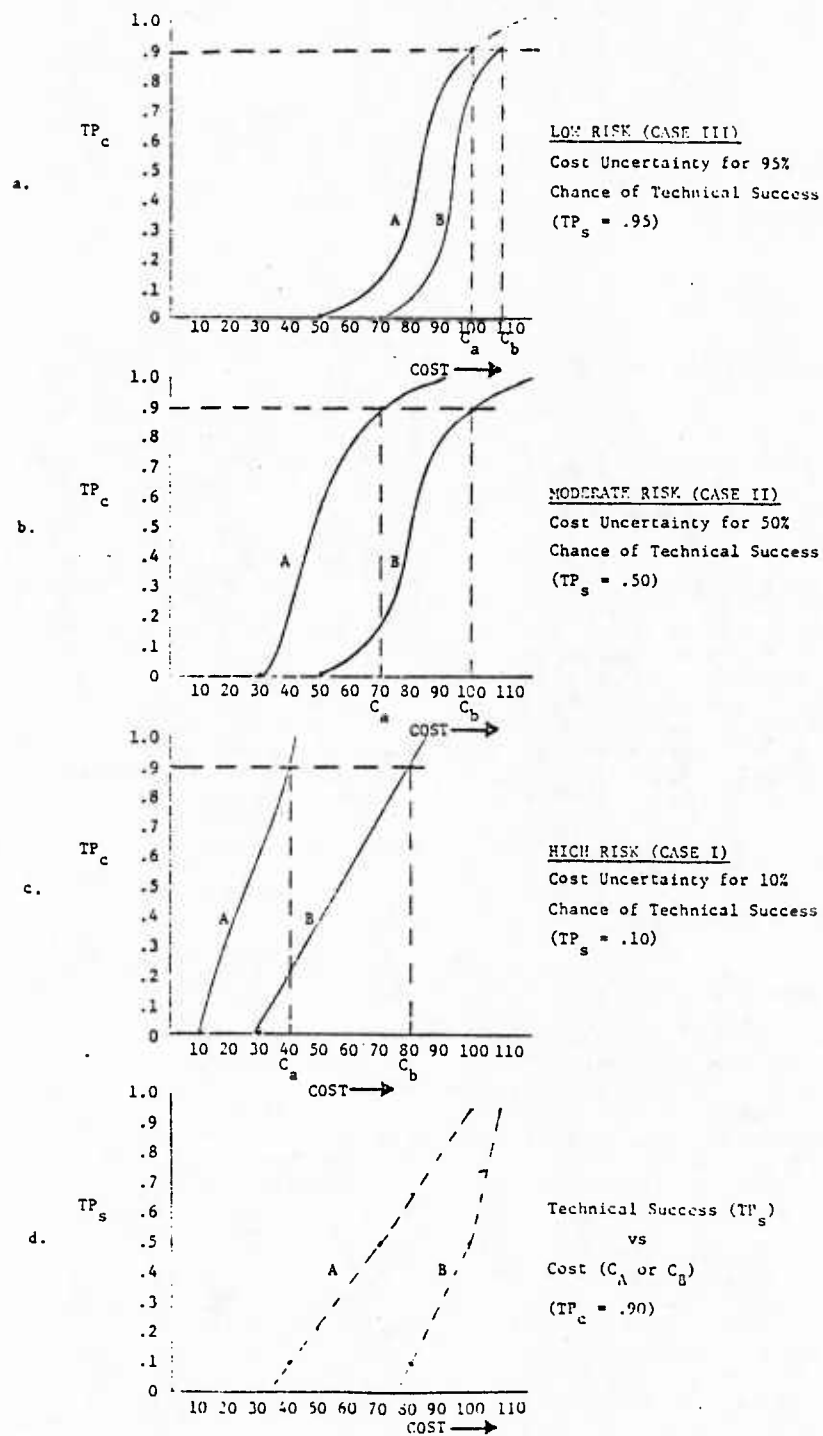


Figure V. COST UNCERTAINTY VS TECHNICAL RISK
FOR SEVERAL DESIGN ALTERNATIVES

UNCERTAINTY DIAGNOSIS AND EARLY LEARNING

Richard Alan Goodman
Graduate School of Management
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Early learning is a critical managerial function which will significantly reduce both schedule and costs overruns. Appropriate uncertainty diagnosis, coupled with selected managerial action, will increase the potential for creating early learning in development projects. In addition, early learning will increase the smoothness of the project management while at the same time assuring appropriate performance levels of the desired product. Understanding this concept is one of the keys to project success. The early learning definition and the description of three types of uncertainty, which follow, provide guidelines for managerial action (Freeman, 1972; Twiss, 1974).

KEYS TO PROJECT SUCCESS

The study of large scale development projects has led to a range of phenomena that are usually present in all successful projects. These phenomena form the basis of the following discussion. The discussion of the individual guidelines will explore both commercial and government development projects and necessarily will be general in nature.

MARKET ORIENTATION. It is clear from the studies that successful projects have a very explicit customer orientation. While not decreasing the need for technical expertise, the successful projects reflect deep and detailed understanding of the customer's technical requirements and the technical context of these requirements. The personnel on such projects work hard to apply and adapt their expertise to these needs. In general, the customer is kept informed of the progress and the technological development. This leads to valuable exchanges of information which in turn allows for appropriate project choices as it becomes evident that, on some dimensions, an ideal solution may not be possible. In other words, these projects utilize a problem solving approach rather than forcing a standardized technology to fit a particular situation. (All too often, technologists become so involved in their approach that they require customer adaptation rather than technological adaptation. A marketing orientation is quite the opposite.)

