BEBR

FACULTY WORKING
PAPER NO. 735

Resource Allocation in a University Environment: A Test of the Ruefli, Freeland and Davis Goal Programming Decomposition Algorithms

David T. Whitford
Wayne J. Davis

College of Commerce and Business Administration
Bureau of Economic and Business Research
University of Illinois, Urbana Champaign

FACULTY WORKING PAPER NO. 735

College of Commerce and Business Administration

University of Illinois at Urbana-Champaign

January 1981

Resource Allocation in a University Environment: A Test of the Ruefli, Freeland, and Davis Goal Programming Decomposition Algorithms

David T. Whitford, Assistant Professor
Department of Finance

Wayne J. Davis, Associate Professor
Department of General Engineering

ABSTRACT

The purpose of this research is to test the computational properties, rates of convergence, and feasibility of implementing four multiple criteria, decomposition algorithms or organizational models. The organizational models recently proposed by Ruefli, Freeland, Davis, and Davis and Whitford were tested on a large university resource allocation problem. Each of the algorithms was implemented on a CDC CYBER-175 computer. With the exception of the Ruefli model, the algorithms performed well, albeit some better than others. Convergence was rapid, and the models' solutions were reasonable. The results of the study indicate that these organizational models can offer a reasonable approach to allocating resources in real world hierarchical organizations.

Resource Allocation in a University Environment: A Test of the Ruefli, Freeland, and Davis Goal Programming Decomposition Algorithms

I. Introduction

During the last several years, scholars in the fields of economics, organizational behavior, and operations research have made great strides in developing models that address themselves to issues of economic agency and its implications [1, 23, 24, and 34], organizational structure and control processes [3, 5, 13, 19, 20, 28, and 29], and mathematical decomposition algorithms [6, 9, 18, 25, and 30]. One of the many goals of these separate studies has been to understand the role that organizational design and information processing play in economic decision making and resource allocation.

In reviewing a number of studies in this area, Ruefli [27, p. 361] states:

> ...perhaps the most discouraging aspect of the subject we are considering is the persistent lack of applications. Modeling efforts usually take place at the theoretical level, and little has been done to link these efforts to actual problem situations and actual (or even strongly representative) data.

The purpose of this research is to fill this void. It will focus upon four, three-level hierarchical, decomposition algorithms developed by Ruefli [25, 26], Freeland [16, 18] (also see Freeland-Baker [17]), Davis [9], and Davis and Whitford [10] and will test their computational properties, rates of convergence, and feasibility of implementation in a university resource allocation setting. A companion paper by the authors [10] analyzes the mathematical structure of these algorithms. Section II will provide an overview of the demographic and economic environments in which universities must operate. Also it will provide a justification for using a multicriteria, hierarchical model for allocating a university's resources. Section III gives an outline of the organizational and algebraic structure of the university resource allocation model. Section IV presents the results of computational tests utilizing a family of multicriteria, decomposition models. A final section gives a summary of the paper, provides concluding remarks, and outlines areas for future research.

II. The University Setting--An Overview

It is quite probable that universities and colleges in the United States will soon enter a no-growth or negative-growth era. For example, the National Center for Education Statistics (NCES) has predicted [15] that the number of bachelor's degrees to be granted in 1986-87 by all U.S. colleges and universities will fall below the number awarded in 1976-77. Moreover, NCES projects that the population of traditional college age students will shrink dramatically beyond the mid 1980's. As an example, the combined enrollment of U.S. elementary and secondary schools in 1976-77 was 49.3 million students. NCES forecasts an 8.3% drop in enrollment to 45.2 million by 1986-87.

In addition to these demographic shifts, universities will likely have to cope with continuing inflation and lagging financial resources. Given this scenario, underlying conflicts among a university's colleges, schools, and departments are apt to surface, thereby exacerbating resource allocation difficulties. In this setting the status quo will be difficult, if not impossible, to maintain. Individual programs may have to be abandoned or reduced to accommodate financial constraints.

Haphazard attempts to cope with problems of resource allocation in this demographic and economic environment are likely to be disastrous.

