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In the last two years, the project has focused on developing tools for representing, mathematically and in software, complex operational problems. We have developed a formal problem class called Dynamic Resource Transformation Problems which captures in a compact way a broad range of complex applications. We have developed a simulation library that captures the specific features of this problem class, in particular the ability to make decisions within the simulation. Finally, we have developed an algorithmic metastrategy that provides an effective way of solving these problems. We consider this work to be an important breakthrough in our ability' to model and solve the types of operational challenges that arise in military airlift operations, as well as a variety of civilian applications such as railroads and trucking, as well as air traffic control.



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## Abstract

In the last two years, the project has focused on developing tools for representing, mathematically and in software, complex operational problems. We have developed a formal problem class called *Dynamic Resource Transformation Problems* which captures in a compact way a broad range of complex applications. We have developed a simulation library that captures the specific features of this problem class, in particular the ability to make decisions within the simulation. Finally, we have developed an algorithmic metastrategy that provides an effective way of solving these problems.

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## 1. Objectives

We are developing a new modeling environment for a broad problem class called *Dynamic Resource Transformation Problems* (or DRTP's). Specific subtasks include:

Task 1) Development of a general representational framework that captures all the dimensions of a DRTP in a compact way.

Task 2) Development of a flexible mathematical notation that captures the structure of this class of problems. Our goal here is a simple, flexible notation that can easily reflect a broad range of complex operational issues (such as those studied by AMC using MASS) and yet still retain the structure of the problem so that we can optimize it (in contrast with MASS, which is a pure simulation).

Task 3) Development of a flexible software object library that allows us to execute the equations developed with the notation system. Our goal here is an architecture that easily handles a high level of complex operational issues yet maintains a separation between the optimization algorithm and the underlying model.

Task 4) Demonstration of our environment using the Airlift Flow Model as a demonstration.

Task 5) Design of algorithms that will produce optimal or near-optimal solutions to problems such as the AFM.

Task 6) Development of gradient estimates that will tell us what are the constraining resources at the end of a simulation.

## 2. Status of effort

Our progress in each of the tasks listed above:

Tasks 1 and 2) We have recently completed a representational paradigm that describes the fundamental dimensions of a DRTP, and provides an elegant mathematical representation. This model is being tested through its application, in three separate projects using different people, to a variety of operational problems.

Task 3) We have a prototype version of the simulation library. This is fully documented using a private web page, but we can provide access to any interested party.

Task 4) We have begun developing our own version of the Airlift Flow Model using data provided by AMC at Scott AFB. We do not intend our model to have all the details of the production version, but we want to have sufficient realism for us to demonstrate proof of concept, and also to investigate new optimization strategies that could be put into the production system.

Task 5) We continue to make progress on algorithms for solving this problem class. This past year, we made progress in a particular problem class which involves stochastic, dynamic resource allocation problems in the presence of multiperiod travel times. All transportation problems exhibit multiperiod travel times, but this presents particular modeling challenges in a stochastic setting.

Task 6) We have only begun research into gradient estimates from a simulation run.

## 3. Accomplishments/new findings

1. **Representation of DRTP's:** The conceptual and mathematical representation of DRTP's has given us a powerful new vocabulary that extends optimization into a dynamic arena, and provides for optimization logic within a simulation setting.

2. **Java-based simulation library for DRTP's:** A major result over the last several years has been the development of a new library for representing DRTP's in software. The implementation closely follows the DRTP paradigm that we have recently completed.

3. **Dynamic programming approximations for resource allocation problems:** We have developed a new class of dynamic programming approximations for resource allocation problems based on the adaptive estimation of piecewise linear functions using the CAVE algorithm. The algorithm appears to give us optimal solutions in certain problem classes, and very good solutions in more general problems. Convergence is fast and stable.

4. **Stochastic allocation problems in the presence of multiperiod travel times:** The challenge of solving resource allocation problems under uncertainty in the presence of multiperiod travel times has been largely overlooked, and yet introduces serious errors in many settings. For example, we may allow an unimportant aircraft to occupy airbase capacity in a congested period just because it took longer to get there, and hence the decision was made farther in the future. We have developed an elegant solution that produces near-optimal results when tested in a deterministic environment (for which optimal solutions are available). Solutions are always integer.

5. **Stochastic allocation problems in the presence of multiperiod travel times:** The challenge of solving resource allocation problems under uncertainty in the presence of multiperiod travel times has been largely overlooked, and yet introduces serious errors in many settings. For example, we may allow an unimportant aircraft to occupy airbase capacity in a

congested period just because it took longer to get there, and hence the decision was made farther in the future. We have developed an elegant solution that produces near-optimal results when tested in a deterministic environment (for which optimal solutions are available). Solutions are always integer.

6. **Pattern matching behaviors in problem representation:** We are developing a pattern-based approach for improving the acceptability of solutions without extensive engineering. This has already proven valuable for our work with Yellow Freight System and Norfolk Southern Railroad, and we are continuing to use this powerful concept in our other work.

