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FINAL REPORT

"Fundamental Investigations in Methods of Operations Research"

U.S. Army Research Office - Durham
ARO-D Project Number P-9239-M
Contract DAHC04-70-C-0058
M.I.T. DSR 72650

Contract Period: July 1, 1970 - June 30, 1973

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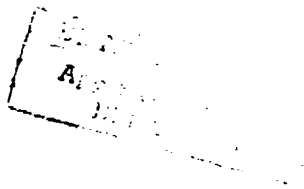
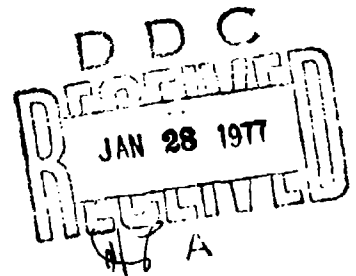
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ARO-D Project Number P-9239-M
Contract DAHC04-73-C-0032
M.I.T. OSP 81219

Contract Period: July 1, 1973 - May 31, 1976

Principal Investigators: John D.C. Little
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FINAL REPORT TO ARO-D

This final report covers the contract period, July 1, 1970 through May 30, 1976. Professor John D.C. Little, former Director of the Operations Research Center, was Principal Investigator from July 1, 1970 through May 30, 1976. Joining him as Co-Principal Investigator during that period was Professor Jeremy F. Shapiro, former Associate Director of the Operations Research Center. Professor Little was on-leave from M.I.T. from June 1, 1975 through May 30, 1976. At the end of that period he resigned as Director of the Operations Research Center. Professor Shapiro served as Acting Director of the Center during Professor Little's leave; he continues to hold that position.

STATEMENT OF PROBLEM STUDIED

This project was concerned with basic research into methods of operations research, especially mathematical programming and their applications to a variety of decision problems. Basic research in mathematical programming included the development and testing of a new duality theory for integer and combinatorial programming, new methods for linear fractional programming, a synthesis of duality theory and dynamic programming and results illuminating the relationship between generalized linear programming and mathematical programming duality theory. Additional basic research was performed on Markovian decision models and fixed point theory, network optimization models and multi-attributed utility theory. Mathematical programming methods and models were applied to a variety of problems including machine replacement, energy planning, pollution control and location problems.

PUBLICATIONS supported entirely or in part by ARO-D during the contract period:

Journal Articles and Books

Fisher, M.L., W.D. Northup and J.F. Shapiro, "Using Duality to Solve Discrete Optimization Problems: Theory and Computational Experience," Mathematical Programming Study 3, North-Holland Publishing Company, 1975, pp. 56-94.

Gartner, N.H. and J.D.C. Little, "Generalized Combination Method for Area Traffic Control," Transportation Research Record 531, Transportation Research Board, Washington, D.C., 1975.

Gorry, G.A. and J.F. Shapiro, "An Adaptive Group Theoretic Algorithm for Integer Programming Problems," Management Science 17, No. 5, January 1971, pp. 285-306.

Gorry, G.A., J.F. Shapiro and L.A. Wolsey, "Relaxation Methods for Pure and Mixed Integer Programming Problems," Management Science 18, No. 5, January 1972, pp. 229-239.

Keeney, R.L., "Utility Independence and Preferences for Multiattribute Consequences," Operations Research 19, No. 4, July-August 1971, pp 875-893.

Publications, cont.

Keeney, R.L., "Utility Functions for Multiattributed Consequences," Management Science 18, No. 5, January 1972, pp. 276-287.

Magnanti, T.L., "Complementary Bases of a Matroid," Discrete Mathematics 8, June 1974, pp. 355-361.

Magnanti, T.L., "Fenchel and Lagrange Duality are Equivalent," Mathematical Programming 7, October 1974, pp. 253-258.

Magnanti, T.L., "Optimization for Sparse Systems," Sparse Matrix Computations, 1976.