It is well established that optimal transfer prices and resource allocation within a for-profit divisionalized corporation must consider all corporate opportunity costs and constraints [12]. Clearly if one is to persue reasonable policies in allocating a university's resources, all organizational opportunity costs and constraints must be considered simultaneously.

The overall organizational structure of a typical university and its subordinate colleges and departments is markedly similar to the hierarchical organization of most multi-division profit maximizing corporations. However, unlike for-profit organizations, a university cannot point to a single criterion, such as profit or shareholder wealth maximization, that can adequately measure economic efficiency. Instead institutions of higher education have multiple and often conflicting goals. Thus the decomposition algorithms such as those developed by Dantzig and Wolfe [6] and Ten Kate [30] which focus upon a single criterion seem inappropriate in this setting. Instead a multicriteria approach appears more appropriate. Indeed, the university planning literature is replete with studies which advocate a goal programming technique which strives to get as close as possible to a stated set of organizational objectives or goals. See [14, 21, and 31] for a limited sample. Accordingly the Ruefli, Freeland, and Davis algorithms which incorporate both hierarchical decomposition and goal programming appear to offer great promise in handling the budgeting dilemma faced by university administrators. This study will investigate and evaluate these models.

III. Specification of the University Model[1]

The university planning model presented in this study focuses upon university resource allocation over a one academic year horizon and is based upon the organization depicted in Figure 1. Georgia State University (GSU) served as the structuring guide for the institution presented in this study, and it should be noted that some of the model's characteristics do not conform to the actual organizational structure at GSU. However, the model is strongly representative of GSU's two largest colleges.

The primary focus of the model's formulation was the academic units of the university. The intent was to isolate the effects and interactions of student demand, educational quality, and fiscal responsibility upon the university's staffing for academic instruction, research, and public service. Problems of providing incremental or decremental administrative and support services such as building maintenance, physical security, and major additions to computer, laboratory, library, classroom, and office capacities and resources were not directly included in the model. From an economic perspective many of these requirements are "sunk" or "fixed" commitments. By omitting these services, one might infer that their current level is considered optimal; however, such a conclusion is unwarranted. By treating the funding of these "sunk cost" resources as a minimum goal, sensitivity analysis utilizing funding deviations or reallocation alternatives could easily evaluate the potential trade-offs of these fixed commitments. An

---

[1] The formulation described in this section is a one year version of a much larger and more complex three year planning horizon model described in Whitford [32, 33].

