

# FY2008 RESEARCH PROJECT PROPOSAL

## Center for Transportation Studies, University of Minnesota

Please complete this form with all information requested.

Maximum proposal length is **5 pages**, not including attached resumes.

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**1. Research Project Title: Optimal Manpower Planning and Shift Scheduling For Snow and Ice Removal**

**2. Proposal Type: (check ONLY one)**

To place an X in the box, below, double click on the box and select "checked".

This proposal addresses:

- Problem Statement:** PS # A08PS11 and G08PS05  
 **Knowledge-Building Priority:** KB # \_\_\_\_\_  
 **Other Research Need**

**3. Principal Investigator:**

**Name:** Diwakar Gupta  
**Department:** Mechanical Engineering  
**Position Title:** Professor & Director of Graduate Studies  
**Phone/E-Mail:** 612-625-1810; [guptad@me.umn.edu](mailto:guptad@me.umn.edu)

**Co-Investigator (if applicable):**

**Name:**  
**Department:**  
**Position Title:**  
**Phone/E-Mail:**

**4. Additional Team Participants (if applicable):**

*Additional team members may include subconsultants and/or other collaborators who will play a significant role in the research.*

**Name:**  
**Affiliation:** (University, Company, Agency, Department or other)  
**Role on Project:** (Subconsultant, or other partner)

**5. Proposal Abstract:**

*A brief (maximum 200 words) description of the research project.*

Shrinking budgets, aging workforce, and high equipment and fuel costs have raised the importance of manpower planning and efficient workforce deployment during snow and ice storms. MnDOT and State counties use different approaches for crew scheduling (split versus standard shifts) and have different Level-of-Service (LOS) goals. It is not clear which approach should be used when. Moreover, there does not appear to be a systematic methodology for estimating manpower needs. The two issues are closely related. Therefore, this proposal will respond to two different problem statements. Manpower requirement planning and crew deployment problems will be first formulated as mathematical optimization problems, with appropriate constraints coming from county engineers' expert judgment and union rules. We will then develop solution algorithms using commercially available optimization software. The PI will use a particular county's data to illustrate the proposed methodology. A number of possible storm scenarios will be analyzed (using Event Logs from AI/RWIS system) and dominant response strategies will be linked with different types of storms. Results of the study will impact efficiency of both the MnDOT and state county snow and ice removal operations. Systematic evaluation will also focus attention on the cost impact of different LOSs.

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6. **Anticipated Duration of Project (in months):** 30 Months
7. **Total Budget (direct costs only):** 146,787
8. **Budget Details (direct costs only):** [Note: Salaries include fringe]
- Salaries:**
- |   |        |
|---|--------|
| Faculty:                                | 39,539 |
| Graduate Students:                      | 95,948 |
| Other (Civil Service, Scientist, etc.): |        |
- Equipment:** 3,200
- Supplies:** (Software) 2,000
- Travel:** (Conferences) 5,100
- Subconsultants:**  
(costs for non-academic subconsultants cannot exceed 50% of the total proposal budget)
- Other:** (Mileage, parking, data acquisition, and duplicating/printing/telephone) 1,000

### 9. Budget Justification:

*If budget includes excessive equipment or other costs, explain the need for these items.*

The PI salary is justified by the fact that PI is paid on a 9-month basis. All 5 major tasks in this project require the support of a graduate RA. The RA will help acquire, clean, interpret and summarize available data. RA will also help the PI in developing optimization algorithms, in writing the necessary computer codes, and in preparing task reports as needed during the course of this project. Due to the intensive data analysis required, the PI and his assistant will need access to a dedicated computer workstation, which is budgeted at \$3000 plus \$200 in setup services. In addition, we have budgeted for the purchase of data analysis software such as SPSS. The PI will travel to one conference in each year of the project. This will help publicize this work and benefit the PI from the feedback received from other researchers with similar interests. Such interactions are very important and help to improve the overall quality of the research, besides giving publicity to the work being performed.

