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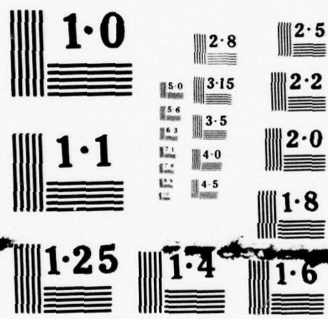

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RESEARCH REPORT NO. 32

COMPUTER-ASSISTED MANPOWER MODELS USING GOAL PROGRAMMING

BY RICHARD J. NIEHAUS

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WASHINGTON, D.C. 20390

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This paper reviews the large number of manpower and personnel models using goal programming developed by A. Charnes, W. W. Cooper, R. J. Niehaus and others. These models are built around embedding Markov processes into a goal programming structure for examining recruiting and internal staffing decisions. A discussion is first provided of the structures of aggregate manpower models and how they can be linked to program planning, equal employment opportunity planning, etc. This is followed by a discussion of assignment/distribution model structures. Here, emphasis is placed on a biased quadradic multi-attribute assignment model and on a capacitated distribution model for organization design which uses "goal artifacts" to move any instabilities in transition rates to a less sensitive part of the model. The final section reviews features such as the introduction of chance-constraints or risk into the models. These features are introduced to illustrate the linking pins to the research frontiers.

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OCP RESEARCH REPORT NO. 32

COMPUTER-ASSISTED MANPOWER MODELS USING GOAL PROGRAMMING

by

Richard J. Niehaus

July 1977

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Navy Department
Washington, D.C. 20390

Introduction

In the latter half of the 1960's the field of manpower planning experienced a marked shift with the development of goal programming models.[1/] This shift is documented by two keystone papers, i.e., "A Goal Programming Model for Manpower Planning" by A. Charnes, W.W. Cooper and R. J. Niehaus [18.2], and "Static and Dynamic Assignment Models with Multiple Objectives and Some Remarks on Organization Design" by A. Charnes, W. W. Cooper, R. J. Niehaus and A. Stedry [18.6]. Since the 1960's, a continuing series of papers has documented the extensions and follow-on efforts which are still in progress today! The purpose of this paper is to review these developments, discuss the current status and project the research frontiers which appear to be on the horizon.

Before moving into the subject of this paper, it is necessary to comment on the people by whom the research was actually accomplished. In a very true sense this paper could be authored by A. Charnes, W. W. Cooper and R. J. Niehaus rather than just the present author. The work has been a team effort from the beginning. A. Charnes, W. W. Cooper and R. J. Niehaus have been the core of the team, which has been augmented and extended by others who participated on a full contributing basis as particular areas of emphasis were encountered. Among these are D. Sholtz, G. L. Thompson, A. Stedry, B. Moore, D. Klingman, L. Mannis, E. Bres, D. Cass, K. A. Lewis, A. Nelson, A. Albanese, K. Padalino, S. Korn, F. Leader, B. Hall and D. Nitterhouse. As long as there is a clear

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1/ See Charnes and Cooper [10] for a recent summary of field of goal programming.

understanding that the work reported is that of a large complex team, the advantage of being the sole author is that the work can be discussed from the vantage point of an insider and at the same time express my privilege of being a colleague of Abe Charnes and Bill Cooper.

There are two types of developments which have resulted from the Navy Civilian Manpower Modeling Program. The first is the models which have been subjected to extensive prototypes and eventually selected for implementation. The second is the models and ideas which have been reported in the literature with little further attention paid to them. The first set of models will be reviewed briefly with the appropriate references so that thrust of the implementation is clear. Attention will also be paid to the second set since many good ideas have been proposed which may very well provide the linking pins to future developments. These parallel tracks will then be used to highlight some of the possible research frontiers.

II. Aggregate Model Structures

The initial model developed by Charnes, Cooper and Niehaus [18.2] was a goal programming model with embedded Markov processes. The variables are defined as :

$E_k^+(t)$, $E_k^-(t)$ = positive or negative deviation, respectively, for k^{th} manpower category on time t.

μ_{kt} = the weight which is applicable to k^{th} manpower category in period t.

$\eta_i(t)$ = the i^{th} component of $\eta(t)$ where $\eta(t) \equiv$ accumulated inventory from hiring to period t.

$g_k(t)$ = net requirement for the k^{th} manpower category after allowance for the available persons remaining in this category growth and attrition which occurred during the t previous periods.

$c_i(t)$ = the i^{th} mean salary value in period t.

$B(t)$ = applicable budgetary ceiling for salary expenditures in period t.

M^t = Markov transition matrix depicting the transfer probabilities between job categories where $M^t = MM...M$ (t times)

a = vector of initial inventory of personnel in all job categories.