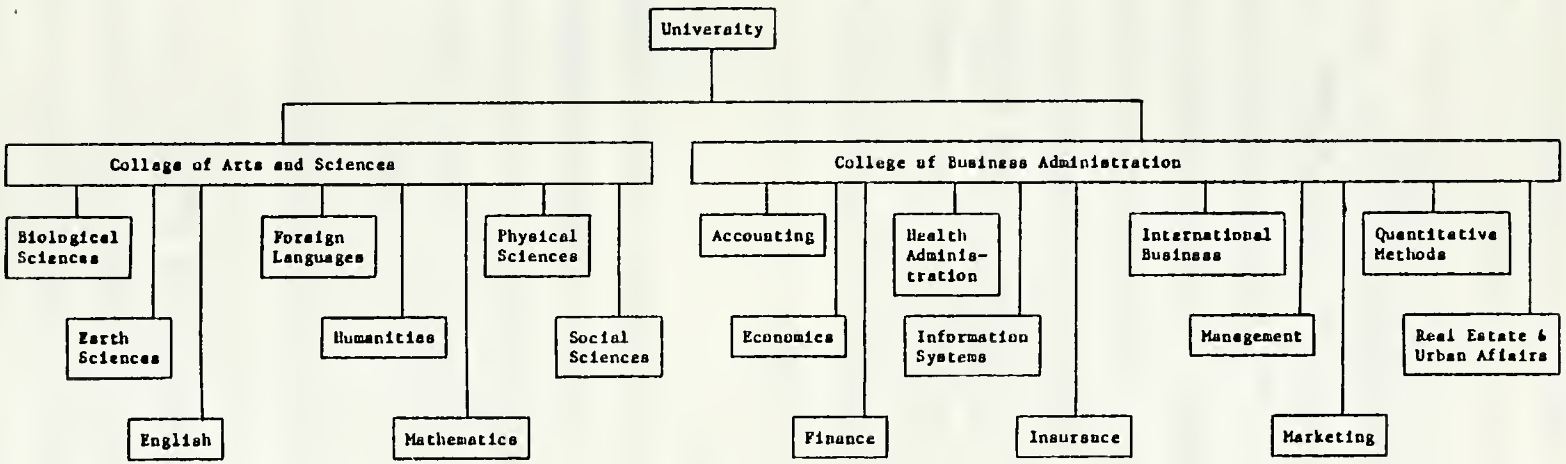

Figure 1

Organizational Structure of the University Model overview of the university, college, and department problems is presented below.

The University, College, and Department Problems

For operational purposes the university is assumed to have six performance goals. These goals relate to the university's discretionary budget, graduate and undergraduate unfulfilled student demand, minimum levels of university-wide undergraduate core course offerings, and faculty composition. In the decomposition framework the colleges review the operating decisions generated by their subordinate departments and submit revised coordination information, transfer prices and/or performance goals, based upon external university and internal college policies.

A. Internal Goals and Policies

Because the majority of a university's course offerings are part of internal college programs, it was not necessary to superimpose external university constraints upon all departmental minimum course offerings. However, there was a need to specify that internal college programs were adequately staffed and funded. To accomplish this, three internal goal sets were imposed; they controlled the colleges' doctoral programs and tenure decisions.

An internal goal relating to doctoral seminars was included for several reasons. Viable doctoral programs can provide opportunities and incentives to faculty members to become involved in research and to remain current in their areas of specialization. Also Ph.D. students can augment departmental teaching lines, and outstanding doctoral candidates tend to reflect favorably upon the university thereby attracting top faculty and students. Unfortunately because most doctoral seminars have small enrollments and are often taught by the best qualified and most highly paid faculty, doctoral programs may not be cost effective. Unless minimum goals were placed upon these seminar offerings, they might not be offered.

The final two internal goals and constraints were related to the granting of tenure. It was felt that including a potential for incorporating promotions, and/or the hiring outstanding, tenured faculty would greatly enhance the planning model. These constraints were not intended to evaluate faculty productivity, but were incorporated as a means to determine the budgetary implications and faculty composition the result from a selected set of tenure policies.

B. External Goals

Each college's problem contained a set of constraints that linked its subordinate departments with university goals. These are targeted at meeting the university stipulated budget, unfulfilled undergraduate and graduate demand, faculty composition, and minimum core course offering goals.

In a decentralized setting, top management is typically interested in the big picture rather than the intricacies of operating details. However, as one moves down the organizational hierarchy, it becomes necessary to consider many operating interactions in detail. Unfortunately, because of space limitations, only a brief overview of the departmental problems can be presented. However, a detailed description is available in [32, pp. 81-107].

C. Departmental Decision Variables

The principal components of the departmental problems are the number, level, and size of course offerings and the type and quality of staffing positions teaching those courses. To link these components each department has seven, full time equivalent (FTE) levels for staff and faculty positions as well as seven levels of course offerings. The staff and faculty variable levels were: (1) secretarial and research associate personnel, (2) graduate student research assistants, (3) graduate student teaching assistants, (4) instructors (nonterminal degree), (5) assistant, (6) associate (tenured), and (7) full (tenured) professors. The course offering levels were: (1) freshman-sophomore core, (2) junior-senior core, (3) junior-senior major-minor, (4) graduate (masters) core, (5) graduate (masters) major, (6) graduate (doctorate) core, and (7) graduate (doctorate) major courses. Also, associated with these course levels are seven variables that capture unfulfilled course demand. Finally, departmental budgets composed of salaries and indirect costs were included as decision variables.