RELEVANCE TO CORPORATE OBJECTIVES. Strong corporate support is an important factor in successful projects and increases in strength

when the project's contribution to corporate objectives is perceived. As the perceptions of such value decreases then the tendency to neglect certain projects increases. Such neglect results in reduction of a project's priority and this in turn results in slackening of performance demands. The natural outcome of such a situation are missed milestones and poorer design quality. The cumulative effect of such a tendency to neglect a project is customer dissatisfaction and a final product which is not as close to the desired outcome as might have been expected.

EFFECTIVE PROJECT SELECTION AND EVALUATION SYSTEM. The likelihood of a project being well suited to the corporate objectives is enhanced by a well designed project selection and evaluation system. Such a system, by its very existence, indicates that corporate support is an issue. In addition, the technical competence of the system increases the likelihood that projects selected will develop in line with the overall corporate objectives. Even a rather crudely designed system will force the project proposers to explicitly consider the corporate objectives.

EFFECTIVE PROJECT MANAGEMENT AND CONTROL. Without a good management and control system the direction of the project cannot be determined, corrective action cannot be taken, and the outcome will be less likely to match original expectations. In addition, the adaptation that is required to correct such a drift in the outcome cannot be anticipated and the customer is often unable to use the product immediately.

SOURCE OF CREATIVE IDEAS. It may seem rather obvious to state that sources of creative ideas are necessary in the development process. By their very nature, engineers and scientists represent such sources. There appears to be significant distinction between the organizations which rely upon their existing technical resources and those which actively pursue a policy of enriching these resources. This enrichment may come from a recruitment policy that continues to bring in fresh personnel. Attendance at professional meetings, for example, will bring in fresh ideas. Some attention to and/or training in creativity techniques is important. All of these approaches seem to be significant features of those organizations which are able to pursue successful projects.

ORGANIZATION RECEPTIVE TO INNOVATION. A management style or climate which is receptive to creativity is extremely important. Scientists and engineers can apply their talents in a creative or an analytic manner. In the latter mode, proposed solutions are analyzed for their respective strengths and weaknesses

and variations suggested to improve the solutions. This mode relies heavily upon the quality of the initial proposed solution. Many projects represent a simple or relatively simple extension of an existing solution or approach. In contrast to this, the "new boy" approach, suggested by Goodman and Abernathy (1978), describes projects whose success is twice the industry average and whose approach was not a simple extension of existing technology but rather, a new "creative" conceptualization. When these two issues are addressed by management, a higher tendency toward finding and employing creative ideas, as appropriate, exists. This tendency seems important in successful projects.

COMMITMENT BY ONE OR FEW INDIVIDUALS.

One last factor which seems to be associated with project success is the existence of a so-called "project champion." It appears that strong commitment by one or a small group of individuals provides a drive and a real concern for the quality of the outcome. This motivational force increases the probability of project success. This initiative and concern usually ensures a more sophisticated understanding of the issues (both technical and customer requirements) and maintains, on the part of the staff, a spirit derived from their sense of the project's importance.

Research on successful projects indicates that in each case these conditions all existed, albeit, in varying intensity. That is, the successful project had a market orientation while at the same time being relevant to corporate objectives. The organization pursuing the project had an effective project selection and evaluation system and an effective project management and control system. Creativity was enhanced by a commitment to developing sources of creative ideas and a management receptive to innovation. Finally, the project was managed by an individual or a small team which was very highly committed to its success.

EARLY LEARNING

The generic nature of research and development can be described in several ways. One very powerful concept is a learning model. The research and development process can be defined as the sequential and/or concurrent purchase of information. An idea is posed, then an analysis is undertaken to understand how the idea might work. Tests are run to gather data about a component of the idea, etc. Each project phase provides new data until the final drawing set and the final test data are available.

This learning model is represented by the sketch in Figure 1, where time and information are the important issues in a project. For

simplicity, a project's objective is to gather 100% of the necessary information for successful completion.

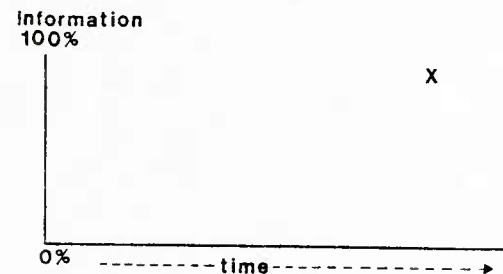


Figure 1.
LEARNING MODEL OF A PROJECT

The notion of a learning path can then be added to the model. That is, learning accomplished during a project could be plotted on this graph and the result is shown by the project's path from the beginning to the successful completion at 100%. One of an infinite number of such paths is illustrated in Figure 2.

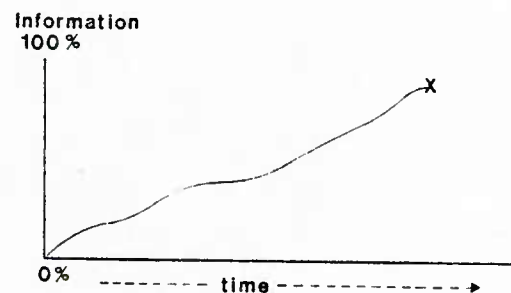


Figure 2.
A LEARNING PATH

For the purposes of this discussion two opposite types of learning paths are used. The path on the left of Figure 3, represents the late learning case. In the former case, the major uncertainty of the project is reduced in the earlier portions of the project and only small problems need to be overcome as the project nears completion. In the latter case, major uncertainty is encountered very late in the project which create great difficulty for managers trying to bring the project to an orderly conclusion.