This initial model can be stated in its transformed and reduced version as:

(Objective - Minimize weighted sum of deviations from net manpower goals:)

$$\text{Min} \sum_k \sum_t \mu_{kt} \left[E_k^+(t) + E_k^-(t)\right]$$

Subject to:

(Goal Constraints)

$$\sum_{i \epsilon Ik} \eta_i(t) - E_k^+(t) + E_k^-(t) = g_k(t)$$

(Manpower Transition Conditions)

$$-(M)_i\ \eta(t) + \eta_i(t+1) \geq 0$$

(Salary Budget Constraints)

$$\sum_i c_i(t)\ \eta_i(t) \leq B(t) - c^T(t)\ M^t a$$

(Non-Negativity Constraints)

$$\eta_i(t),\ E_k^+(t),\ E_k^-(t) \geq 0$$

The above model was tested via numerical examples [23], [18.3] and a number of extensions appeared warrented. The first of these involved revising the transition matrix to include an adjustment for retirements [18.3]

This was necessary since the Navy civilian workforce at that time had a large age bulge of personnel nearing retirement. An extension was also made by Charnes, Cooper and Niehaus [18.4] to include training explicitly in the models. Subsequently, upon closer examination, it was determined that the data was not available in any form which would make this extension useful to studying training problems.

The training extension turned out to be highly important for another reason. The initial model requires a large number of pre-computed numbers (i.e., net manpower requirements, adjusted budgetary numbers etc.). This means that time-consuming and thus expensive computer processing was necessary for pre-processing. Even more relevant was the fact that all these intermediate numbers required by the model made it necessary to provide extensive explanations to Navy managers with a resulting high level of confusion. The revised generalized network model permits relevant numbers in terms that managers can understand to be input directly without change. Similarly, there was no need for translation of the outputs. In this form, the net numbers previously pre-computed are automatically developed in the solution of the linear program.

Another missing element in the initial model was the ability to accommodate fires or Reductions-In-Force (RIF's) in the model. This became particularly important as the Navy drewdown its civilian workforce in the early 1970's (from 425,000 to 300,000 in three years). Also, in the use of the model for skills balancing, particularly in the naval industrial facilities, information on such possible adverse impacts is desirable. The generalized network form lent itself to this change since hiring and firing appear explicitly as variables which can be appropriately weighted in the objective function. This version can be found in Charnes, Cooper, Niehaus and Sholtz [18.5] and in Niehaus [18.1]. The Recruiting Requirement Model (RRM), as this model was named, has become the workhorse of the operational modeling system. The variables are defined as:

$E_k^+(t)$, $E_k^-(t)$ = positive or negative deviation, respectively, for k^{th} manpower category in time t.

$x_k(t)$ = manpower on-board (in place) in the k^{th} manpower category in period t.

$y_k(t)$ = hires in k^{th} manpower category in period t.

$z_k(t)$ = fires or Reductions-In-Force (RIF's) in the k^{th} manpower category in period t.

$G_k(t)$ = manpower requirement (goal) for the k^{th} manpower category in period t.

α_{kt} = the weight which is applicable to the positive goal discrepancy for the k^{th} manpower category in period t.

β_{kt} = the weight which is applicable to the negative goal discrepancy for the k^{th} manpower category in period t.

γ_{kt} = the weight on the hires in the k^{th} manpower category in period t.

δ_{kt} = the weight on the first or Reductions in Force (RIF's) in the k^{th} manpower category in period t.

M = Markov-like transition matrix depicting the probabilities of internal personnel movement

a = vector of initial inventory of personnel in all job categories

e^T = sum vector (i.e. $e^T = (1,1,\ldots 1)$

C(t) = manpower ceiling for period t.

s^T = average salary vector in period t.

B(t) = salary budgetary ceiling for period t.

The structure of the model in its transformed and reduced form is as follows:

(Objective - Minimize weighted sum of deviations from gross manpower goals and weighted number of hires and fires (Reductions-In-Force))

$$\text{Min} \sum_k \sum_t [\alpha_{kt} E_k^+(t) + \beta_{kt} E_k^-(t) + \gamma_{kt} y_k(t) + \delta_{kt} z_k(t)]$$

Subject to:

(Goal Constraints)

$$x_k(t) - E_k^+(t) + E_k^-(t) = G_k(t)$$

(Manpower Transition Conditions)

$$x_k(0) = a$$

$$- M x_k(t-1) + x_k(t) - y_k(t) + z_k(t) = 0$$

(Manpower Ceiling Constraints)

$$e^T x_k(t) \leq C(t)$$

(Salary Budget Constraints)

$$s^T(t) x_k(t) \leq B(t)$$

(Non-negativity Constraints)

$$x_k(t), y_k(t), z_k(t), E_k^+(t), E_k^-(t) \geq 0$$

This basic model was also extended by Charnes, Cooper, Niehaus and Sholtz [18.5] in a number of ways. One was the extension to incorporate input-output considerations to study program planning. This extension was discussed in detail by Niehaus [18.1], including the development of a numerical prototype. Work progressed through the programming of the necessary extensions to the linear programming matrix generator and report writer. Implementation was not carried beyond this point, however, due to lack of resources to continue its development. The additional variables of this revised model are:

$F_i^+(t)$, $F_i^-(t)$ = positive or negative deviation, respectively, for the i^{th} final user support category in period t.