D. Departmental Operating Constraints and Goals

Each departmental formulation incorporated five categories of operating constraints: (a) class size and enrollments, (b) teaching loads and levels, (c) secretarial and research support, (d) direct and indirect budgetary expenses, and (e) tenure obligations. These incorporate university policy in regard to average class size and professorial teaching levels for the seven course levels offered within the departments. In addition these policy constraints specify that courses offered at various levels cannot exceed the pool of faculty capable of teaching at that level. For example, only professors are allowed to teach doctoral courses; however, as the pool of course offerings expands to include the freshman-sophomore level all teaching levels are included.

Each department's problem included constraints which provide minimum and maximum levels of secretarial and departmental administrative support, and levied maximum and minimum levels for departmental graduate student-research assistant support. Each problem also contained equations which defined departmental salaries, minimum and maximum indirect cost levels, and a total departmental budget. Finally constraints which insured that tenure obligations were fulfilled were incorporated.

E. Organizational Priorities and Goal Directions' Weightings

A comparison of the Ruefli, Freeland, and Davis algorithms reveals the key role played by the goal deviations' penalty weightings in determining the eventual allocation of resources. See [10] for an in depth comparison of these organizational models. The intricacies of the university model's weightings are rather cumbersome, and because they are given elsewhere [32], only a few details are provided here. First, the weights assigned to both colleges' budget overrun deviations were equal and received the highest weighting. Accordingly, neither college had a relative advantage in terms of budgetary bargaining power or bureaucratic political clout. There were differences in the other goal deviation priorities. For example, Business Administration and its departments tended to place higher priorities on doctoral programs. In contrast, the College of Arts and Sciences and its departments were more concerned with undergraduate programs. These weightings seem entirely rational in light of the current educational environment characterized by an oversupply of potential faculty and undersupply of students in the liberal arts disciplines and the opposite conditions in many Business Administration fields.

Before describing the results of computational testing, a few points should be noted. The Davis Generalized Hierarchical Model (GHM) can incorporate actual cost vectors associated with decision variables at each level of the decision making hierarchy. Neither the Ruefli nor Freeland models contained these costs in their objective functions. Although operating costs and budget expenses are incorporated within the constraint structure of the university model, they were not directly inserted in any of the algorithms' objective functions. However, they were included indirectly via deviations from budgetary goals. Thus the university model's formulation was compatible with the goal programming structure of each algorithm. (For an application that includes both costs and penalty weights assigned to goal deviations, see the design problem in Davis [8].) Finally, the GHM utilizes a goal programming structure at each level of its hierarchy. For convenience, the departmental penalty weights, associated with goal deviations at the lowest level of the organization, were given the same values as corresponding deviations as their superordinate college.

IV. Computational Testing of the Algorithms

An Overview of the Organizational Models

This section reports on the results of computational tests on a series of multiple criteria, three-level hierarchical organizational models. In total five models were tested: two versions of Ruefli's Generalized Goal Decomposition Model [25, 26] (GGD-I and GGD-II, respectively); the Freeland [16, 18] and Freeland and Baker [17] model (F-B); the Davis Generalized Hierarchical Model [9] (GHM); and finally a hybrid of the Freeland and Baker and Davis models [10] (F-B/D). Although a description of the structure of these organizational models is given in a companion paper [10], a very brief outline of each follows.

The first of the multicriteria organizational models was developed by Ruefli [25, 26] over ten years ago. In describing his algorithm, Ruefli was somewhat ambiguous on exactly what informational flows and constraints should be incorporated. He suggested [25, p. B510] but mathematically did not use a convex combination constraint at the middle or managerial level of the organizational hierarchy. This convex combination constraint would be used to compute a composite proposal vector for the lowest or operating unit level of the decision-making hierarchy. Instead, the original GGD allowed each manager to select a proportion, between zero and one, of the latest proposal vector generated by a given operating unit. Two unfortunate consequences could result from the omission of this convex combination constraint. First, the manager's proposal selection might lie outside the feasible region of an operating unit's decision space. Second, convergence of the GGD model cannot be demonstrated. Accordingly, two versions of the GGD formulation were tested: the original version, GGD-I, and a convex combination version, GGD-II. The GGD-II model employed convex combination constraints at the managerial level in order to generate composite proposal vectors.