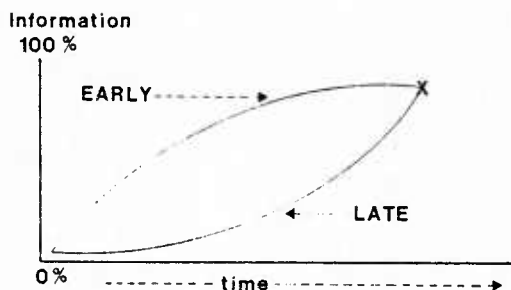


Figure 3.
EARLY AND LATE LEARNING PATHS

The basic thesis of this middle section is the proposition that, in any development process, THE KEY MANAGEMENT TASK IS TO CREATE AN EARLY LEARNING PATH. Guidelines for managerial actions which lead to early learning are contained in the third major section of this chapter. Before considering those guidelines, the resource implications of the early and late learning paths will be discussed.

The typical resource expenditure in development work follows the underlying project stages or phases. The initial phase normally requires a small number of personnel to work together very closely. As conceptualization becomes firmer, the project work can begin to include other organizational members. The increasing rate of personnel utilization means that the expenditure rate continues to increase as research blends into development and development blends into design, etc. Simply speaking, more and more people can be effectively employed on the project as the project develops. If the phases were well bounded and explicit, this increasing rate of expenditure would look like a step function similar to Figure 4. Otherwise the increase would be a bit more smooth.

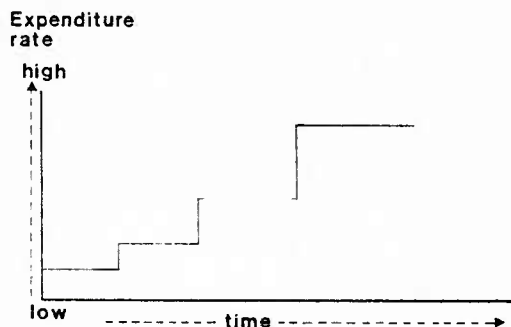


TABLE 4.
EXPENDITURE RATE OVER TIME

In general, the cost associated with an error will be higher in the later stages of a project. This occurs because the project develops more and more collateral documentation as time progresses. An early change in a basic concept may require only a rewrite to a few persons. The same change in a basic concept later in the project has a more substantial effect. Then, drawing sets and parts lists, test and operations manuals, schedules, and many other documents are affected. In addition, the coordination of such a change among design, test, financial, manufacturing, logistics and reliability, etc. requires an enormous effort. Thus, ceteris paribus, a change which occurs early will be less costly than that same change occurring later in the project.

The value of the learning path concept can be enriched even further. The learning path position is a measure of the areas of remaining uncertainty. As these uncertainties are reduced, changes are often required. In some cases the uncertainty reduction simply moves the project's original estimate of the correct solution from uncertain to certain. The more usual result is the need for a minor or major change.

The superimposition of the expenditure rate graph with the learning path graph provides an indication of the likely cost impacts. The conclusion is rather obvious. The uncertainty reduction on the early learning path occurs at a time when the rate of expenditure is low and thus, when the cost of change is low. In late learning many of the problems of the project are uncovered during the high rate of expenditure phases and the concomitant change costs are quite high. Thus, the reasonable conclusion is that THE KEY MANAGEMENT TASK IS TO CREATE AN EARLY LEARNING PATH.

So far this has been a conceptual discussion. There are many points which can be argued and probed and otherwise contested. These points, however, would not detract from the general conclusion that early learning is very valuable and that it is an important management responsibility to try to proceed on an early learning path. To accomplish such a result would require omniscience on that part of management. This is clearly not realistic. The lack of omniscience does not logically suggest that this presentation is not useful. Instead, what is called for are guidelines for managerial action that allow the project to move toward the ideal early learning path. That is, improvements in management style are possibly based upon both concept and data. The next section of this chapter raises the question of uncertainty diagnosis and suggests

appropriate managerial guidelines to follow the diagnosis.

UNCERTAINTY DIAGNOSIS

Guidelines for managerial actions depend upon the quality of the initial diagnosis and the ability to carry out the actions diagnostically suggested. To sharpen the manager's diagnostic capability, three distinct categories of uncertainty are defined: TECHNOLOGICAL, USE, and PROCESS. Within each category the issues of identification, of assessment and of implied managerial actions are discussed.

TECHNOLOGICAL UNCERTAINTY. The manager must initially examine each of the basic technologies which are to be used in the development project. Of particular interest is the question of the specific technological approach to be used in each of the key areas or subsystems. The diagnostic questions that should be asked about each approach focus on both the staff engaged in the approach and the technology itself. In the former category is the specific staff familiarity with the approach. In the latter category is the age or history of the approach, the ability to use analysis in problem solving and the level of intensity of previous work.

First, examine the selected approach's age. In a number of situations, the specific technological approach will be a standard design approach that has often been previously used. The staff will certainly have to adapt the approach to the explicit parameters of the situation but the approach itself is well known. This situation represents one end of the approach age spectrum. At the other end of the spectrum is an approach which has been created solely in response to the current presenting problem. This is an approach which looks very promising on paper but has not been tested. The managerial question here is whether the proposed approach can be reduced to practice in the time available for project completion. The managerial alternatives are to use an older and more certain approach, if it will deliver the performance necessary, or to take the risk and use the new approach. Sometimes, there are middle ground approaches which improve performance potential but still reduce the uncertainty of success.

A second diagnostic question focuses on the ability of a particular technology to be analyzed. Some technologies are clearly analytical and can be rather well defined without the gathering of test data or experience. Other technologies can only be approximated by analysis. Then test must be gathered and judgement applied to this test data before a successful solution is found.