## 4. Personnel supported

Faculty:

- Professor Warren B. Powell

Research staff:

- Dr. Jack Gelfand, Senior Research Scientist

Graduate students:

- Greg Godfrey
- Joel Shapiro
- Huseyin Topaloglu
- Mike Spivey
- Katarina Papadaki

Undergraduates

- Steve Woolbert

## 5. Publications (10/1/97 - 9/30/98)

### 5.1. Submitted but not yet accepted:

"Network Representation, Column Generation and Branch and Bound for Parallel Machine Scheduling with Multiple Job Families," (with Zhi-Long Chen) Submitted to Operations Research, March, 1998.

"Adaptive Estimation of Daily Demands with Complex Calendar Effects," submitted to Transportation Research (with G. Godfrey). September, 1997.

"A Multiplier Adjustment Method for Dynamic Resource Allocation Problems," submitted to Transportation Science (with Tassio Carvalho). Under revision, July, 1998.

Powell, W.B. and J. Shapiro, "A Dynamic Programming Approximation for a REALLY BIG Large-Scale Driver Scheduling Problem," submitted to Operations Research. March, 1998.

Godfrey, G. and W.B. Powell, "An Adaptive Approximation Method for Stochastic, Dynamic Programs, with Applications to Inventory and Distribution Problems," submitted to Management Science, July, 1997.

Chen, Z.-L. and W.B. Powell, "A Convergent Cutting Plane and Partial Sampling Algorithm for Multistage Linear Programs with Recourse," submitted to JOTA.

"Adaptive Labeling Algorithms for the Dynamic Assignment Problem," submitted to Transportation Science (with W. Snow and R. Cheung). Under revision for resubmission.

"A Representational Paradigm for Discrete Dynamic Resource Transformation Problems," submitted to Annals of Operations Research on Modeling (Fourer, Gay and Geoffrion, eds). March, 1998.

J.J. Gelfand, S.L. Epstein and W.B. Powell, "Integrating Pattern Learning in Multimodal Decision Systems,"

G. Godfrey and W.B. Powell, "Control of Multistage, Stochastic, Dynamic Resource Allocation Problems," submitted to Operations Research, under revision.

J. Shapiro and W.B. Powell, "An Object-Oriented Framework for Dynamic Resource Transformation Problems," submitted to Informs Journal on Computing, September, 1998.

## 5.2. Accepted but not yet published:

Powell, W.B., M.T. Towns and A. Marar, "On the Value of Globally Optimal Solutions for Dynamic Routing and Scheduling Problems," Transportation Science, To appear.

R. K.-L. Cheung and W.B. Powell, "The Convergence of Hybrid Stochastic Gradient Methods in Stochastic Programming, with an Application to Dynamic Networks with Random Arc Capacities," Operations Research. To appear.

"A Column-Generation Based Decomposition Algorithm for a Parallel Machine Just-In-Time Scheduling Problem," European Journal of Operations Research (with Zhi-Long Chen). March, 1997. To appear.

"Solving Parallel Machine Scheduling Problems by Column Generation," Informs Journal of Computing (with Zhi-Long Chen). To appear.

## 5.3. Published:

Powell, W.B. "On Languages for Dynamic Resource Scheduling Problems," in Fleet Management and Logistics, (T. G. Crainic and G. Laporte, eds.), Kluwer Academic Publishers, Boston, 1998.

"A Generalized Threshold Algorithm for the Shortest Path Problem with Time Windows," in Network Design: Connectivity and Facilities (P. Pardalos, D. Du, eds.), pp. 303-318 (1998). (with Zhi-Long Chen).

"An Optimal Control Formulation of Large-Scale Multiclass Machine Scheduling Problems," in *Network Optimization, Lecture Notes in Economics and Mathematical Systems*, (P. Pardalos, D. Hearn and W. Hager, eds.), Springer-Verlag, New York, pp. 423-440, 1997 (with Z.-L. Chen).

"Dynamic Control of Logistics Queueing Networks for Large Scale Fleet Management," Transportation Science, Vol. 32, No. 2, pp. 90-109, 1998.

Powell, W.B. and T. Carvalho, "Real-Time Optimization of Containers and Flatcars for Intermodal Operations," Transportation Science, Vol. 32, No. 2, pp. 110-126, 1998.

"Finding the Yellow Brick Road: Part VII: I Finally Have a Brain!," *Interfaces*, Vol. 27, No. 5, pp. 9-14, (with Don Mayoras).

"Finding the Yellow Brick Road: Part VI: Courage!" *Interfaces*, Vol. 27, No. 4, pp. 12-22 (1997). (with Don Mayoras)

"Finding the Yellow Brick Road: Part V: Through the Crystal Ball" *Interfaces*, Vol. 27, No. 3, pp. 14-21 (1997). (with Don Mayoras)

"Dynamic Control of Multicommodity Logistics Queueing Networks," European Journal of Operations Research, Vol. 98, No. 3, 1997. (with Tassio Carvalho).