$v_i(t)$ = amount of support for the i^{th} final user in terms of its dollar budget in period t.

$w_j(t)$ = amount of output of the j^{th} producer in terns of its dollar budget in period t.

ψ_i = the weight which is applicable to the positive goal discrepancy for the i^{th} final user in period t.

ϕ_{it} = the weight which is applicable to the negative goal discrepancy for the i^{th} final user in period t.

$U_i(t)$ = requirement (goal amount) of support in terms of its dollar budget for the i^{th} final user in period t.

$P_j(t)$ = dollars budget of the j^{th} producer in period to.

R = the matrix of rators of support producers provides to final users.

f^T = vector of manpower per dollars of output.

The revised model can be depicted as follows in its transformed and reduced form as:

(Objective - Minimize weighted sum of deviations from final user support requirements and weighted sum of deviations from gross manpower goals and weighted number of hires and fires (Reductions-In-Force))

$$\text{Min} \sum_i \sum_t [\psi_{it} F_i^+(t) + \phi_{it} F_i^-(t)) + \sum_k \sum_t (\alpha_{kt} E_k^+(t) + \beta_{kt} E_k^-(t) + \gamma_{kt} y(t) = \delta_{kt} z(t)]$$

Subject to:

(Final User Goal Constraints)

$$v_i(t) - F_i^+(t) + F_i^-(t) = U_i(t)$$

(Final User-Producer Balancing Conditions)

$$v(t) = R\,w(t) \qquad = 0$$

(Producer Budget Constraints)

$$w_j(t) \qquad \leq P_j(t)$$

(Producer Manpower Balancing Conditions)

$$f^T w_j(t) - \Sigma_k x_k(t) \qquad = 0$$

(Manpower Goal Constraints)

$$x_k(t) - E_k^+(t) + E_k^-(t) \qquad = G_k(t)$$

(Manpower Transition Conditions)

$$X(0) \qquad = a$$

$$-M\,x(t-1) + x(t) - y(t) + z(t) \qquad = 0$$

(Manpower Ceiling Constraints)

$$e^T x(t) \qquad \leq C(t)$$

(Salary Budget Constraints)

$$s^t x(t) \qquad \leq B(t)$$

(Non-negativity Constraints)

$$v_i(t),\ w_j(t),\ x_k(t),\ y_k(t),\ z_k(t),$$
$$F_i^+(t),\ F_i^-(t),\ E_k^+(t),\ E_k^-(t) \qquad \geq 0$$

This model was extended further by Charnes, Cooper, Niehaus, and Sholtz [18.5] to include a chance-constrained form, which will be discussed as part of the final section of this paper. Also a very useful numerical prototype was developed [21] which showed how the models could be integrated into a total military-civilian manpower planning system. This was a case where the process of developing the prototype itself helped to make the issues clearer, and even without further implementation efforts the results had practical significance.

A series of implementation efforts were now underway. The strategy, methodology and status of this work was provided in 1972 by Niehaus [18.1]. Also, most of the reports of the work from its inception were drawn together in a monograph by A. Charnes, W. W. Cooper and R. J. Niehaus [18] and also summarized in the Naval Research Logistics Quarterly [19]. Implementation efforts continued, with emphasis on local naval installations. These included the work at the Naval Underwater Systems Center discussed by A. Charnes, W. W. Cooper, R. J. Niehaus and K. Padalino [22] and at the Naval Air Rework Facility at San Diego reported by E. Bres and R. J. Niehaus [4]. Also included was the investigation of conversational computer-assisted techniques by R. J. Niehaus, D. Sholtz and G. L. Thompson [34]. This latter work grew into the Shore Activity Manpower Planning System (SAMPS) project which is aimed at investigating large-scale versions of the models at local installations using the latest technology of computers and telecommunications networks, as discussed by R. J. Niehaus and D. Sholtz [33], and R. J. Niehaus [31].

Returning to the mathematical developments, parallel efforts were started to find ways to increase the computational efficiency of the solution methodology. One of these efforts by A. Charnes, W. W. Cooper, D. Klingman and R. J. Niehaus [12], [13] set forth a method to calculate explicit solutions in convex goal programming. Since these references are recent and the ideas were also summarized in [10], the comments in this paper will be limited to the fact that the methods are of much greater generality than just to the field of manpower planning. In fact, a non-exhaustive list of goal programs to which these methodologies apply includes:

a. Absolute value functions, including those with asymmetric weights and multi-goal components;

b. General piecewise linear functionals;

c. Goal interval functions;

d. Hypermedium functionals and related functionals in extensions of ordinary goal programming.