The third diagnostic question is an inquiry about the level of intensity of previous work. A crude scale of intensity would start at the low end with simple analysis and proceed through component level tests performed on prototypes or partial mock-ups to higher level intensities such as tests of a full prototype in the laboratory. At the highest end would be testing of the approach with a production piece of equipment within the actual use environment.

Of course, the existence of a well developed approach does not drastically reduce the uncertainty, if this approach is being applied by a new technical staff. Very few complex ideas can be communicated for sophisticated use by simply reading about them. The subtleties of any technological product is, more often, than not a subject that can only be learned by experience. The so-called NIH (Not Invented Here) phenomena basically arises when talented personnel attempt to use an approach which they have read about but not experienced. Thus, in addition to the basic diagnostic questions that relate to the various technological approaches, one must ask about the specific experience of the project team.

This section's basic issue is the presentation of some guidelines for diagnosis so that the development manager can focus the project's various technological uncertainties. For clarity, the discussion has necessarily been an approximation of the true complexity of development. Enlightened management will use these guidelines to identify their uncertain areas and to search for ways to reduce these uncertainties in the early phases. What follows are some suggestions about appropriate actions that management might take under the various conditions of uncertainty.

The guidelines here are initially drawn from extensive examination of the parallel strategies used in the development of torpedo systems for the United States Navy. (Abernathy, 1979). This has been extended into commercial situations in the automobile industry (Abernathy, 1978).

Under conditions of staff inexperience, it is appropriate to develop a functional prototype early in the project and subject it to simulated use tests. This provides, as quickly as possible, an understanding of many of the subtleties of the overall design approach and serves to more quickly reduce major uncertainties. This approach may not be the obvious approach if other conditions in the technological area are straightforward but the key deficiency that arises from staff inexperience can only be helped by the experience of a rush-to-prototype test strategy.

When the age of the approach is ascertained, several managerial actions may be required. Early managerial intervention will be the best action if the subsystem approach has too short a history. As a simple guideline, unless a particular approach has been under serious investigation for approximately a year, then serious cause for concern exists and contingency plans should be formulated. New approaches are usually selected when performance requirements are higher than can be promised by the older approaches. But, in general, a new approach has a high probability of not being reducible to practice in time for current project needs. That is, the approach may still be sufficiently uncertain when the time comes to enter the production phase that serious delays and cost overruns are highly likely.

When such a new approach is selected, there are high probabilities that the project team will eventually find it necessary to fall back on an older approach. This older approach will still have to be adapted to the current project. The adaptation cost, at a late date, is significantly higher than would have occurred if the fallback approach had been carried along as a contingency. The managerial action suggested in this situation is to bring along the older approach in parallel with the newer approach. As well as adapting the older subsystem approach to the newer application, it is important that the larger system be designed so that it can relatively easily accept either of the two approaches. This enabling condition in the design involves additional costs, but should the contingency plan be necessary, these costs would have been incurred at the earlier less expensive phase of the project.

Of course, another possibility is to refuse to use approaches which have so little history and to select an approach with a high success probability. When high performance requirements are necessary this more conservative strategy would seem to be unattractive. But, then the contingency plans suggested above become much more important.

When a computer or other analytic assistance can determine the eventual system performance then the most appropriate uncertainty reducing method is the employment of an analytic strategy in the early phase of the project. On the other hand, when analysis can only approximate the performance results then other alternatives become better for early uncertainty reduction. Initially a system analysis is performed, followed by a sensitivity analysis of the results. The sensitivity analysis would indicate whether the range of likely results are acceptable. If they are acceptable then there is no particular problem. If the range of likely

results show areas where the performance may be unacceptable then the appropriate managerial action would be the initiation of a testing program aimed directly at the areas of potential underperformance. This two stage approach would seem to be the most effective in early reduction of the approach's uncertainty.

Even when management determines that the technical approach has been pursued for an extended period of time, they do not have sufficient cause for assuming a high probability of success. They still must ascertain the approach's intensity level. The higher the intensity level, the less the uncertainty. While the parallel strategy works well for low experience situations, it does not help in low intensity of experience situations. Here the more appropriate strategy is to quickly develop a prototype and engage in a testing program. An increase of the development's intensity level, even with only prototype hardware, will more quickly reduce the inherent uncertainty of the situation and still occur in the low cost early project phase.

To summarize, different situations suggest different strategies. This is captured in Table 1. In the area of technological uncertainty certain diagnostic questions can be asked and the answers can be used to suggest explicit managerial action that would serve to reduce the uncertainty of the project in the early phase and create an EARLY LEARNING PATH.

STAFF INEXPERIENCE	STAFF EXPERIENCE
Rush-to-prototype	Normal process
LOW AGE OF APPROACH	HIGH AGE OF APPROACH
Parallel Strategy	Single Strategy
NOT ANALYZABLE	ANALYZABLE
Normal Testing	Anal/Sens. Test Analysis
LOW EXPR. INTENSITY	HIGH EXPR. INTENSITY
Rush-to-Prototype	Analyze

Table 1.
STRATEGIES FOR TECHNOLOGICAL UNCERTAINTY

USE UNCERTAINTY. When envisioning a new product, process or service, an idealized image of the new idea's use is created. This simplification of the actual use situation provides a powerful communication device which can ease the explanation of the new concept's essential features. When faced with developing this concept, much attention is required to adapt it to the multifaceted details of actual use. The less a project team knows about the rich details of use, and possible misuse, the more use uncertainty exists. Here the term use uncertainty is meant to convey the level of knowledge of the actual use environment.

This uncertainty is a specific characteristic of the team undertaking the development.