Morse, P.M., "Search Theory and Browsing," The Library Quarterly 40, No. 4, October 1970, pp. 391-408.

Morse, P.M., "Measures of Library Effectiveness," The Library Quarterly 42, No. 1, January 1972, pp. 15-30.

Morse, P.M., "Optimal Linear Ordering of Information Items," Operations Research 20, No. 4, July-August 1972, pp. 741-751.

Morse, P.M. and H.J. Jaffe, "A Queueing Model for Car Passing," Transportation Science 5, No. 1, February 1971, pp. 48-63.

Shapiro, J.F., "Generalized Lagrange Multipliers in Integer Programming," Operations Research 19, No. 1, January-February 1971, pp. 68-76.

Shapiro, J.F., "A Decomposition Algorithm for Integer Programming Problems with Many Columns," Proceedings of 25th Annual ACM Conference, Boston, August 1972, pp. 528-533.

Shapiro, J.F., "Constructive Duality in Integer Programming," SIAM Journal of Applied Mathematics 27, July 1974, pp. 31-52.

Shapiro, J.F., "OR Models for Energy Planning," Computers and Operations Research 2, December 1975, pp. 145-152.

Shapiro, J.F., "Brouwer's Fixed Point Theorem and Finite State Space Markovian Decision Theory," Journal of Mathematical Analysis and Its Applications 49, March 1975, pp. 710-712.

Shapiro, J.F., "A Survey of Applications of Integer and Combinatorial Programming in Logistics," Chapter 16 in Modern Trends in Logistics Research, edited by W.H. Marlow, MIT Press, 1976.

Shapiro, J.F., "Multiple Criteria Public Investment Decision Making by Mixed Integer Programming," in Multiple Criteria Decision Making, edited by H. Thiriez and S. Zionts, Springer-Verlag, 1976, pp. 170-182.

Publications, cont.

Welsch, R.E., "A Weak Convergence Theory for Order Statistics from Strong-Mixing Processes," Annals of Mathematical Statistics 42, No. 5, October 1971, pp. 1637-1646.

Welsch, R.E., "Limit Laws for Extreme Order Statistics from Strong-Mixing Processes," Annals of Mathematical Statistics 43, No. 2, April 1972, pp. 439-446.

Technical Reports and Working Papers

Asser, S.E.T., "An Algorithm to Solve the N^{th} Shortest Path Problem," Technical Report No. 89, M.I.T. Operations Research Center, January 1974.

Bell, D.E., "A Utility Theory Approach to Preferences for Money Over Time," Technical Report No. 72, M.I.T. Operations Research Center, June 1972.

Bell, D.E., "The Resolution of Duality Gaps in Discrete Optimization," Technical Report No. 81, M.I.T. Operations Research Center, August 1973.

Bell, D.E. and J.F. Shapiro, "Nuclear Reactor Refueling Optimization," Working Paper WP-74-32, International Institute for Applied Systems Analysis, Vienna, Austria, August 1974.

Bell, D.E. and J.F. Shapiro, "A Finitely Convergent Duality Theory for Zero-One Integer Programming," Working Paper OR 043-75, M.I.T. Operations Research Center, May 1975.

Bitran, G.R. and T.L. Magnanti, "Duality and Sensitivity Analysis for Fractional Programs," Working Paper OR 035-74, M.I.T. Operations Research Center, May 1974.

Bitran, G.R. and T.L. Magnanti, "Fractional Programming: Duality, Algorithms, Sensitivity Analysis and Applications," Technical Report No. 92, M.I.T. Operations Research Center, July 1974.

Bitran, G.R. and T.L. Magnanti, "Duality and Sensitivity Analysis for Fractional Programs, Working Paper OR 042-75, M.I.T. Operations Research Center, April 1975.

Crowston, W.B. and M.H. Wagner, "Lot Size Determination in Multi-Stage Assembly Systems," Working Paper 508-71, M.I.T. Sloan School of Management, 1971.