### 10. Matching Funds or Other Partnership Contributions:

*Identify matching funds, in-kind or other contributions that will be made in support of this research. List sources and estimated amounts.*

None.

### 11. Research Objectives:

*What problem will be addressed? What impact will be made as a result of this research?*

The proposed research has the three major thrusts summarized below. A particular state county will be chosen to serve as a test case for the proposed work. All data references are to the data from that county.

#### **Theme 1:** *(From data to model inputs)*

1. What are the snow removal objectives in terms of LOS and time to clear? How clean the road surfaces should remain during a storm? How soon after the storm should all snow and ice be removed from road surfaces? What are the implied penalties for not meeting these targets? Can this data be used to find managerially relevant snow-removal priorities, e.g., high, medium, and low, for each street or highway segment?
2. What are common snowfall patterns during storms? Can this data be grouped into a few relevant categories for planning purposes, e.g., light, normal, and severe?
3. How can we combine climate data, snow removal objectives, vehicle routes, and engineers' expert judgment to develop hourly crew requirements as a function of the relevant variables?

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### **Theme 2:** *(Crew deployment)*

1. Given hourly requirements, current crew size, possible choices of shift lengths (e.g., full or split), what is the optimal crew deployment strategy? Specifically, this exercise will provide answers to the following questions:
  - a. How many snowplow drivers should be on split shift schedule and how many on full shifts?
  - b. What should be the shift start times for each driver?
2. How well does a particular crew-deployment strategy perform under different types of storms? To what extent does it meet stated goals? How many different deployment strategies are necessary to respond adequately to commonly-occurring storm patterns?

### **Theme 3:** *(Optimal manpower requirements)*

1. Given crew costs, implicit costs of not meeting snow-removal objectives, and equipment constraints, what is the optimal number of crew to hire?
2. What other sources of flexible workforce exist? Should the State create a pool of crew across several counties that could be tapped by the participating counties in case of snow emergencies? How will crew be allocated to different counties when multiple counties have snow emergencies? How cost effective are such strategies?

Each theme of this research will have a beneficial impact on manpower planning and crew scheduling operations. For example, knowing crew requirements under different snowstorm patterns will help to develop good strategies that can be implemented quickly in case of an emergency. Knowing optimal deployment patterns in advance will also lead to a smooth transition to *active* status and to a greater acceptance from the drivers. As a result of Theme 3, it will be possible to make a case to the State and County administrators for the required number of crew, and to develop an appropriate hiring and retention plan.

## **12. Summary of Previous Work Related to this Proposed Research:**

*Include background information pertinent to the research described in this proposal.*

Upon performing a search on the Transportation Research Board's web page on recently completed and in-progress projects (<http://rip.trb.org/>), the PI found 12 projects with the keyword "snowplow" and 33 projects with the keyword "snow removal." These projects range in scope from designing intelligent vehicles (snowplows), measuring and reducing impact of salt and deicer on road surface, designing snowplow sensors, designing a simulator to train snowplow drivers, using road weather information systems, and developing advanced snowplow driver assistance systems. None of these projects deal with manpower planning and deployment issues.

Only one TRB project was found to have some common elements with the proposed project (Wright 1994). The project titled "Optimal Network Re-Partitioning for Improved Maintenance Management," TRB Accession Number: 722866, performed by Purdue University/Indiana Dept of Transportation, focused on finding optimal snowplow routes using a network partitioning technique. However, it did not deal with manpower management problems, such as those proposed in this project. Workforce deployment and requirement planning is concerned with aggregate requirements and although capacity loss caused by the routing plan is an important input, route-level details are not included in manpower planning problem formulations. Capacity losses typically come from the dead travel time of snowplows and salt trucks, i.e. travel to the start of the plowing route and return travel to the depot to refill salt and deicer, refuel, or change drivers.