The importance of the use environment can be illustrated with a rather simple example. When the procurement process is studied, certain logical decision rules are evident. If two proposals for a deep space experiment are received and they are identical in technical approach then there is no basis for selecting one over the other. If the organizations proposing the projects differ by the amount of experience they have in the deep space environment, then the one with greater knowledge would clearly be selected, *ceteris paribus*. This decision rule speaks to the generally held notion that a more thorough understanding of the use environment is a significant measure of the higher likelihood of success. Thus, a conventional wisdom is clearly on the side of the importance of level of knowledge of the use environment or its converse, the concept of use uncertainty.

In theoretical terms, the work of Richard Normann (1969) provides another explanation of this concept's importance. He defines two concepts: domain and distant environment. An organization's domain is the environmental sector with which it has frequent interaction. Because of this frequent interaction, the organization has developed a structure for receiving environmental information and making sense from it. This ability to read subtle cues in the environment allows the organization to proceed with relative sureness when it is operating within its domain. The distant environment represents the remaining environmental sectors. The key phenomena about stimuli arising in the distant environment is the organization's inability to make sense of the stimuli. The organization then must employ a mediator (consultant) to make sense of the stimuli and to inform the organization.

When the management determines that high use uncertainty exists, then one of two generic approaches can be taken to accomplish early uncertainty reduction. One is a rush-to-prototype approach which quickly provides the project team with equipment for field test. The field test provides first hand knowledge of many subtle details and possible problems in the proposed specific design. The second is the recruitment of personnel who have detailed knowledge of the use environment. This approach is similar to the NASA decision to have the astronauts as major members of the design teams. The astronauts provided insight and information that was far better than might have been provided by only an analytic approach. When faced with low use uncertainty management can look to the technical arena and make appropriate decisions based upon the uncertainties determined. High use uncertainty would suggest explicit rush-to-prototype or

recruitment strategies even if there were low technical uncertainty.

PROCESS UNCERTAINTY. This refers to the uncertainty introduced into the development processes by less than ideal management processes. Given two identical proposals with similar experience in the use environment there is no logic for selection. But when the respective managements are considered, there is often a clear cut distinction. Here, as above, conventional wisdom supports the importance of process uncertainty. It would be beyond the scope of this presentation to detail the diagnostic questions necessary for ascertaining the level of process uncertainty in a given situation. Suffice it to say that planning and control on one hand and organization on the other would be the natural focus of such questions.

SUMMARY

In brief, this chapter has argued, that THE KEY MANAGEMENT TASK IS TO CREATE AN EARLY LEARNING PATH. It has then followed this argument with the concept that uncertainty diagnosis is indeed possible and that differential findings would suggest different managerial actions. For this purpose, a set of guidelines for diagnosis and action within the three categories of TECHNOLOGICAL USE AND PROCESS UNCERTAINTY were proposed.

BIBLIOGRAPHY

- Freeman, R., et.al.; "Success and Failure in Industrial Innovation," Centre for the Study of Industrial Innovation, University of Sussex, 1972.
- Twiss, Brian; MANAGING TECHNOLOGICAL INNOVATION, (London: Longman, 1974).
- Goodman, Richard A. and Abernathy, William J., "Contributions of 'New Boy' Phenomena to Increasing Innovation and Development in New Technology," R & D MANAGEMENT, 9, 1, 33-41, 1978.
- Abernathy, William J., "Decision Strategies in R&D Projects," Graduate School of Management, UCLA, 1969.
- Abernathy, William J., THE PRODUCTIVITY DILEMMA: ROADBLOCK TO INNOVATION IN THE AUTOMOBILE INDUSTRY, (Baltimore: Johns Hopkins Press, 1978).
- Normann, Richard, "Some Conclusions from Thirteen Case Studies of New Product Development" Stockholm, Swedish Institute for Administrative Research, 1969.

ECONOMIC AND FINANCIAL
PERSPECTIVES ON
UNCERTAINTY IN AEROSPACE CONTRACTING

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ABSTRACT

Uncertainty in DOD Systems Acquisition lies specifically in the lack of knowledge characteristic in development of Systems requiring 'state-of-the-art' technology. While perhaps overly ambitious the only structured way to investigate these phenomena is with the assumption of macro efficiency and system delivery; and the use of a series of macro models. Consideration of the macro model leads to the following three hypotheses: first, for all firms as research to sales increases cost of sales ratio decreases; second, the above hypothesis will be more pronounced for civilian firms; third, civilian firms will be more efficient than government contractors in periods of high inflation variability.

INTRODUCTION

This paper has evolved from a study of the impact of inflation and other financial and managerial factors upon the economic viability of firms in the aerospace industry.

The study differs from other financial/managerial studies of the aerospace industry in that it accesses a data base that is extremely comprehensive, namely the publicly-reported business and financial information covering a large proportion of all prime as well as sub-contractor aerospace firms. Further, the methodology employed is unique in that it seeks to examine the financial strengths of firms by class of product or service offered, so that defense capabilities can be assessed more thoroughly.

PART I of the paper defines risk and uncertainty and compares the two concepts in light of tentative conclusions generated by a review of defense contracting over two decades.

PART II discusses preliminary version of an uncertainty model developed from the financial/managerial study of aerospace contracting firms progresses.

PART I

COMPARISON OF RISK AND UNCERTAINTY

1. Risk

Risk may be defined as a historically conceived phenomenon for which a historical probability may be established. For instance, it is well-known fact that all persons die at one time or another. Given society's and business's long experience with this phenomenon, certain tables have been developed to show that a person at a given age will, in all probability, live for n more years, or will live until N_1 .

Insurance policies, written for large numbers of persons of a given age, can "insure" the person against a premature death--death prior to his expected life span. If the company writes sufficient policies, the person who dies unexpectedly at a younger age will find the insurance policy monies will be sent to his/her estate, while the company recovers/overall costs from all insurance premiums plus investment earnings.