D'Aversa, J.S. and J.F. Shapiro, "Optimal Machine Maintenance and Replacement by Linear Programming," Working Paper 609-72, M.I.T. Sloan School of Management, August 1972.

D'Aversa, J.S., J.F. Shapiro and J.R. Holding, "Optimal Machine Maintenance and Replacement by Linear Programming," Working Paper OR 032-74, M.I.T. Operations Research Center, February 1974.

Publications, cont.

Fisher, M.L. and J.F. Shapiro, "Constructive Duality in Integer Programming," Working Paper OR 008-72, M.I.T. Operations Research Center, April 1972.

Fisher, M.L. and J.F. Shapiro, "Constructive Duality in Discrete Optimization," Working Paper 625-72, M.I.T. Sloan School of Management, November 1972.

Gartner, N.H., "Area Traffic Control and Network Equilibrium," Working Paper OR 041-75, M.I.T. Operations Research Center, March 1975.

Gartner, N., J.D.C. Little and H. Gabbay, "Optimization of Traffic Signal Settings in Networks by Mixed-Integer Linear Programming," Technical Report No. 91, M.I.T. Operations Research Center, March 1974.

Golden, B.L., "A Minimum-Cost Multicommodity Network Flow Problem Concerning Imports and Exports," Technical Report No. 105, M.I.T. Operations Research Center, September 1974.

Golden, B.L., T.L. Magnanti and H.Q. Nguyen, "Implementing Vehicle Routing Algorithms," Technical Report No. 115, M.I.T. Operations Research Center, September 1975.

Gorry, G.A., W.D. Northup, J.F. Shapiro and C.H. Zakovi, "A Group Theoretic Integer Programming Algorithm: System Design and Computational Experience," Working Paper 513-71, M.I.T. Sloan School of Management, February 1971.

Green, C. and T.L. Magnanti, "Some Abstract Pivot Algorithms," Working Paper OR 031-74, M.I.T. Operations Research Center, February 1974.

Green, C. and T.L. Magnanti, "Some Abstract Pivot Algorithms," Working Paper OR 037-74, M.I.T. Operations Research Center, August 1974.

Haehling von Lanzanauer, C. and D.D. Wright, "Developing an Optimal Repair-Replacement Strategy for Pallets," Working Paper OR 047-76, M.I.T. Operations Research Center, February 1976.

Handler, G.Y., "Minimax Network Location: Theory and Algorithms," Technical Report No. 107, M.I.T. Operations Research Center, November 1974.

Hauser, J.R., "Modeling Decisions of Choice Among Finite Alternatives: Applications to Marketing and to Transportation Demand Theory," Working Paper OR 038-74, M.I.T. Operations Research Center, October 1974.

Hauser, J.R. and G.L. Urban, "A Normative Methodology for Modeling Consumer Response to Innovation," Technical Report No. 109, M.I.T. Operations Research Center, May 1975.

Keeney, R.L., "Risk Independence and Multiattributed Utility Functions," Working Paper OR 001-71, M.I.T. Operations Research Center, June 1971.

Publications, cont.

Kleindorfer, P.R. and W.M. Hawkins, III, "Optimal Distributed Lags and the Horizon Problem," Technical Report No. 62, M.I.T. Operations Research Center, May 1971.

Kleitman, D.J. and T.L. Magnanti, "On the Number of Latent Subsets of Intersecting Collections," Working Paper OR 012-72, M.I.T. Operations Research Center, October 1972.

Magnanti, T.L., "Complementary Bases of a Matroid," Working Paper OR 013-73, M.I.T. Operations Research Center, January 1973.

Magnanti, T.L., "A Linear Approximation Approach to Duality in Nonlinear Programming," Working Paper OR 016-73, M.I.T. Operations Research Center, April 1973.