By way of background, the PI has learnt that MnDOT and county operations differ substantially in current practice. A typical county approach is to call their crew early at the onset of a storm and to deploy either every available or the needed number of snowplows until work is finished. In contrast, MnDOT combines split shifts with a rotation schedule to maintain a constant coverage during the storm. With rotating split

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shifts, the maximum number of drivers on the road at any given time is smaller. In contrast, full deployment leads to larger number of drivers on the road in the beginning, but once drivers' shift is over, there may not be any coverage for a while until they are legally able to return to work. Full shifts can also be rotated. This too leads to fewer drivers on the road at any given time. Technical personnel in maintenance operations can be trained and called upon to drive plows during emergencies, but counties have limited access to such personnel due to the smaller size of their operations. Therefore, the key question that this project will attempt to answer is "Which of the two methods of workforce deployment is appropriate under which types of storm conditions?" The PI will also test the robustness of either approach in presence of uncertainty about how storms develop, i.e., storm pattern deviations from meteorological forecasts.

A Dutch company Quintiq ([www.quintiq.com](http://www.quintiq.com)) makes general-purpose workforce planning software. In addition, enterprise-level software suites like Oracle's Peoplesoft and HR Entre contain modules to manage workforce related issues – scheduling, leaves, salary and other HR management functions (see <http://www2.2020software.com/software/display.asp?tMethodID=14&tMethod=industry> for a quick comparison of the 17 most popular business solutions). To the PI's knowledge, none have the functionality to compare and contrast shift-scheduling strategies. The PI is not aware of any commercially available Decision Support System (DSS) that is tailor-made for manpower planning for snow removal operations.

This project focuses on research, not on the development of professional software. However, the models and algorithms developed during the course of this project could be turned into advanced-planning software that would interact with enterprise-level software to provide an automated decision support tool. Developing an advanced planning module could be undertaken as the next phase of this project.

### 13. Literature Search:

*Give an overview of relevant literature and describe how this project relates to other similar research and development activities.*

Workforce planning problems arise in many different application areas, ranging from military, manufacturing, mining, construction, healthcare, call centers, and every other type of service. Concomitantly, there is a large literature in different application domains that focuses on manpower planning problems in those domains. There is also Operations Research and Management Science (OR/MS) literature that is application-domain independent. OR/MS articles develop optimization methodology for solving large classes of shift scheduling and manpower requirement planning problems. Examples from the domain-specific and the OR/MS literature can be found in the section titled References. However, in the interest of brevity, we do not discuss each paper separately. Instead, we summarize previous contributions and discuss their relationship to the proposed research.

Upon searching various domain-specific databases, the PI found only one article that deals directly with snow and ice removal operations (Cook and Alprin, 1976). This article focuses on developing a dynamic routing heuristic that minimizes the time it takes for a given number of salt spreaders to traverse all streets in a network. This study is not concerned with workforce planning issues. Moreover, it assumes that all roads have to be traversed exactly once and storm variables are not modeled. In reality, both LOS priority (which could be based, for example, on average daily traffic or ADT counts) and storm variables are extremely important in choosing an appropriate routing protocol.

Domain-specific articles from areas of application other than snow and ice removal propose special purpose techniques that are not suitable for snow and ice removal. For example, in nurse scheduling applications, an important problem arises from the need to match skill-level requirements in each hospital ward with the training levels of available staff. In call center applications, the key performance metric is the number of callers who quit due to long waits. In manufacturing and construction project management,

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labor assignment to jobs has to match customer due dates and project schedules, respectively. Moreover, in all these applications, shifts and workforce assignments are based on a perpetual schedule that repeats daily or weekly, as appropriate.