The risk that the person (any given person or persons) will die before the given life expectancy is included in the premium charged. There is no doubt that the person will (eventually) die. The only doubt is WHEN the person will die. That doubt--risk of early death--could be insured against.

2. Uncertainty

Certainty or uncertainty finds its key in the existence of knowledge.¹ The relationship is inverse in that as the level of knowledge increases the degree of uncertainty decreases. It is precisely the fact that uncertainty is greatest when knowledge is at its lowest level that distinguishes uncertainty from risk.

Uncertainty and risk can be seen clearly in the case of prime contracting for major weapons systems, designed to fulfill a specific mission and judged at least partially with reference to the kind of mission. The mission purpose is often found to require an advanced technology or high degree of technological skill that has not been perfected. The technology required may not be simply 'state-of-art.' At this point, not knowing the design, production and performance problems required to produce the system the areas of uncertainty are highest precisely because the level of knowledge regarding design, technology cost and contractor performance is lowest.

3. Department of Defense Views of Risk and Uncertainty in the Weapons System Contracting Process: A Question of Priorities

Certainty for the Department of Defense in the design and acquisition of a weapons system would exist only if the Air Force decided to design and let for contract production and acquisition of a weapons system already known, such as the F4 Phantom. For that kind of weapons system there would be certainty in the contracting process, and the DOD would be in the comfortable position of being able to manage the entire process from conception to operation and support. Certainty would exist because there would be complete knowledge, with the possible exception of erratic or inflationary cost increases.

Uncertainty, however, would exist if the Air Force were attempting to develop a new system that involved a technology in advance of 'state-of-the-art' technology. The uncertainty would exist because of the simple fact of lack of knowledge. The lack of knowledge or uncertainty would inevitably cause errors.

In the period before 1962 when the Department of Defense employed cost-plus contractual arrangements, emphasis was placed upon performance rather than cost control. The cost was increased or the schedule was delayed until the problem was solved, such that the system could perform at the desired level. Since 1972, with the establishment of the incentive contract, a higher priority has been placed on cost minimization. In the light of present contracting policies implemented by the Congress, White House and Department of Defense, uncertainty must be examined in light of cost minimization.

4. Categories of Uncertainty and The DOD

To this end, let us examine this question as it has been presented in the DOD/FAI Acquisition Research Symposia. The DOD appears to be concerned with three types of uncertainty in the contracting-acquisition process:

Design and technology uncertainty;

Uncertainty regarding the ability of the contractor to meet the terms of the contract (scheduling); and

Cost uncertainty.

a. Design Uncertainty

Uncertainty with respect to design often results from uncertainty about technology. "This type of uncertainty is and probably will remain a fact of life for the Department of Defense. Defense contracting deals with an unparalleled rate of technological development which makes costly programs a way of life."² Technology problems have led to 60% of cost overruns.³

If the rate of technological innovation and demand by the DOD for sophistication continues as in the past, technological/design uncertainty will continue to be a major issue in consideration of the contracting process.

b. Contractor Uncertainty

The second type of uncertainty involves the ability of the contractor to meet the terms of the contract. Here, the DOD is concerned with quality and delivery. Will the contractor be able to produce the product as contracted? Will we get the goods in time? Contractor uncertainty also includes terms of maintenance and, possibly, support. Will the contractor be able to back his product? Will the product be useful for an appropriate period of time?

c. Cost uncertainty

Cost uncertainty arises because of incorrect projections of increases in prices of input factors such as labor and materials. These uncertainties are economic by nature. But cost uncertainty may also encompass the uncertainties of the previously mentioned types. In other words, besides not being certain what the project will cost given that we are assured of optimal conditions, the other conditions of uncertainty also contribute to cost fluctuation.

5. Risk, Uncertainty and The Goals of The DOD

Before outlining the DOD's approach to these three types of uncertainty, it is important that we consider the goals of the DOD. The survey of the literature indicates the goals which are important:

1. Performance--having the best or most appropriate weapon system. Here, design and technology are key factors;
2. Scheduling--being able to deliver the system where and when it is needed; and
3. Cost minimization.

These goals are often conflicting and may even be exclusive of one another. For example, to get the best weapon, one may need to wait for (X+1) amount of time, even though the weapon is needed at time (X). And the best weapon at an optimal time could be the most expensive. It is obvious that these conditions can occur in the course of the contract. How does the DOD reach a decision? The "Goal Programming Approach," outlined in the literature, seems to best describe the DOD decision making process. The Goal Programming Approach seeks to satisfy a set of goals (often conflicting) which are structured as constraints. The importance of each goal is indicated by the priority placed on the goal.⁴ The vital ques-

tion to be asked in each specific case of procurement is "What priority is placed on each goal?" And "What priority should be placed on each goal?" These questions may have different answers.