Magnanti, T.L., "Nonlinear Programming and the Maximum Principle for Discrete Time Optimal Control Problems," Working Paper OR 018-73, M.I.T. Operations Research Center, July 1973.

Magnanti, T.L., "Fenchel and Lagrange Duality are Equivalent," Working Paper OR 036-74, M.I.T. Operations Research Center, July 1974.

Magnanti, T.L., J.F. Shapiro and M.H. Wagner, "Generalized Linear Programming Solves the Dual," Working Paper OR 019-73, M.I.T. Operations Research Center, September 1973.

Marsten, R.E. and T.L. Morin, "An Algorithm for Nonlinear Knapsack Problems," Technical Report No. 95, M.I.T. Operations Research Center, May 1974.

Marsten, R.E. and T.L. Morin, "Parametric Integer Programming: The Right-Hand-Side Case," Working Paper OR 050-76, M.I.T. Operations Research Center, March 1976.

Marsten, R.E. and T.L. Morin, "A Hybrid Approach to Discrete Mathematical Programming," Working Paper OR 051-76, M.I.T. Operations Research Center, March 1976.

Mehta, C.R., "Multiperiod Adaptive Control of the Wellhead Price of Natural Gas: A Bayesian Decision Theoretic Approach," Technical Report No. 100, M.I.T. Operations Research Center, August 1974.

Morse, P.M., "Optimal Linear Ordering of Information Items," Technical Report No. 65, M.I.T. Operations Research Center, June 1971.

Morse, P.M., "The Geometric and the Bradford Distribution, A Comparison," Working Paper OR 049-76, M.I.T. Operations Research Center, February 1976.

Patel, N.R., "A Model for Optimal Dynamic Control of Emissions," Working Paper OR 009-72, M.I.T. Operations Research Center, May 1972.

Publications, cont.

Patel, N.R., "Optimal Control of Sulfur Dioxide Emissions at Power Stations: Models and a Case Study," Technical Report No. 82, M.I.T. Operations Research Center, September 1973.

Robinson, W.O., "Multivariate Probability Assessment," Technical Report No. 60, M.I.T. Operations Research Center, May 1971.

Rousseau, J.M., "A Cutting Plane Method for the Fixed Cost Problem," Technical Report No. 108, M.I.T. Operations Research Center, March 1975.

Shapiro, J.F., "A Generalized Programming Algorithm for Integer Programming Problems with Many Columns," Working Paper 556-71, M.I.T. Sloan School of Management, August 1971.

Shapiro, J.F., "A New Duality Theory for Mixed Integer Programming," Working Paper OR 033-74, M.I.T. Operations Research Center, April 1974.

Shapiro, J.F., "A Survey of Applications of Integer and Combinatorial Programming in Logistics," Working Paper WP-74-35, International Institute for Applied Systems Analysis, Vienna, Austria, August 1974.

Shapiro, J.F., "A Note on the Primal-Dual and Out-of-Kilter Algorithms for Network Optimization Problems," Working Paper OR 040-75, March 1975.

Shapiro, J.F., "Multiple Criteria Public Investment Decision Making," Working Paper 788-75, M.I.T. Sloan School of Management, May 1975.

Shapiro, J.F., "OR Models for Energy Planning," Working Paper 799-75, M.I.T. Sloan School of Management, July 1975.

Shapiro, J.F., "Steepest Ascent Decomposition Methods for Mathematical Programming/Economic Equilibrium Energy Planning Models," Working Paper OR 046-76, M.I.T. Operations Research Center, February 1976.

Shapiro, J.F., "Sensitivity Analysis in Integer Programming," Working Paper OR 048-76, M.I.T. Operations Research Center, February 1976.

Shwimer, J., "Interaction Between Aggregate and Detailed Scheduling in a Job Shop," Technical Report No. 71, M.I.T. Operations Research Center, May 1972.

Tien, J.M., "Control of a Two Customer Class Interactive-Multi-Facility Queuing System," Technical Report No. 73, M.I.T. Operations Research Center, June 1972.