The second parallel track was to investigate methods using the latest versions of commercial linear programming computer codes. The ideas from the explicit solution research indicated that one might be able to secure a good advanced start by the simple assumption that the final solution will satisfy the goals. This in fact, turned out to be the case, and for larger problems an improvement by a factor of ten was generally possible. Also, it was suggested that the use of a reduced dual form of the model, which has been known for a long time (see Charnes and Cooper [8]), might secure an added improvement.[2/] This turned out to be particularly true with the latest generation of commercial linear programming codes which use a threaded list to minimize storage and access time of data during processing. These developments obviated the need to proceed any further with the implementation of the ideas obtained in the explicit solution research. This is particularly true, since almost a complete revision of the input side of the computer support system would have been required to test the explicit solution methodologies with an operational size problem.

2/ See also Armstrong and Hultz [2]. The work on the advanced basis was accomplished by S. Korn and the suggestions to use the reduced dual formulation were provided by J.J.H. Forrest and J.C. Jennings of Scicon Computer Services, Ltd., during the installation of the model on the Computer Sciences Corporation INFONET telecommunications network.

In 1975 work started on an extension to the model to incorporate equal employment opportunity (EEO) planning into the goal programming framework. A comprehensive model was developed by A. Charnes, W.W. Cooper, K.A. Lewis and R.J. Niehaus [14] which included two essential new features: (1) a set of dual goal constraints to include both workload goals and EEO goals by race-sex (ethnosexual) categories; and (2) a "flexibility" feature to allow the model to recommend ways to adjust the internal transition matrix. Thus, both the outside as well as the inside possibilities could be evaluated through use of the same model. The definitions used in this model are as follows:

θ_{ikt} = the weight applicable to the personnel of ethnosexual type k in job category i in period t for positive goal deviations.

ξ_{ikt} = the weight applicable to the personnel of ethnosexual type k in job category i in period t for negative goal deviations.

$D_{ik}^{+}(t)$, $D_{ik}^{-}(t)$ = positive or negative deviation, respectively, for the personnel of ethnosexual type k in job category i in period t.

γ_{ikt} = the weight applicable to hires of personnel of ethnosexual type k in job category i in period t.

δ_{ikt} = the weight applicable to fires (Reductions-In-Force (RIF's)) of personnel of ethnosexual type k in job category i in period t.

α_{it} = the weight applicable to the personnel of job category in period t (associated with workload goals) for positive deviations.

β_{it} = the weight applicable to the personnel of job category i in period t (associated with workload goals) for negative deviations.

$E_i^+(t)$, $E_i^-(t)$ = positive or negative deviations, respectively, for the personnel of job category i (associated with workload goals) in period t.

$H_i^k(t)$ = EEO goal for personnel of ethnosexual type k in job category i in period t.

$G_i(t)$ = workload goal for personnel of job category i in period t.

$x_i^k(t)$ = number of personnel of ethnosexual type k in job category i in period t.

$y_i^k(t)$ = number of hires of ethnosexual type k in job category i in period t.

$z_i^k(t)$ = number of fires (Reductions in Force (RIF's)) of ethnosexual type k in job category i in period t.

a_i^k = initial inventory of personnel in ethnosexual type k in job category i.

m_{ij} = current or "historical" transition rate from category j to category i.

$q_{ij}^k(t)$ = number of personnel of type k in category j of period t additionally transferred to category i for period t.

$r_{ij}^k(t)$ = number of personnel to type k in category j not transiting to category i in period t via expected transition rate m_{ij}.

$h_{ij}^k(t)$ = "policy parameter" to limit the amount of additional internal transfers to the "historical" transition rate in period t.

$p_i^k(t)$ = minimum proportion of ethnosexual type k in job category i in period t.

$c_i^1(t)$ = mean salary of job category i in period t.

$c_{ij}^2(t)$ = transfer costs (salary plus training) for the flexible transfers from job category j to job category i in period t.

$c_i^3(t)$ = recruiting costs for new hires into job category i in period t.

$c_i^4(t)$ = firing (Reduction In Force (RIF)) costs from job category i in period t.

$b^1(t)$ = total salary budget in period t.

$b^2(t)$ = total flexible transfer (upward mobility) budget in period t.

$b^3(t)$ = total hiring budget in period t.

$b^4(t)$ = total firing(Reduction In Force (RIF)) budget in period t.

e^T = sum vector (i.e. (1,1...1)

$C(t)$ = total manpower ceiling in period t.

The model can be written in its transformed and reduced form as:

(Objective - Minimize weighted sum of deviations from EEO goals by ethno-sexual category including weighted hires and fires (Reductions In Force) and weighted sum of deviations from workload goals by job category)

$$\text{Min} \sum_i \sum_k \sum_t [\theta_{ikt} D^+_{ik}(t) + \xi_{ikt} D^-_{ik}(t) + \gamma_{ikt} y^k_i(t) + \delta_{ikt} z^k_i(t)] + \sum_i \sum_t [\alpha_{it} E^+_i(t) + \beta_{it} E^-_i(t)]$$

(EEO Goal Constraints)

$$x^k_i(t) - D^+_{ik}(t) + D^-_{ik}(t) = H^k_i(t)$$

(Workload Goal Constraints)

$$\sum_k x^k_i(t) - E^+_i(t) + E^-_i(t) = G_i(t)$$

(Transition Conditions)

$$x^k_i(0) \quad \text{for all } i, k \quad = a^k_i$$

$$- \sum_j [m_{ij} x^k_j(t-1)] - \sum_j q_{ij}^k(t) + \sum_j r_{ij}^k(t) + x^k_i(t) - y^k_i(t) + z^k_i(t) = 0$$