6. Relationships Among Uncertainty, Goals and Cost Minimization

Design/Technology Uncertainty affects the goal of performance. To be uncertain of whether a design is appropriate or whether the technology will be effective will affect both the performance and quality of the system eventually delivered. Thus, the reduction of uncertainty is design/technology would enhance performance. It is therefore relevant and important for DOD to deal with uncertainty in this respect. Similarly, uncertainty concerning the contractor's ability to meet contractual arrangements affects the goal of scheduling. And finally, cost uncertainty affects the cost minimization goal. In addition, all of the above uncertainties compound the effect on cost. Thus, the goal of cost minimization is affected at every stage of uncertainty: "High systems cost and cost growth (cost uncertainty) appear to arise primarily from efforts to subdue difficult technology (technology uncertainty)...and the acceptance of optimistic assumptions about long term predictability of technology and the cost of coping with it (all three uncertainties).⁵ Cost overruns have been documented in the literature to be as high as 243% over original estimates and could be even greater.⁶

The design-to-cost concept DTC was formulated by the DOD with the specific objective of cost minimization. The earliest DTC literature studied (1972) states the objectives: "The DOD directive 5000.1 has placed new emphasis upon designing to a specific cost objective. This concept of controlling costs-to-produce while a product is being developed is supported with adequate industrial management disciplines which are within the public body-of-knowledge."⁷ The procedure has operated on the basis of cost "ceilings," thus, it seems that cost-minimization has been the primary goal, and the performance goal had been subordinated: the DOD contracted for "The most performance for the approved cost-function." But, as the design-to-cost concept has progressed through time and experience, the focus has shifted. There is still cost awareness, but performance is rapidly becoming the primary goal:

"Today, government and industry find themselves operating in an environment that entails responsibility for selecting design concepts, materials, and processes that, in combination, yield systems that require the least cost to acquire and maintain while still achieving performance goals."⁸

(See also notes 9 - 15)

7. Reflections

Much of the remainder of the discussions in the Symposia proceedings deal with how the DOD can minimize the uncertainty in the contracting process. As long as cost minimization is a priority of the DOD,

design and performance uncertainty will remain. One way of solving the 'knowledge gap' in the areas of technology is using money for research. However, even if money were available in unlimited amounts for contracting, it is not clear that uncertainty could be eliminated. When systems require technology that is in advance of 'state-of-the-art' technology, uncertainty will probably remain the critical element in DOD systems acquisition.

PART II

THE ASSESSMENT OF UNCERTAINTY

1. Uncertainty, Priorities, and The Research Function

As stated in Part I, uncertainty forces decision makers to resort to priorities in dealing with the unknown. The point of attack has been research. The approach is to employ pure research as an aid in setting priorities at the outset and then to use the resulting priorities in selecting the applied research projects to help in resolving performance, delivery, and cost uncertainties.

Many techniques for setting priorities may be involved. The setting of priorities may encompass goal programming, for example. Basic research may employ the DELPHI technique as well as scientific experimentation.

2. DOD Policy and The R & D Expenditure

Research expense (R & D) is one of the outlays most readily controllable in cost control programs, since it is a managed or budgeted cost. As a result, R & D expense has probably decreased as a percentage of government aerospace contracting cost, consequently firms may have become less efficient in meeting delivery and performance standards. Many problems which could have been detected early through R & D do not appear until well into the production or the deployment stage, where they become much more expensive to correct.

Developers of military aerospace systems probably confront more unknowns than do developers of civilian aerospace systems. For example, it is probably more difficult to discern the reprisal tactics of an enemy than of a competitor. And the stakes are immensely higher, adding to the pressure for correct decisions.

Yet civilian aerospace expenditures for research may be higher, in proportion to sales, than is true of the military. There may be just as pronounced a relationship between the R & D expenditure level and the efficiency of the civilian aerospace firm. One significant factor in this relationship may be capital intensity. Where proper equipment exists, research may be more fruitful and may be encouraged, as could be the case more often with non-government aerospace contractors.

3. Efficiency, R & D and Uncertainty

It is possible to design a model for investigating the efficiency/R & D? uncertainty issue at an aggregate level. Employing the variables discussed above, the following model may be considered:

$$\text{COS} = f(\text{GSALE}, \text{RESALE}, \text{COR})$$

The variables are identified as follows:

- COS Ratio of COST OF SALES to SALES,
 (the independent efficiency variable);
- GSALE Percent of SALES to government,
 (independent profit variable distinguishing military from civilian contractors);
- RESALE Ratio of R & D EXPENDITURES to SALES
 (independent variable denoting level of research effort); and
- COR Capital Output Ratio, Ratio of TOTAL ASSETS
 to NET SALES
 (independent variable denoting capital intensity.)

The research issues to be confronted. The central issue, oversimplified initially, is whether firm efficiency is related to R & D expenditures. The GSALE variable allows us to ask this question of civilian contractors first, then of military contractors, dividing the sample into the two groups, for more effective study.

Our fundamental premise is that, if firms in general are efficient at the (macro) cost level, using COS, then individual firms in that group will also be efficient in fulfilling design and contractor performance requirements at the micro level. For example, a firm that meets customer demands for quality in civilian markets or on civilian contracts, maintaining cost control and profitability, is also likely to meet government contracting standards and still control costs. Symbolically, we may express the relationship as follows:

$$\text{COS} \uparrow = \text{EFFICIENCY} \uparrow = \text{More Effective Design and Contractor Performance on All (Including Government) Contracts}$$

Specific hypotheses to be investigated.

1. For all aerospace firms, military and civilian, as RESALE increases COS ratio decreases and vice versa. Symbolically:

$$\frac{\Delta \text{COS}}{\Delta \text{RESALE}} < 0$$

- ii. The above relationship will be more pronounced for civilian contractors because COR may be higher for civilian firms. Symbolically:

$$\left[\frac{\Delta \text{COS}}{\Delta \text{RESALE}} \right]_C < \left[\frac{\Delta \text{COS}}{\Delta \text{RESALE}} \right]_M$$

- iii. Civilian contractors will be even more efficient than military contractors in periods of high variability in inflation rates, in spite of the advantages of the incentive type of military contract. This is because R & D--including value analysis, will aid in controlling cost increments. The civilian contractor has more flexibility in using the R & D budget for cost control, (intensifying applied research and de-emphasizing pure research as conditions dictate).