The third organizational algorithm applied to the university resource allocation model was developed by Freeland [16, 18] and Freeland and Baker [17]. Based upon the results of the Ruefli models, an additional constraint was added to the middle level problem of their original formulation. This constraint was identical to the modification made to obtain the GGD-II version, and it insured feasibility of the department's operating proposals.

The fourth organizational model tested was the Davis GHM [9, 32, 33]. The solution structure of the GHM differs from the other models in that it utilizes a goal programming formulation at each level of the hierarchy. In addition, instead of shadow prices, the GHM focuses upon goals and goal deviations as coordinative mechanisms.

The final algorithm tested in this research represents a hybrid of the Freeland-Baker and Davis GHM dubbed the F-B/D model. As seen in Freeland [18] the original Freeland-Baker model represented a restructuring of Ruefli's GGD formulation. At the highest level of the decision-making hierarchy, the F-B model included Benders' cutting-plane formulation [2]. The lowest level was left unchanged. In contrast, the GHM utilized a goal programming decision structure at each level of the hierarchy. The F-B/D model incorporates the top two levels of the Freeland-Baker model in conjunction with the GHM goal programming structure and essential coordinative informational flows at the lowest level of the organization.

<u>Computational Requirements and Methods</u>

The size of the overall problem of the university planning model presented in the previous section is rather large. In total this problem has approximately 2,400 variables and 900 constraints. Because of the man-hours required to formulate and solve the iterative stages of each algorithm, it was necessary to write a computer program that could implement each of the organizational models. These five programs were coded in FORTRAN and were tested on a Control Data Corporation CYBER-175 computer. The linear programming optimization subroutines for the various programs utilized a sparce matrix inversion process and were developed by Marsten [22]. These computer programs offered several benefits. First, they eliminated the possibility of data manipulation errors creeping into the informational flows as they were passed from one subproblem to another. Second, they greatly reduced data input time. Finally, they provided extraordinary computational speed and ease. For example compilation of each FORTRAN program required approximately 3.5 seconds of central processing unit (CPU) time. Execution time was also quite fast. No algorithm required more than 95.3 CPU seconds for convergence, and some converged in as little as 10.5 CPU seconds.

Results of the University Resource Allocation Model

The results of the computational testing of each algorithm on the university planning model provided an interesting contrast. In order to access the efficacy of each algorithm in dealing with various levels of "managerial indigestion," three versions of the university model were tested. The first incorporated a total budget ceiling of $8 million; the second and third had total budget ceilings of $7.5 and $7.0 million, respectively. Initial analysis indicated that an overall budget of $8.0 was adequate to meet both colleges' programs. However, there was no budgetary slack in this highest funding level. As the total budget level was reduced, the problem of rationing scarce resources became more significant. And at the $1 million reduction level, budgetary problems became critical.

Table 1 provides a summary of the results of these tests. Several interesting and somewhat surprising characteristics appear in Table 1. First, with the exception of the GGD versions, none of the algorithms required more than five planning, programming, and budgetary reviews (iterations) for convergence. These results are even more surprising when one considers the fact that no hueristic starting procedures were utilized in any of the models. In fact if one disregards the first iteration, which is required for model initialization, the number of iterations required for convergence is markedly similar to those experienced by most decentralized organizations. When compared with the results of previous applications [3, 4, 7, 11], these results are extraordinary.

Perhaps the most disappointing aspect of these test results was the inability of either version of Ruefli's GGD model to provide acceptable results. Although the objective function values of the GGD-I runs appear vastly superior to the other models, the underlying results of the GGD-I runs are disastrous. The previous discussion of the GGD-I and GGD-II differences indicated that a college's selection of an individual department's operating proposals might not be feasible. That is, the proposals might violate the department's operating constraints. This was precisely what happened in the tests of the GGD-I model. The decisions generated by GGD-I even at the $8.0 million level suggested that departments with more than adequate enrollments should shut down their operations.