(Maximum Additive Flexibility)

$$- q_{ji}^k(t) + h_{ji}^k(t) [\sum_l m_{li}] x^k_i(t-1) \geq 0$$

(Maximum Subtractive Flexibility)

$$- r_{ij}^k(t) + m_{ij} x^k_j(t-1) \geq 0$$

(Additive-Subtractive Balance Conditions)

$$\sum_i q_{ij}^k(t) - \sum_i r_{ij}^k(t) \quad = 0$$

(Minimum EEO Proportions)

$$x_i^k(t) - p_i^k(t)\ H_i^k(t) \quad \geq 0$$

Budget Constraints

$$\sum_i \sum_k c_i^1(t)\ x_i^k(t) \quad \leq b^1(t)$$

$$\sum_i \sum_j \sum_k c_{ij}^2(t)\ q_{ij}^k(t) \quad \leq b^2(t)$$

$$\sum_i \sum_k c_i^3(t)\ y_i^k(t) \quad \leq b^3(t)$$

$$\sum_i \sum_k c_i^4(t)\ z_i^k(t) \quad \leq b^4(t)$$

(Manpower Ceiling Constraints)

$$e^T\ x_i^k(t) \quad \leq C(t)$$

(Non-negativity Constraints)

$D_{ik}^+(t)$, $D_{ik}^-(t)$, $E_i^+(t)$, $E_i^-(t)$, $x_i^k(t)$, $q_{ij}^k(t)$, $r_{ij}^k(t)$, $y_i^k(t)$, $z_i^k(t)$ are non-negative for all i, j, k, t.

The model was then tested via a numerical example and found to be computable. Subsequently, as outlined in Burroughs and Niehaus [6], at the request of the Assistant Secretary of the Navy (Manpower and Reserve Affairs), a reduced version of the model was developed. The results showed with little doubt that the existing Navy civilian EEO goals policy needed substantial revision. The implemented version eliminated the flexibility features and also made it possible to use much of the existing large-scale software system which is in place. Rough estimates were made of the EEO goals as reflected in existing policy. Essentually, all that was added to the Recruiting Requirements Model was the EEO goals equations, with the budgetary constraints also eliminated. Using the previous definitions, this model can be stated as follows:

(Objective - Minimize weighted sum of deviations from the EEO goals by ethnosexual category including weighted hires and fires (Reductions In Force) and weighted sum of workload goals by job category)

$$\text{Min} \sum_i \sum_k \sum_t [\theta_{ikt} D^+_{ik}(t) + \xi_{ikt} D^-_{ik}(t) + \gamma_{ikt} y^k_i(t) + \delta_{ikt} z^k_i(t)]$$
$$+ \sum_i \sum_t [\alpha_{it} E^+_i(t) + \beta_{it} E^-_i(t)]$$

(EEO Goal Constraints)

$$x^k_i(t) - D^+_{ik}(t) + D^-_{ik}(t) = H^k_i(t)$$

(Workload Goal Constraints)

$$\sum_k x^k_i(t) - E^+_i(t) + E^-_i(t) = G_i(t)$$

(Transition Conditions)

$$x^k_i(0) \text{ for all } i, k = a^k_i$$

$$-\sum_j [m_{ij} x^k_j(t-1)] + x^k_i(t) - y^k_i(t) + z^k_i(t) = 0$$

(Minimum EEO Proportions)

$$x^k_i(t) - p^k_i(t) H^k_i(t) \geq 0$$

Manpower Ceiling Constraints

$$e^T x^k_i(t) \leq C(t)$$

Non-negativity Constraints)

$D^+_{ik}(t)$, $D^-_{ik}(t)$, $E^+_i(t)$, $E^-_i(t)$, $x^k_i(t)$,

$y^k_i(t)$, $z^k_i(t)$ are non-negative for all i, j, k, t.

There was clear interest in the Navy to move forward towards implementation. Preliminary work was accomplished by Burroughs, Korn, Lewis, and Niehaus [5] to develop a methodology to estimate the goals. The work was continued by Lewis [28] into the development of comprehensive prototypes and of a systems concept for implementation. Along the way, it was found that the model would not work at the local level due to the small cell sizes required. The led to the development of a coherence model by Charnes, Cooper, Lewis and Niehaus [15] which uses "artifact" goals in a capacitated distribution format.

The current implementation stategy is to develop a computer support system for the version without flexibility of the aggregate EEO model for headquarters planning. Included will be an accountability system to put the top line officials of the Navy in a strong position to monitor and control progress towards the goals. Emphasis will also be placed on the development of a labor market analysis system for use throughout the Navy. Research is continuing on the models for local installation planning. This work will be described in the next section of this report.