Turning next to the domain-independent methodologies (see, for example, Koole and Sluis 2003, Campbell 1999, Aykin 1996, and Thompson 1995), such approaches cannot be applied directly to the target application domain. They need to be adapted and appropriately reworked. For example, a majority of previous studies deal with continuous operations, whereas response to snow storms is episodic. The duration and severity of snowstorms can change significantly from the initial forecasts. It is therefore necessary to study the robustness of deployment strategies with respect to uncertain storm conditions. The OR/MS literature considers a deterministic environment where the demand for workers remains fixed. Moreover, in previous work, per-period operator requirements are treated as “hard” constraints, which must be met by the proposed solution. In snow and ice removal, work-requirement constraints are “soft” constraints. That is, if the desired amount of work is not completed during a period, it can be completed in a subsequent period at a cost. This is the cost of increased inconvenience of having snow-covered roads for a longer period of time. Finally, in the snow and ice removal application domain, it is important to first meld historical data, road surface cleanliness objectives and expert judgment to develop estimates of demand for workers. This step is typically missing in workforce planning and deployment exercises.

Commonly used methodologies for solving shift-scheduling and manpower-planning problems are as follows. Shift-scheduling problems are typically formulated as mathematical optimization problems with integer decision variables. Since the resulting integer programs lead to computationally hard problems, a variety of heuristics are then proposed. These could be based either on the reduction of the integer program to a linear program, or on some other simplification/reduction of the original formulation. In the latter category, heuristics based on genetic algorithms and simulated annealing have been proposed and shown to work well in certain cases.

Manpower planning problems fall into three categories: forecasting, optimizing, and managing flows. Forecasting deals with predicting manpower requirements with respect to a higher organizational goal. Mathematical optimization formulations are then used to determine the needed number of personnel with each skill set to maximize an overall objective function consistent with the organizational goals, net of personnel costs. Flow models focus on the random nature of hiring and attrition. The decision maker controls advertising budgets and incentives that could affect both recruitment and retention rates.

### **14. Expected Benefits and Users of this Research:**

*What benefits are anticipated, why are they important, and how will they be measured? Who will use the results of this research?*

This project will streamline the work of MnDOT and county engineers and provide them with the tools to make better workforce planning and deployment decisions. By utilizing a scientific approach for the utilization of available personnel, it is also likely to improve driver acceptance of shift schedules. Finally, this approach will help make the case to Minnesota taxpayers for the level of resources needed to provide the level of service they expect. Specific benefits are as follows:

1. Development of a uniform and consistent approach toward assignment of resources that utilizes staff and equipment in a cost-effective manner.
2. Better service to Minnesota taxpayers at lower cost.
3. Improved models for manpower requirement planning and retention strategies.
4. Generation of innovative solutions for county based operations, e.g., understanding the effect of workforce pooling.

The results of this research will be used by engineers at MnDOT's and counties' snow and ice removal operations. Its impact can be measured by surveying the opinion of appropriate engineers, by comparing

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inflation-adjusted before and after cost of operations, and by comparing before and after Event Logs for the effectiveness of crew deployment approaches.

### **15. Summary of Research Methodology:**

*Provide an overview of the proposed research approach.*

The three themes of this project can be thought of as three steps in a hierarchy, with results of an earlier step providing input to a later step. Methodologies needed to accomplish each theme are as follows.

#### **Theme 1: From data to model inputs**

The PI will first obtain all relevant data in electronic format. Event Logs, that constitute a part of the AI/RWIS system, are an important source of historical data. Additional storm data is available through the Climatology Working Group's web page at [www.climate.umn.edu](http://www.climate.umn.edu) and from the Midwest Regional Climate Center at <http://mcc.sws.uiuc.edu/overview/overview.htm>. Event logs and climate data will be combined to develop a system of categorizing different storm types. The PI will work with country engineers to develop an estimate of the number of plows needed to be in service for each hour of service for each type of storm. This exercise will use a variety of inputs including road and highway network, LOS designations, ADT counts, desired time to clear, equipment types, average speeds, and location of salt depots. During this exercise, it may be necessary to use statistical tools to estimate certain relationships from historical data, if available. Depending on the complexity of operations in a given county, it may be necessary to also develop a computer simulation model to estimate workload requirements during this step. The PI will use the structured interview techniques developed for probability encoding and assessment of uncertainty in decision analysis (Spetzler and Von Holstein, 1975), while preventing commonly-occurring biases (Tversky and Kahneman 1974).