Table 1
Computational Results of the Organizational Models

Objective Function Value

Model	Budget	1	2	3	4	5	6	7	8	9	10	
						Iteration #:						
	$8.0	9245	10115	7805	12000	9820	12000	10330	12000	10330	etc. ...	
GGD-I	$7.5	9245	10115	7805	12000	9820	12000	10330	12000	10330	etc. ...	
	$7.0	9245	10115	7805	12000	9820	12000	10330	12000	10330	etc. ...	
	$8.0	689180	540580	620300	539460	616550	539160	613550	539680	613550	539680	etc. ...
GGD-II	$7.5	689180	540580	620300	539460	616550	539160	613550	539680	613550	539680	etc. ...
	$7.0	689180	540580	620300	539460	616550	539160	613550	539680	613550	539680	etc. ...
	$8.0	689180	0	0	etc.	...						
F-B	$7.5	689180	35883	57854	57854	etc.	...					
	$7.0	689180	110880	99862	99862	etc.	...					
	$8.0	1250900	0	0	etc.	...						
GHM	$7.5	1250900	24862	24862	etc.	...						
	$7.0	1250900	99862	99862	etc.	...						
	$8.0	689180	0	0	etc.	...						
F-B/D	$7.5	689180	50133	43604	43604	etc.	...					
	$7.0	689180	125130	99562	88127	88127	etc.	...				

By comparison, the operating proposal results of GGD-II were much better; however, the objective function values of this version indicate a rather curious pattern. They are identical, regardless of which budget level was used. This same pattern also appeared in the GGD-I results. Further a two iteration cycling pattern emerges at iteration six for GGD-I and iteration seven for GGD-II. Analysis of these versions' results indicates that one factor is causing both the cycling and equal objective function value problems. In the discussion of the GGD-II algorithm, strong emphasis was placed upon the need to incorporate a convex combination "proposal constraint" at the managerial level. Ruefli noted [25, p. B510] that it also might be necessary to place a similar constraint on all previously generated goals. This type of constraint was not included in the GGD-II version, because as Freeland [18] has pointed out, it would totally destroy the algorithm's decomposition structure. Our results indicate that without a convex combination goal constraint, the GGD-I and II algorithms will cycle between corner points of the feasible decision space for the highest level of the decision-making hierarchy. Beyond question, the Ruefli GGD model was a landmark breakthrough in multi-level, multicriteria decision-making. Further, it laid the foundation for each of the models tested in this study. Unfortunately it appears that a meaningful application of the GGD model is not possible.

The third row in Table 1 describes the results of the Freeland or Freeland and Baker (F-B) algorithm. Again it should be noted that the version tested in this study incorporated a convex combination constraint similar to the one employed in GGD-II. This constraint was omitted from the original version of the F-B model. Initial testing indicated that omission of the constraint generated results that were as nonsensical as those of the GGD-I runs. With the constraints, the model performed reasonably well. Convergence was rapid; the proposals were deemed reasonable; and cycling was not a problem. However, careful analysis of the F-B results for the $7.5 million budget reveals a curious pattern. That is, the value of the objective function for iteration two is <u>less</u> than those of all subsequent iterations. This anomoly results from the introduction of new cutting-planes into the university-level problem at each iteration. The introduction of new constraints or cutting-planes is important because a previous goal vector could be rendered infeasible or non-optimal on a subsequent iteration. Even more important is the fact that once cutting-planes are introduced, they remain for all subsequent iterations. In defining the cutting-planes, the simplex multipliers from the college level decisions are used. The major concern here is that in the early iterations, these simplex multipliers may have little or no relation to the overall optimum solution. In fact, their values may be detrimental to the decomposition process. Because the F-B model is dependent the procedure used to initiate the iterative process (i.e., assign initial goals to the college-level problems), this type of anomoly can exist.

Although the F-B model generated good results, by comparison the GHM's and F-B/D's solutions were even better. The GHM runs converged in no more than three iterations, while the F-B/D model needed four for the $7.5 million funding level and five at the $7.0 level. These models yielded identical results at the $8.0 budget level. In terms of objective function values, the GHM outperformed the F-B/D model at the $7.5 million level, while at the $7.0 million level the F-B/D was slightly better.