Ting, H.M., "Aggregation of Attributes for Multiattributed Utility Assessment," Technical Report No. 66, M.I.T. Operations Research Center, August 1971.

Publications, cont.

Wagner, M.H., "Constructive Fixed Point Theory and Duality in Nonlinear Programming," Technical Report No. 67, M.I.T. Operations Research Center, September 1971.

Welsch, R.E., "A Weak Convergence Theorem for Order Statistics from Strong-Mixing Processes," Technical Report No. 57, M.I.T. Operations Research Center, December 1970.

Wilde, N.W.G., "Numerical Analysis and Approximation Methods in Discrete-Time Dynamic Programming," Technical Report No. 64, M.I.T. Operations Research Center, June 1971.

SCIENTIFIC PERSONNEL supported entirely or in part by ARO-D during the contract period:

Professor John D.C. Little

November 1, 1970 - May 31, 1971
September 1, 1971 - May 31, 1972
September 1, 1972 - May 31, 1973
September 1, 1973 - May 31, 1974
September 1, 1974 - May 31, 1975
September 1, 1975 - January 15, 1976

Professor Thomas L. Magnanti

June 1, 1972 - June 30, 1972
January 16, 1973 - May 31, 1973
September 1, 1973 - May 31, 1974
September 1, 1974 - May 31, 1975

Professor Philip M. Morse

April 1, 1971 - May 31, 1971
October 1, 1972 - June 30, 1973
September 1, 1973 - May 31, 1974
September 1, 1974 - September 30, 1974

Professor Jeremy F. Shapiro

July 1, 1970 - July 31, 1970
June 1, 1971 - June 30, 1971
July 1, 1973 - July 31, 1973
July 1, 1974 - July 31, 1974
July 1, 1975 - July 31, 1975

Professor Ronald W. Wolff

October 1, 1971 - May 31, 1972

Steven M. Barta

September 1, 1973 - December 31, 1973
September 1, 1974 - January 15, 1975

David E. Bell

September 1, 1971 - January 15, 1972
September 1, 1972 - June 30, 1973

Oded Berman

September 1, 1974 - March 31, 1975

Jeremy A. Bloom

September 1, 1973 - September 30, 1973
March 1, 1974 - March 31, 1974

Robert E. Brooks

July 1, 1975 - August 15, 1975

Kenneth R. Chelst

March 1, 1973 - April 30, 1973

Scientific Personnel, cont.

Samuel S. Chiu
September 1, 1975 - January 15, 1976

Joseph S. D'Aversa
January 16, 1974 - May 31, 1974
September 1, 1975 - January 16, 1976

Rene Dionne
September 1, 1970 - May 31, 1971

Dorothy P. Elliott
September 1, 1975 - April 30, 1976

Susan Finger
September 1, 1974 - May 31, 1975

Henry Gabbay
January 1, 1973 - May 31, 1973

Bruce L. Golden
September 1, 1973 - December 31, 1974
February 1, 1975 - April 30, 1975

John R. Hauser
September 1, 1974 - January 15, 1975

John A. Mazzarino
September 1, 1974 - May 31, 1975

Scott A. Neslin
December 1, 1974 - January 15, 1975

Nitin R. Patel
September 1, 1972 - January 15, 1973

Jean-Marc Rousseau
October 1, 1970 - May 31, 1971
September 1, 1971 - May 31, 1972

Hubert M. Tavernier
September 1, 1970 - January 31, 1971

Norman W.G. Wilde
July 1, 1970 - January 15, 1971

DEGREES AWARDED during contract period, supported (in part) by ARC-D:

Abtahi, Saeed, "Application of Integer Programming to Municipal Bond Bidding," S.M. thesis, supervised by Prof. J.F. Shapiro, September 1973.

Degrees Awarded, cont.