A spinoff of the EEO prototype work was the development of a promotion planning model. Here, the ethnosexual categories were eliminated with a model study undertaken to evaluate the promotion policies of the naval laboratory system as described by Albanese, Korn, Niehaus and Padalino [1]. In turn, further work is now underway by Cooper, Niehaus and Nitterhouse [24] to develop a better workforce goals planning system for the naval laboratories. This is also tied into the research into conversational models in a telecommunications environment underway by Niehaus [31].

In addition to the aggregate planning model applications selected for feasibility testing, there have been a number of mathematical developments which hold promise for the future. These ideas will be discussed after the next section concerned with model of the assignment/distribution type.

III. Assignment/Distribution Model Structures

As was mentioned at the beginning of this report, models of the assignment/distribution type have been an important part of the research program. The initial work by Charnes, Cooper, Niehaus and Stedry [18.6] showed that the classical assignment model might be extended in two ways. The first involves the use of multiple characteristics for each of the individuals and jobs. The second involves the dynamic or assignment-reassignment aspects of career planning and organization design. Research has also been accomplished on ways mathematically to relate this planning for individual persons and jobs with the type of aggregate planning described in the previous section of this report.

In order to begin development of the assignment models, the decision was made to limit the first numerical examples to the static (one-period) case. This was done to ensure that the solution algorithms would reflect properly the multiple characteristic feature of assignment planning. At this point, a biased quadratic form of the static model was formulated by Charnes, Cooper, Niehaus and Sholtz [18.7] along with a spectral analysis model for career planning. Following this work, a solution algorithm was formulated by Charnes, Cooper, Klingman and Niehaus [11]. A statement of this algorithm follows:

Let

x_{is} = part of individual s assigned to job i.

a_{sj} = amount of j^{th} attribute possessed by individual s.

r_{ij} = amount of j^{th} attribute desired in job i.

m_{ij} = amount of j^{th} attribute required in job i.

k_{ij} = weight on discrepancy for attribute j in job i.

c_{is} = "cost" for assigning individual s to job i.

J_i = set of all attributes j relevant to job i.

The model can then be stated as:

(Objective - Minimize the sum of "costs" across all of the attributes for all assignments made)

$$\text{Min} \sum_i \sum_s c_{is} x_{is}$$

$$\text{where } c_{is} = \sum_{j \varepsilon J_i} a_{sj} [a_{sj} - (2r_{ij} + k_{ij})]$$

subject to

$$\sum_s x_{is} = 1 \quad \forall_{ij} \quad \sum_i x_{is} = 1 \quad \forall_s \quad (x_{is} = 0, 1 \; \forall i, s)$$

$$0 \le r_{ij} \le 10 \; j \quad 0 \le a_{sj} \le 10 \; j \quad k_{ij} \ge 10 - r_{ij}$$

$$x_{is} = 0 \text{ if } \exists \; a_{sj} < m_{ij} \text{ for } j \varepsilon J_i$$

Two field tests were conducted at naval installations as described by Moore and Sholtz [30] and by Bres, Leader, Moore and Sholtz [3]. An extensive investigation of task analysis techniques was made by Moore [29]. In the computer support system, the very efficient capacitated distribution codes developed by Glover, Karney, Klingman and Napier [26] were used. The results from the tests showed that computationally the models could be supported efficiently. However, because of the number of attributes involved, in both field tests the collection of data was time consuming. Also, there was a very apparent problem in trying to get first line supervisors to designate needed positions: most tended either to describe the current organization, or simply to furnish a description for each kind of position as formally defined in the civil service. Beyond these specific problems, there was little if any management interest in the recommended assignments. In both cases management could find uses for by-products of an assignment model based on task inventories, but external constraints such as unions and government regulations seem to render less than valuable the use of assignment models for civil service workforces. This may very well not be the case for military workforces, where the assignment systems are generally much more centralized.

In addition to the civilian personnel planning, help is being provided to the Bureau of Naval Personnel in the design of models for officer distribution. The initial models were developed by Cass, Charnes, Cooper and Niehaus [7]. Two models were proposed: (1) a static goal programming model which is transformed into a distribution model for solution; and (2) a dynamic multi-page model for evaluating officer rotations. The static model has been implemented and development is continuing on conversational and bargaining assignment extensions by Eubanks and Thompson [25]. Further assistance is being provided by Charnes and Cooper in continuing the development of the dynamic models. More recently, they are also examining some aspects of the enlisted planning process.

During the development of the aggregate EEO models, it became clear that they would not be applicable to local installation planning. As mentioned previously, this was due to the small cell sizes which would be required. However, from the Navy's management viewpoint, it did not appear useful to develop upward mobility plans at headquarters. It is felt that such upward mobility plans should be developed locally, since that is where the civilian personnel promotion and intra-organizational transfer decisions are made. As a result, Charnes, Cooper, Lewis and Niehaus [15] developed the coherence model, or multi-level EEO model (MEEO). This model is designed to be in coherence with the aggregate headquarters or master EEO model. In the MEEO the Markov transition constraints are approximated by "goal artifacts" which relax the constraints to goals with convex goal functionals on certain dyadic cell variables. The flexibility features which are desired are also included by means of features of a form of a warehousing model.