These improved results vis-à-vis the F-B model are attributable to the goal deviations and performance goals incorporated at the lowest level of the decision-making hierarchy. When compared with the shadow prices or dual variables utilized by the other algorithms, the goal deviations and sequential goal generation techniques incorporated in the GHM and F-B/D algorithms offer a more attractive and effective mechanism for coordinating organizational decision-making. On the other hand, additional testing of the GHM and F-B/D algorithms is necessary to determine if a Benders' partitioning technique is consistently superior or inferior to the goal deviation-sequential goal generation technique at the highest level of the decision making hierarchy. The theoretical results cited in our comparison paper [10], point to the conclusion that incorporation of a quadratic objective function within each algorithm could solve many of the difficulties found in this family of multiple criteria organizational models. If this is the case, the relative advantage of either the Benders' or goal deviation-generation technique in a linear model would be a moot issue.

V. Summary and Conclusions

The purpose of this research has been to test the computational properties, rates of convergence, and feasibility of implementing four, three-level, multicriteria, decomposition models. The organizational models developed by Ruefli, Freeland (and Freeland and Baker), Davis, and Davis and Whitford were tested upon a relatively large university resource allocation problem. Section II provided an overview of the economic and demographic environment faced by U.S. universities and provided a justification for using a multiple criteria, decomposition approach in a university setting. Section III outlined the structure and constraints of the university resource allocation model tested in this study. The model was structured around the two largest colleges at Georgia State University and contained three hierarchical levels. The highest level represented the university's administration. The middle level contained two colleges, Arts and Sciences and Business Administration. The lowest level contained nineteen departments, eight subordinate to Arts and Sciences and eleven subordinate to Business Administration. Section IV described computational tests of the algorithms. Also the fourth section gives a brief overview of the algorithms, their computational requirements, and solution results. With the exception of the Ruefli GGD versions, the models performed well. Thus even in an environment characterized by multiple and conflicting goals, lack of unaniminity in organizational priorities, and severe financial restrictions, these organizational models performed well, albeit some better than others. The number of information exchanges or iterative reviews required for convergence were relatively few and were strikingly similar to those experienced by many decentralized organizations. These convergence results were achieved without heuristic starting procedures.

The relative success of the organizational models tested in this study does not imply that future research is unwarranted. Currently work is in progress that will incorporate a quadratic objective function optimization option in the FORTRAN computer codes of each algorithm. It is likely that this type of nonlinear objective function will solve many of the "nonoptimality" problems associated with this family of multiple criteria, hierarchical models. These quadratic results will be reported as research continues.

REFERENCES

1. Arrow, K. J. Essays in the Theory of Risk Bearing. North-Holland, Amsterdam, 1976.

2. Benders, J. F. Partitioning procedures for solving mixed-variables programming problems. NUMERISCHE MATHEMATIC 4 (January-February, 1960), 238-252.

3. Burton, R. M. and Obel B. The efficiency of the price, budget, and mixed approaches under varying a priori information levels for decentralized planning. MANAGEMENT SCIENCE 26 (April, 1980), 401-417.

4. Christensen, J. and Obel, B. Simulation of decentralized planning in two Danish organizations using linear programming decomposition. MANAGEMENT SCIENCE 24 (November, 1978), 1658-1667.

5. Cyert, R. and March, J. A Behavioral Theory of the Firm. Prentice-Hall, Englewood-Cliffs, N.J., 1973.

6. Dantzig, G. B. and Wolfe, P. Decomposition principles for linear programming. OPERATIONS RESEARCH 8 (February, 1960), 101-111.

7. Davis, W. J. and Talavage, J. J. Three-level models for hierarchical organization. OMEGA 5 (December, 1977), 709-722.

8. Davis, W. J. A generalized decomposition procedure and its application to engineering design. JOURNAL OF MECHANICAL DESIGN 100 (October, 1978), 739-746.

9. Davis, W. J. Multi-level decomposition models via penalty functions and sequential goal generation. Working Paper, Department of General Engineering, University of Illinois at Urbana-Champaign (March, 1979).

10. Davis, W. J. and Whitford, D. T. A comparative investigation of mathematical models for resource allocation in an organization. POLICY ANALYSIS AND INFORMATION SYSTEMS (this issue).