#### **Theme 2: Crew Deployment**

In order to obtain a tractable problem formulation, time will be discretized into 30-minute intervals. Note, other interval lengths can be chosen as well. A 30-minute interval is usually a good choice in manpower planning problems. For each storm scenario, the PI will then formulate an optimization problem whose objective is to minimize deviations from desired snow removal objectives in each half hour interval by assigning available crew to shift types and choosing the start times of each shift. Shift type determines the rules surrounding the length and timing of breaks, which form the constraints under which the optimization is carried out. For example, crew who work 6-hour shifts, followed by 6 hours of off time, must have a break after 12 periods that is at least 12 periods long. Additional constraints will come from available equipment by type and number of crew. This formulation will be solved using a standard optimization solver, e.g., CPLEX. Depending on the size of the problem, computing an optimal solution can be time consuming. If the computation time is too large, fast heuristic procedures will be developed to solve these problems.

After developing a problem formulation and a solution technique for a single storm scenario, the PI will use a stochastic programming framework to develop robust solutions for each major category of storm. For each category, a set of scenarios will be generated and a stochastic optimization algorithm will be used to find the deployment strategy that provides the most robust solution under storm pattern uncertainty. Care will be taken to include *stress* scenarios – low probability events that place a very high workload on the snow and ice removal operations. Page limits on this proposal do not permit a clear articulation of the stochastic optimization technique; details can be found in Birge and Louveaux (1997), among other places.

#### **Theme 3: Optimal Manpower Requirements**

The PI will first find bounds on crew requirements as follows. Starting with a typical storm scenario and using hourly crew requirements from Theme 1 corresponding to that scenario, the crew deployment problem in Theme 2 will be solved iteratively until each period's work is performed in that period with

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the smallest number of drivers. This is achieved by setting a very high penalty for deviating from crew requirements and increasing the number of crew one by one until a feasible solution is found. This exercise provides an upper bound on the number of crew required. A lower bound is obtained by using a similar procedure, but allowing work to be pre- or postponed, as needed. This is obtained by setting a very low cost of deviating from hourly crew requirements, so long as all snow removal work is completed within a specified time-to-clear target. Neither bound is economically desirable, but this exercise will limit the search space for an optimal solution. The PI will then solve the crew deployment problem for each workforce level within this range and obtain an estimate of the cost of deviating from the objectives. This cost will be added to the cost of maintaining that workforce level. Overall optimal workforce level is one that minimizes total cost thus obtained.

Next, the PI will consider manpower planning problems arising in adjacent counties to study the benefits of creating a pool of crew who would be shared among the counties. The deployment of shared crew will be similar to the use of technical personnel for driving snow plows in the event of an extreme emergency, but each county's cost will be lower.

### **16. Tasks:**

*List and describe the major tasks proposed that are needed to complete this research project.*

#### Task 1:

Select a county to serve as a test case. Availability of data in electronic format is assumed and that will be a consideration in selecting an appropriate county. If only paper records are available, that will increase the time and cost of performing this step. The data will include street and highway network with all intersections, snowplow and salt truck routes, location of refill depots, number and type of equipment, available crew size, average speeds, ADT counts, current classification of roads and highways by LOS, time-to-clear objectives, and implicit penalties for not meeting performance targets. The PI will also obtain Event Log data from the AI/RWIS system and meteorological data. He will work with engineers from the chosen county to develop representative storm scenario and hourly manpower requirements for each storm scenario. This step requires close and repeated interactions with county engineers.

#### Task 2:

Use hourly manpower requirements data and cost of deviating from required snow removal objectives to formulate the crew deployment problem as a discrete optimization problem. Solve the problem using commercially available solver (CPLEX). If necessary, develop heuristic solution algorithms for large problems. Interact with county engineers and tweak the model as needed. Identify good solutions under different storm scenarios.