"A Note on Bertsekas' Small-Label-First Strategy," Networks, Vol. 29, No. 2, pp. 111-116 (with Zhi-Long Chen).

### 5.4 Technical reports

1 "A Generalized Threshold Algorithm for the Shortest Path Problem with Time Windows," submitted to Journal on Computing. (with Zhi-Long Chen).

## 6. Interactions/transitions

### 6.1. Participation/presentations at meetings, conferences, etc.

Invited talks:

"Approximate Methods for Multistage Dynamic Programs for Discrete Dynamic Resource Allocation Problems," Stochastic Programming Conference, Vancouver, BC, August, 1998 (with G. Godfrey).

"A Convergent Cutting Plane Algorithm for Multistage Stochastic Programs," Stochastic Programming Conference, Vancouver, BC, August, 1998 (with Z.-L. Chen).

"Models, Formulations and Algorithms for Multi-Layered Resource Scheduling Problems," Air Products and Chemicals, Allentown, PA, July, 1998.

"Locomotive Scheduling as a Dynamic Resource Transformation Problem," Research conference, Norfolk Southern Railroad, Atlanta, GA, July, 1998.

Invited tutorial: "A Representational Paradigm for Dynamic Resource Transformation Problems," Triennial Symposium on Transportation Analysis III, Puerto Rico, June, 1998.

"Approximate Methods for Dynamic Resource Allocation Problems," Triennial Symposium on Transportation Analysis III, Puerto Rico, June, 1998 (with G. Godfrey).

"Implementation of a Dynamic Fleet Management System," Triennial Symposium on Transportation Analysis III, Puerto Rico, June, 1998 (with A. Marar).

"Dynamic Resource Transformation Problems: Problem Representation and Solution Algorithms", New World Vistas Conference, sponsored by Air Force Office of Scientific Research, Monterey, CA, May, 1998.

"Dynamic Resource Transformation Problems: A New Modeling Approach for Air Mobility Problems," Air Mobility Users Group Conference, Air Force Academy, Colorado Springs, CO, May, 1998.

"Management Issues in Transportation Modeling and Optimization," Freight Transportation Short Course, Georgia Institute of Technology, Atlanta, Georgia, August, 1997.

"Control of Dynamic Resource Transformation Problems: An Overview of CASTLE Laboratory," Airlift Mobility Command, St. Louis, MO, July, 1997.

Conferences: Numerous talks at the biannual INFORMS meetings.

### 6.2. Consultative and advisory functions

I regularly meet with the group at the Airlift Mobility Command, both at Scott AFB and one or twice a year at their air mobility group users meetings. We have begun developing our own version of the airlift flow module so that we can work directly with their data, and thereby better understand the specific issues they are grappling with. This simulator will allow us to try out ideas that might be implementable in the production version of the code.

### 6.3. Transitions

A major thrust of my research program is the development of general purpose analysis tools for dynamic resource management problems. This approach allows us to identify opportunities for applications of our developments in different arenas, although our focus is entirely on transportation problems similar to those faced by AMC.

Specific transitions that have occurred include:

1 Transition: We have applied our optimal control methodology based on our new "logistics queueing network" (LQN) formulation, to the management of their intermodal flatcar fleet.

Recipient: Norfolk Southern Railroad and Burlington Northern Sante Fe Railroad.

2 Transition: We have applied our optimal control methodology to the management of the linehaul network for LTL motor carriers. These problems involve tactical planning of over 6,000 drivers.

   Recipient: Yellow Freight System, Inc.

3. Transition: We have adapted our multiattribute labeling algorithm to handle real-time load planning for truckload motor carriers.

   Recipient: Burlington Motor Carriers

4. Transition: Adaptive estimation of exogenous information events. This past year we produced a major refinement of a hierarchical exogenous activity estimation system. This year (1998) it went into production to help Yellow Freight System forecast shipper activity and network performance.

   Recipient: Yellow Freight System

5. Transition: An algorithm for multi-layered dynamic resource transformation problems.

   Recipient: Air Products and Chemicals

Last year saw the first wave of transitions by Transport Dynamics which is working with technology produced by CASTLE Lab, licensed from Princeton University. Two of these transitions include:

6. Transition: Driver scheduling and capacity forecasting in a stochastic environment for a fast-response motor carrier. This system was licensed by the University to Transport Dynamics.

   Recipient: Roberts Express, implemented by Transport Dynamics under license from Princeton University.

7. Transition: Dynamic load planning for less-than-truckload motor carriers

   Recipient: Roadway Package System, implemented by Transport Dynamics under license from Princeton University.

## 7. New discoveries, inventions or patent disclosures

This fall we will make a formal disclosure of our new simulation library, developed in Java, for simulating dynamic resource transformation problems.

## 8. Honors/awards

Our research has produced six awards for graduate student research. Last year we learned of:

Winner, 1997 Transportation Dissertation Prize Competition, won by Tassio Carvalho, Dissertation title: Dynamic Control of Spatial Resource Allocation Problems."