11. Dirickx, Y. M. I. and Jennergren, L. P. Systems Analysis by Multilevel Methods. John-Wiley, New York, 1979.

12. Dopuch, N. and Drake, D. F. Accounting implications of a mathematical programming approach to the transfer price problem. JOURNAL OF ACCOUNTING RESEARCH 2 (Spring, 1964), 10-24.

13. Drucker, P. The Practices of Management. Harper and Row, New York, 1954.

14. Dyer, J. and Mulvey, J. An integrated optimization/information system for academic department planning. MANAGEMENT SCIENCE 22 (August, 1976), 1332-1341.

15. Frankel, M. K. (ED.) National Center for Education Statistics, U.S. Department of Health, Education, and Welfare. Projections of Education Statistics to 1986-87. U.S. Government Printing Office, Washington, D.C., 1978.

16. Freeland, J. R. Conceptual models for the resource allocation decision process in hierarchical decentralized organizations. Ph.D. Dissertation (1973), Georgia Institute of Technology, Atlanta, Georgia.

17. Freeland, J. R. and Baker, N. R. Goal partitioning in a hierarchical organization. OMEGA 3 (December, 1975), 673-688.

18. Freeland, J. R. A note on goal decomposition in a decentralized organization. MANAGEMENT SCIENCE 23 (September, 1976), 100-102.

19. Freeland, J. R. and Moore, J. H. Implications of resource directive allocation models for organization design. MANAGEMENT SCIENCE 23 (June, 1977), 1050-1059.

20. Jennergren, L. P. On the design of incentives in business firms--A survey of some research. MANAGEMENT SCIENCE 26 (February, 1980), 180-201.

21. Lee, S. M. and Clayton, E. R. A goal programming model for academic resource allocation. MANAGEMENT SCIENCE 18 (April, 1972), B395-B408.

22. Marsten, R. E. XMP: a structured library of subroutines for experimental mathematical programming. Technical Report 351, Department of MIS, University of Arizona (1978).

23. Mirrless, J. A. The optimal structure of incentives and authority within an organization. BELL JOURNAL OF ECONOMICS 7 (Spring, 1976), 105-131.

24. Ross, S. The economic theory of agency: The principal's problem. AMERICAN ECONOMIC REVIEW 63 (May, 1973), 134-139.

25. Ruefli, T. W. A generalized goal decomposition model. MANAGEMENT SCIENCE 17 (April, 1971), B505-B518.

26. Ruefli, T. W. PPBS--An analytic approach. In Byrne, R. F. et al. (ED.) Studies in Budgeting, Vol. II of Budgeting of Interrelated Activities. North Holland, Amsterdam, 1971.

27. Ruefli, T. W. Analytic models of resource allocation in hierarchical multi-level systems. SOCIO-ECONOMIC PLANNING SCIENCES 8 (December, 1974), 353-363.

28. Simon, H. A. Administrative Behavior. Free Press, New York, 1957.

29. Sweeny, D. J., Winkofsky, E. P., Roy, P., and Baker, N. R. Composition vs. decomposition: two approaches to modeling organizational decision processes. MANAGEMENT SCIENCE 24 (October, 1978), 1491-1499.

30. Tenkate, A. Decomposition of linear programs by direct distribution. ECONOMETRICA 40 (September, 1972), 883-898.

31. Walters, A., Mangold, J., and Haran, E. G. P. A comprehensive planning model for long-range academic strategies. MANAGEMENT SCIENCE 22 (March, 1976), 722-738.

32. Whitford, D. T. Resource allocation in a university setting: A generalized hierarchical goal decomposition model. Unpublished Ph.D. dissertation, Georgia State University, Atlanta, Georgia (1980).

33. Whitford, D. T. A generalized hierarchical goal decomposition model of resource allocation within a university. College of Commerce and Business Administration working paper #705, University of Illinois at Urbana-Champaign (August, 1980).

34. Wilson, R. On the theory of syndicates. ECONOMETRICA 36 (January, 1968), 119-132.

D/33