For this initial version each ethnosexual category is handled individually by the model. Thus, to accommodate all the ethnosexual categories, each has to be computed separately and added up to obtain the organizations' manpower totals. Later versions will allow all the ethnosexual categories to be evaluated via a single model.

The model was found to be computationally feasible on a small numerical example in [15] and in a more extensive example by Lewis [28] using a general purpose linear programming code for solution. With these initial computational results in hand, a project has been started to build enough of a computer support capability to begin testing at a field site. The preliminary step was to begin testing with large-scale highly efficient network codes such as PNET [26], which can handle multiple arcs between nodes as well as lower and upper bounds on arc flows.

A new, more general, non-linear goal-arc network model has been developed by Charnes, Cooper, Nelson and Niehaus [17] to be used in connection with the PNET code. This model which is an extension of the version suggested by Charnes, Cooper, Lewis and Niehaus uses the following variables:

Let

$x_{ij}(t)$ = the number of personnel of type α transferred from job category i to job category j in period t;

M_{ij} = the current or "historical transition rate" from job category i to job category j;

p_i^α = the desired or actual proportion of personnel of type α in job category i;

$a_i(t)$ = the aggregate workforce goal for job category i in period t;

$g_{ij}^\alpha(t-1,t) = \langle p_i^\alpha a_i(t-1) M_{ij} \rangle$ = the number of personnel of type α expected to transfer from job category i to job category j in period t;

$p_i^\alpha a_i(t)$ = the projected workforce goal for personnel of type α in job category i in period t;

$x_{oi}(1)$ = the number of personnel of type α initially aboard in job category i;

i_o = subscript indicating natural attrition

j_o = subscript indicating outside source or firing;

$\overline{y}_i(t)$ = the total number of personnel of type α in job category i in period t.

To each job category in each period we assign two nodes an antecedent and a consequent. We designate the class of antecedent "job" nodes for period t as $J^-(t)$; the class of consequent "job" nodes by $J^+(t)$. $J_i^-(t)$ is the i^{th} job antecedent node; $J_j^+(t)$ is the j^{th} job consequent node.

$x_{ij}^k(t)$ = the flow from node $J_i^-(t)$ to node $J_i^+(t)$ on the k^{th} individual arc of the "goal arc".

For each proper (real) job between two periods we designate a "value" node to receive the goal arc flow from the consequent node of the immediate past period. Let $V_i(t)$ denote the "value" node for job i between period t-1 and t.

$y_i^k(t)$ = the flow on arc k from node $J_i^+(t-1)$ to node $V_i(t)$.

$L_{ij}^k(t)$ and $U_{ij}^k(t)$ are lower and upper on the flow from $J_i^-(t)$ to $J_j^+(t)$ via the k^{th} arc. For some k, $U_{ij}^k(t) = g_{ij}^{\alpha}(t-1,t)$. $L_i^k(t)$ and $U_i^k(t)$ are lower and upper bounds respectively on the flow from $J_i^+(t)$ to the "value" node $V_i(t)$. From some k, $U_i^k(t) = p_i^{\alpha} a_i(t)$.

The model can be written as:

(Objective - minimize the sum of deviations of actual transitions from expected transitions between job categories over all times periods and the sum of deviations of the number of personnel in job categories from the targeted workforce goal for the job categories over all time periods.)

$$\text{Min} \sum_t \sum_k \sum_j \sum_{i \neq i_o} c_i^k x_{ij}^k(t) + \sum_k \sum_t \sum_{\substack{i \neq i_o \\ i \neq j_o}} d_i^k y_i^k(t)$$

Subject to

(Goal Conditions)

$$\sum_k x_{ij}^k(t) - x_{ij}(t) = 0$$

$$\sum_k y_i^k(t) - \overline{y}_i(t) = 0$$

(Manpower Flow Conditions)

$$\sum_{j \neq i_o} \sum_i x_{ij}(n) + \sum_t x_{ji_o}(t) - \sum_{i \varepsilon J^-(1)} x_{oi}(1) = 0$$

$$x_{oi} - \sum_{j \varepsilon J^+(1)} \sum_k x_{ij}^k(1) = 0$$

$$\sum_k \sum_{i \varepsilon J^-(1)} x_{ij}^k(1) - \sum_r y_j^r(t) = 0$$

where $j \neq j_o$

$$x_{oj_o} + \sum_k \sum_{i\varepsilon J^-(1)} x_{ij_o}^k(1) - \sum_r y_{j_o}^r(1) = 0$$

$$\bar{y}_i(t) - \sum_k \sum_j x_{ij}^k(t) = 0 \text{ for } t > 1$$

$$\sum_k \sum_{i\varepsilon J^-(t)} x_{ij}^k(t) - \sum_r y_j^r(t) = 0$$

(Bounded Variables Conditions)

$$L_{ij}^k(t) \leq x_{ij}^k(t) \leq U_{ij}^k(t)$$

$$L_i^k(t) \leq y_i^k(t) \leq U_i^k(t)$$

(Non-Negativity Constraints)

$$x_{ij}(t),\ x_{ij}^k(t),\ y_i^k(t),\ \bar{y}_i(t) \geq 0 \text{ for all } i, j, k, t.$$

One of the next steps will be to bring together the aggregate planning and assignment/distribution type models into one model system. Such systems have been suggested by Cass, Charnes, Cooper and Niehaus [7] for officer distribution planning and by Charnes, Cooper, Lewis and Niehaus [16] for EEO planning.