#### Task 3:

Formulate a stochastic optimization problem, based on the results of Task 2. This formulation will explicitly model many different snowfall scenarios for the same storm forecasts and test the goodness of fixed deployment plans when snowfall patterns deviate from the forecast. The purpose of this exercise is to identify robust deployment solutions.

#### Task 4:

Develop lower and upper bounds on manpower requirements for typical storm scenarios using either very high or very low penalty for deviating from hourly crew requirements. Solve the crew deployment problem for each workforce level within the lower and upper bound and calculate total cost by adding the cost of not meet the snow and ice removal objectives to the cost of maintaining that level of workforce. Identify the least costly solution overall.

#### Task 5:

Study economic feasibility of using pooled crew in adjacent counties. Many service industries smooth manpower requirements by creating server pools to respond to peak demand in several different locations. Economic feasibility will be studied by estimating the value of having weather-dependent availability of additional crew from the common pool maintained by adjacent counties. If shown to be economical, some counties may consider running a pilot to test the feasibility of implementing such a plan as a follow up.

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### References

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### 33. 17. Resumes:

Attach resume for PI and Co-Investigators. Maximum length = 2 pages per person.

#### Curriculum Vitae of DIWAKAR GUPTA

##### Contact Information

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##### Education

- |   |                        |                 |
|---|------------------------|-----------------|
| 1. Indian Institute of Technology, New Delhi, India | Mechanical Engineering | B. Tech., 1982  |
| 2. University of Windsor, Ontario, Canada           | Industrial Engineering | M. A. Sc., 1984 |
| 3. University of Waterloo, Ontario, Canada          | Management Sciences    | Ph.D., 1988     |

##### Appointments

1. Professor, Mechanical Engineering, University of Minnesota, 2003 – present.
2. Associate Professor, Mechanical Engineering, University of Minnesota, 1999 – 2003.
3. Associate Professor, Production and Management Science, McMaster University, 1993–2001.
4. Assistant Professor, Production and Management Science, McMaster University, 1989 – 1993.
5. Assistant Professor, Industrial Engineering, Technical University of Nova Scotia, 1988 –1989.

##### Selected Peer-reviewed Publications (from 51 articles)

1. Amaruchkul, K., Cooper, W. L., and Gupta, D. 2006. "Single-Leg Air-Cargo Revenue Management," *Transportation Science*, to appear.
2. Gupta, D., Natarajan, M., Gafni, A., Wang, L., Shilton, D., Holder, D., and Yusuf, S. 2006 "Capacity Planning for Cardiac Catheterization: A Case Study", *Health Policy*, in press.
3. Gupta, D., and Wang, L. 2006. "Capacity Management for Contract Manufacturing", *Operations Research*, in press.
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9. Gupta, D., and Cooper W.L., 2005, "Stochastic Comparisons in Production Yield Management," *Operations Research*, 53, 377-384
10. Denton, B., and Gupta, D., 2004, "Strategic Inventory Deployment in the Steel Industry," *IIE Transactions*, 36, 1083 – 1097.
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# FY2008 RESEARCH PROJECT PROPOSAL