The obvious overall issue is whether high--R & D--expenditure firms have customarily delivered high quality, timely, low cost systems. We have used a linkage assumption--namely, that efficient firms at the aggregate level usually deliver more effectively. This assumption bears further investigation.

A second complication relates to the sources and objectives of R & D funding. Two possibilities exist. First, firm-sponsored, general R & D is not necessarily attributable to specific government (or even to specific aerospace) projects. Second, government-sponsored R & D (say Milestone I research) is generally attributable to specific government projects.

In order to draw more realistic conclusions, it may be necessary to distinguish between sources and objectives of R & D expenditures for each segment in the sample.

PART III

SUMMARY AND CONCLUSIONS

The investigative approach described in this paper employs financial data relative to a large sample of both government and non-government contracting firms in an effort to assess uncertainty in government contracting. Three elements of uncertainty are discussed: contractor performance, design/technology, and cost. Since financial data can be applied only to the cost element, a critical assumption is that firms that control costs effectively are also successful in meeting design and performance criteria. Since producers find themselves resorting to priorities in resolving uncertainty issues, it is found that research is helpful in setting the critical priorities. Since those firms with a more modern plant (including laboratories) may be better equipped to do research, capital intensity probably has a significant bearing

upon the quality and usefulness of the research carried out.

The factors discussed are combined into a set of hypotheses that appear promising in the assessment of uncertainty. A first hypothesis states that those firms that control costs more efficiently engage in research more intensively than is true of less efficient firms. A second hypothesis is that more highly capital intensive firms may be better equipped to do research and that, consequently, firms that engage in research more intensively are more cost efficient. A third hypothesis states that, because of the more intensive research efforts of civilian contractors, they will be more efficient than military contractors in controlling costs, meeting design criteria and meeting performance criteria in periods of highly variable inflation rates. To investigate these hypotheses, the authors have designed a research model relating COST EFFICIENCY, (as the dependent variable), to PERCENT OF SALES TO THE GOVERNMENT, RESEARCH EXPENDITURE/REVENUE ratio and CAPITAL INTENSITY ratio (as the independent variables). The research design contemplates examining the model's various relationships through periods of both high and low inflation variability in order to test the hypotheses and to assess uncertainty.

BIBLIOGRAPHY

1. 1977, Major William J. Weida, "A General Technique for R & D Cost Forecasting," p. 61.
 2. 1978, E. B. Cochran, "Measuring and Predicting Production Disruption: Costs Due to Design Uncertainty and Delivery Urgency," p. 67.
 3. 1973, "Cost Estimating Summary," p. 138. This article states the 60% figure for 1973. The high rate of technological development in the last seven years could mean that this figure is substantially higher.
 4. 1975, John M. Gleason, "Goal Programming Approach to Purchasing Decisions," p. 8.
 5. 1977, E. B. Cochran and A. J. Rowe, "The Sources of Disruption to Project Cost and Delivery Performance" p. 536 Parentheticals mine.
 6. 1977, p. 32, Table summing statistics. This summary only includes nine projects that were surveyed. High technology could cause overruns to be even higher, as analysis should not be limited to this survey of 9 projects.
 7. 1972, Raymond D. Gilbert, "Designing for Cost - To Produce," p. 60.
 8. 1978, M. Elkin, "Integrated Manufacturing Cost Estimating System," p. 89.
 9. 1973, R. E. Freeman, "Keynote Speech," p. 74.
 10. 1973, "Cost Estimating Summary," p. 139.
 11. 1977, Martin D. Martin, "Uncertainty Assessment for the Development Contract," p. 113.
 12. 1973, Freeman, p. 85.
 13. 1974, Jon Byers, "Risk Analysis," p. 219.
 14. 1977, Cochran and Rowe, pp. 560-62.
 15. 1977, *Ibid*, p. 535.
- Additional References:
16. 1978, J. F. Drake, "The Maverick AGM-65A, A Successful Total Package Procurement," p. 144.
 17. 1977, Felix, M. Fabian, "Mixed Procurement and the Management of Risk," p. 611.
 18. 1972, Raymond G. Hunt, "Extra-Contractual Incentives and the Award Fee," p. 77.
 19. 1978, Richard De Mong, "The Effectiveness of Incentive Contracting: What Research Tells Us," p. 265.
 20. 1978, *Ibid*, p. 264.
 21. 1975, Robert Lucas and Robert Tripp, "Risky Trend in Warranties," pp. 175-8.
 22. 1974, Peter De Mayo, "The Use of Warranties to Support a Reliability/Maintainability Philosophy," p. 72.
 23. *Ibid*, p. 77.
 24. 1978, Harold S. Balaban and Martin H. Meth, "Contractor Risk Associated with Reliability Improvement Warranty," p. 290.
 25. 1975, Joseph E. Boyett, Lynn M. Lynch, and Neil V. Raymond, "Cost Estimating Relationships for Life Cycle Cost," p. 71. See also 1978, p. 59.
 26. 1978, Joleroy Gauger, "A New Prediction Methodology - The Mature Industry Approach," p. 59.
 27. 1975, A. M. Feiler, "Project Management through Simulation," p. 140.
 28. 1975, *Ibid*, p. 140.
 29. 1977, Cochran and Rowe, p. 568.
 30. 1973, R. G. Freeman, p. 65.
 31. 1978, Robert Judson, "Mission Management: The Responsibility of Project Managers," p. 239.
 32. 1978, Thomas G. Farrell and Edward T. Timberlake, "Project Meteor: Motivating Everyone to Enhance Operational Reliability Maintainability," p. 377.

32. Adams, J. R., Stephen E. Barndt and Martin D. Martin, Managing By Project Management. (Universal Technology Corporation 1656 Mardon Drive, Dayton, Ohio, 45432, 1979.)