IV. Other Extensions and Research Frontiers

In a long term modeling research program such as this one, many other extensions have been developed without implementation, full or partial. This has been due to either lack of resources for implementation, change in focus of the project, or the need for more mathematical development than could be accomplished at the time. Several of these ideas will be reviewed so that a discussion of the research frontiers might be more complete.

The idea of planning under uncertainty or risk was advanced in 1970 by Charnes, Cooper and Niehaus [18.4] and developed further by Charnes, Cooper, Niehaus and Sholtz [18.5] through the introduction of the use of chance-constrained programming. In particular, a discussion was provided in [18.4] of extending the Markov matrix notations of the Recruiting Requirements Model to chance-contrained intrepretations. In [18.5] these chance constrained applications were extended further to deal with risk variations in the right hand sides.

One means of doing this is by employing "zero-order decision rules" of chance-constrained programming. Under this rule the values of the decision variables are all chosen in advance of knowledge of the sample values of the random variables. Using the notation of the Recruiting Requirements Model, we can examine the new elements which the use of chance-constrained programming introduces. For illustration, the k^{th} Manpower Goal would be written as:

$$P\,[x_k(t) \leq G_k(t)] \geq \omega_{kt}$$

This means that the "k^{th}" manpower on-board in period t must be chosen so that it does not exceed the k^{th} Manpower Goal in period t with a probability of at least ω_{kt}. Note that $G_k(t)$ is a random variable whose sample value is not known when the planning decision for $x_k(t)$ must be made. It is required, however, that $x_k(t)$, when selected, must not exceed $G_k(t)$ by a probability ω_{kt} which is also stipulated prior to the knowledge of the sample value of $G_k(t)$. Only the probability distribution for $G_k(t)$ is known when the planning decisions are to be made.

With the zero-order decision rules, the chance constraints may be inverted to obtain a new linear programming problem of virtually the same structure as the deterministic case. The details of this process can be found in [18.5]. The testing of the chance-constrained extension was not accomplished because of more immediate implementation considerations. Now, however, the civilian manpower modeling program is again moving toward the frontiers of goal setting in the areas of EEO and program planning. At an appropriate point, at least a numerical prototype will be constructed to check such issues as management acceptance, data availability, and computer support requirements.

Tracing another thread, it is interesting to see how an idea, dormant for several years, reappears in an improved form. Such is the case with the possibility observed in 1971 by Charnes, Cooper, and Niehaus [20] of redesigning the system transition matrices to obtain a stable desired mix of personnel. In this case one wishes to insure "as closely as possible" the possibility of effecting transfer and the costs of influencing transfer rates subject to constraints on available resources to obtain this stable mix. This was rephrased mathematically by letting the vector of desired proportions be represented by π and the desired matrix of transitions by M. Ideally, for a steady state, or equilibrium result, this would be

$$\pi = M\pi$$

If, in any actual situation, the current transition matrix is designated by M_o, the possible changes will be

$$M = M - M_o$$

with the constraint system

$$G \ (\Delta M) \geq H$$

where G is a coefficient matrix and H is a matrix of constants.

The above equations then lead to the goal programming problem: (Objective - minimize the weighted discrepancies between the desired proportions and the desired proportions multiplied by the system transition matrix)

$$\text{Min } w^T|\pi - M\pi|$$

subject to

(Constraint System)

$$G \ (\Delta M) \geq H$$

This model can be seen, of course, as the initial conceptual development of the flexibility features which are included in the EEO models and in the promotion planning model.

The above example illustrates the desirability of maintaining a fundamental mathematical research program as part of an on-going system development which has many parts operational or nearing implementation. There are still many other frontiers which are worth exploring for future improvements. The work on explicit solutions to convex goal programs will more than likely reappear as larger and larger systems are brought together. Also on the horizon might be the integration of information theoretic statistics with mathematical programming as suggested by Charnes and Cooper [9] in their other research.

Still other scientific disciplines are being integrated into the Navy Civilian manpower modeling research program. It is clear that the fields of behavioral science, managerial economics, management information, and labor economics are as much a part of the effort as is the mathematical research on which this paper has concentrated. These interactions might better be held as subjects of continuing reports. It is fitting, however, to conclude this paper by saying that the pioneering efforts which make this integration possible would not have been accomplished without the contributions of Abe Charnes and Bill Cooper. In all likelihood their efforts will continue to set the stage for the 1990's and beyond.

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