## Center for Transportation Studies, University of Minnesota

16. Gupta, D., Gunalay, Y., and Srinivasan, M. M., 2001, "On the Relationship between Preventive Maintenance and Manufacturing System Performance," *European Journal of Operational Research*, 132, 146 – 162.
17. Benjaafar, S., and Gupta, D., 1999, "Workload Allocation in Multi-Product, Multi-Facility Production Systems with Setup Times," *IIE Transactions*, 31, 339 – 352. (Winner of 1999 best paper award)
18. Gupta, D., and Malina, R. 1999, "Group Testing in Presence of Classification Errors," *Statistics in Medicine*, 18, 1049 – 1068.
19. Gunalay, Y., and Gupta, D., 1998, "Threshold Start-Up Control Policy for Polling Systems," *Queueing Systems: Theory and Applications*, 29, 399 – 421.
20. Sheikhzadeh, M., Benjaafar S., and Gupta D., 1998, "Machine Sharing in Manufacturing Systems: Total Flexibility versus Chaining," *International Journal of Flexible Manufacturing Systems*, 10, 351 – 378.
21. Gupta, D., and Srinivasan, M. M., 1998, "How Does Product Proliferation Affect Responsiveness?" *Management Science*, 44, 1017 – 1020.
22. Benjaafar, S., and Gupta, D., 1998, "Scope versus Focus: Issues of Flexibility, Capacity, and Number of Production Facilities," *IIE Transactions*, 30, 415 – 425. (Winner of 1998 best paper award)
23. Duenyas, I., Gupta, D., and Lennon, T., 1998, "Control of a Single-Server Tandem Queueing System with Setups," *Operations Research*, 46, 218 – 230.
24. Gunalay, Y., and Gupta, D., 1997, "Polling Systems with a Patient Server and State Dependent Setup Times," *IIE Transactions*, 29, 469 – 486.
25. Gupta, D., and Srinivasan, M. M., 1996, "Polling Systems with State-Dependent Setup Times," *Queueing Systems: Theory and Applications*, 22, 403 – 423.
26. Gupta, D., and Buzacott, J. A., 1996, "A Goodness Test for Operations Measures of Manufacturing Flexibility," *International Journal of Flexible Manufacturing Systems*, 8, 233 – 245.
27. Gupta, D., and Srinivasan, M. M., 1996, "The Variance Paradox and its Implications for Japanese Production Theory," *Interfaces*, 26, 69 – 77.
28. Gupta, D., 1996, "The (Q,r) Inventory System with an Unreliable Supplier," *INFOR*, 34, 59 – 76.
29. Srinivasan, M. M., and Gupta, D., 1996, "When Should a Roving Server be Patient?" *Management Science*, 42, 437 – 451.
30. Gerchak, Y., Gupta, D., and Henig, M., 1996, "Reservation Planning for Elective Surgery under Uncertain Demand for Emergency Surgery," *Management Science*, 42, 321 – 334.
31. Gupta, D., and Gerchak Y., 1995, "Product Durability and Lot Sizing Models," *European Journal of Operational Research*, 84, 371 – 384.
32. Gupta, D., 1993, "On Measurement and Valuation of Manufacturing Flexibility," *International Journal of Production Research*, 31, 2947 – 2958.
33. Gupta, D., and Buzacott, J.A., 1993, "Models for First-Pass FMS Investment Analysis," *International Journal of Flexible Manufacturing Systems*, 5, 263 – 286.
34. Gupta, D., Gerchak, Y. and Buzacott, J.A., 1992, "The Optimal Mix of Flexible and Dedicated Manufacturing Capacities: Hedging Against Demand Uncertainty," *International Journal of Production Economics*, 28, 309 – 319.
35. Gupta, D., 1992, "On the Economic Lot Scheduling Problem with Backlogging: the Common Cycle Approach," *Operations Research Letters*, 12, 101 – 109.

### Awards and Recognition

1. Departmental Editor, *IIE Transactions on Scheduling and Logistics* (since January 2004), Editorial Board Member *IJFMS* (since September 1996), and the *M&SOM Journal* (January 2003-06).
2. Developed a prototype decision support tool titled "Slab Design Optimisation Tool" based on results from NSF-sponsored project (DMII 9988721) and interactions with a steel mill (joint work with B. Denton).
3. Winner of the 2005 *IIE Outstanding Publication Award*. Winner of the *IIE Transactions best paper award in 1998, 1999 and 2005*.
4. Winner of 1994-95 the *Basu Memorial Award for excellence in teaching in the MBA program* at McMaster University.
5. Winner of 1996 and 1997 Meritorious Service Award for exceptional work performed on behalf of the Editorial Board of the Journal *Operations Research*.

### Number of Graduate Students/Postdoctoral Scholars Advised/Under Supervision

M.S. Candidates – 9; Ph. D. Candidates – 6; Postdoctoral Scholars – 2