Asser, Sylvain, E.T., "An Algorithm to Solve the N^{th} Shortest Path Problem," S.M. in O.R. thesis, supervised by Prof. E.G. Frankel and Prof. T.L. Magnanti, February 1974.

Bell, David E., "A Utility Theory Approach to Preferences for Money Over Time," S.M. in O.R. thesis, supervised by Prof. R.L. Keeney, June 1972.

Bell, David E., "The Resolution of Duality Gaps in Discrete Optimization," PhD in O.R. thesis, supervised by Prof. J.F. Shapiro, September 1973.

Bitran, Gabriel R., "Fractional Programming: Duality, Algorithms, Sensitivity Analysis and Applications," S.M. in O.R. thesis, supervised by Prof. T.L. Magnanti, June 1974.

Bitran, Gabriel R., "Admissible Points and Vector Optimization: A Unified Approach," PhD in O.R. thesis, supervised by Prof. T.L. Magnanti, February 1975.

Brooks, Robert E., "Allocation of Natural Gas in Times of Shortage: A Mathematical Programming Model of the Production, Transmission, and Demand for Natural Gas Under Federal Power Commission Regulation," PhD in O.R. thesis, supervised by Prof. T.L. Magnanti, September 1975.

D'Aversa, Joseph S., "Optimal Equipment Maintenance, Rebuilding and Replacement Policy," S.M. in O.R. thesis, supervised by Prof. J.F. Shapiro, June 1972.

Golden, Bruce L., "A Minimum-Cost Multicommodity Network Flow Problem Concerning Imports and Exports," S.M. in O.R. thesis, supervised by Prof. T.L. Magnanti, February 1974.

Hauser, John R., "A Normative Methodology for Predicting Consumer Response to Design Decisions: Issues, Models, Theory and Use," PhD in O.R. thesis, supervised by Prof. J.D.C. Little, June 1975.

Hien, Nguyen Q., "Multi-Depot Vehicle-Routing Problems," S.M. in Mgt., supervised by Prof. T.L. Magnanti, June 1975.

Patel, Nitin R., "Optimal Control of Sulfur Dioxide Emissions at Power Stations: Models and a Case Study," PhD in O.R. thesis, supervised by Prof. J.D.C. Little, June 1973.

Robinson, William O., "Multivariate Probability Assessment," S.M. in E.E. thesis, supervised by Prof. R.L. Keeney, September 1970.

Rousseau, Jean-Marc, "A Cutting Plane Method for the Fixed Cost Problem," PhD in O.R. thesis, supervised by Prof. J.F. Shapiro, September 1973.

Shwimer, Joel, "Interaction Between Aggregate and Detailed Scheduling in a Job Shop," PhD in Mgt. thesis, supervised by Prof. P.R. Kleindorfer, June 1975.

Degrees Awarded, cont.

Tavernier, Hubert M., "Mathematical Analysis of Infinite Horizon Planning Models," PhD in O.R. thesis, supervised by Prof. J.F. Shapiro, February 1971.

Tien, James M., "Control of a Two Customer Class Interactive-Multi-Facility Queuing System," PhD in O.R. thesis, supervised by Prof. G.P. Wadsworth, June 1972.

Wagner, Michael H., "Constructive Fixed Point Theory and Duality in Nonlinear Programming," PhD in Mgt. thesis, supervised by Prof. J.F. Shapiro, September 1971.

Weymuller, Stanislas B., "Duality Theory and Economic Analysis," S.M. in O.R. thesis, supervised by Prof. J.F. Shapiro, June 1972.

Wilde, Norman W.G., "Numerical Analysis and Approximation Methods in Discrete-Time Dynamic Programming," PhD in Math. thesis, supervised by Prof. J.F. Shapiro, June 1971.

ABSTRACTS OF RESEARCH FINDINGS supported entirely or in part by ARO-D during the contract period and cited in this final report were appended to all progress reports and are not included here.