OR FORUM

TWENTY YEARS OF ROUTING AND SCHEDULING

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(Received November 1989; accepted January 1990)

I have 20 years of experience in solving practical routing and scheduling problems, as well as the associated problems of crew scheduling. In this paper, I offer some reflections on the history and practice in this field and project some future directions for it.

For the past 20 years I have been working in the area of routing and scheduling vehicles and crews. During this period, the field has evolved from solving these problems in a batch mode on a mainframe computer to a discipline in which microcomputer-based systems are able to find usable and implementable routes and schedules.

This paper begins with a discussion of some of my experiences in solving routing and scheduling problems. After describing the characteristics and constraints encountered when solving vehicle routing and scheduling problems in practice, it discusses three important components of practical vehicle routing and scheduling systems: the algorithmic approaches that have been designed for solving these problems in practice, the computer environment for practical vehicle routing systems, and the role of geographic information systems in vehicle routing and scheduling systems. The paper concludes with some projections of the future.

SOME EXPERIENCES

Over the years I have collaborated on many interesting routing and scheduling projects. They have included scheduling street sweepers, barges, and hoist compactors for New York City, scheduling household-refuse collection vehicles for the Town of Oyster Bay, New York, scheduling school buses for various school districts, scheduling planes and crews for two package-delivery airlines, scheduling logistics operations for the Military Airlift Command (MAC), and scheduling meter readers for public utilities. This section describes some of these experiences.

The Chart Day Problem

The Chart Day Problem for scheduling sanitation workers in the New York City Sanitation Department was the first routing and scheduling project on which I worked (Beltrami 1977). This problem turned out to be one of the more successful manpower scheduling projects ever undertaken.

In 1970 New York City had approximately 10,000 sanitation workers to assign to various activities—household-refuse collection, street sweeping, hoist-compactor collection, and so on. The rotation schedule under which the sanitation workers operated had these attributes:

- The sanitation workers were divided into 6 brackets of approximately 1,666 workers each.
- Each bracket received a different day of the week off, so that in a particular week, the workers in bracket 1 received Monday off, the workers in bracket 2 received Tuesday off, and so on.
- All sanitation workers received Sunday off.
- The schedule for the workers rotated. In other words, the workers in bracket 1 in a particular week became the workers in bracket 2 in the next week, and the workers in bracket 3 in the week after that, and so on.
- This schedule rotated through a complete cycle every 6 weeks. In the complete cycle, each sanitation worker received one 3-day weekend and no 2-day weekend.

Subject classifications:

0030-364X/90/3804-0571 $01.25

Figure 1 shows the six-bracket chart for the sanitation workers for 2+ weeks.

The failure of the system was that there were not enough workers on Monday and Tuesday to meet all the demands for service. However, there were enough workers available the other days of the week not only to meet all the demands for services on these days, but to handle all the missed collections from Monday and Tuesday. The Sanitation Union asked for an increase of about 200 sanitation workers at a cost to New York City of about $6,000,000 per year in order for all work on every day of the week to be completed on the day scheduled, while maintaining the six-bracket chart. If New York City paid overtime on Monday and Tuesday to avoid these missed collections, the cost was estimated to be about $3,000,000 per year.

My colleagues (Ed Beltrami, Stan Altman and Bob Nathans) and I proposed a 30-bracket chart that allowed all work to be carried out on the scheduled day of the week and required neither overtime pay nor new sanitation workers. After protracted union-management negotiations (in which we participated), our proposal was accepted by New York City and the union and implemented.

Two marginal aspects of this work are of interest. We were able to arrive at the solution by hand, but both management and the union required a computer output. I wrote a simple computer program that read-in the 30-bracket chart and printed out a 30-week schedule for each bracket. This output pleased both management and the union. And Italian National Television made a 45-minute documentary on this study.

School Bus Scheduling

In a school-bus routing and scheduling study, I pointed out to the superintendent of a school district that one bus could be saved if the starting time for the kindergarten class was changed from 9:30 to 9:00 a.m. He decided to have the bus show up at 9:00, and the class to begin at 9:30. When he told me that the teachers were not responsible for the class until 9:30, so that the 5-year-old children in the class would run around the school unattended for 30 minutes, I threatened not to give him my routes. He relented and paid for the extra bus.

In another situation, an owner of a fleet of buses suggested that four school districts merge their transportation activities in order to save money and he would provide the service at a fixed cost per bus. I was asked to evaluate the situation and concluded that a considerable cost saving could be realized. The four districts put out a Request for Proposal (RFP) for providing this service. The low bid was almost $10,000/bus higher than the price originally quoted and the original owner did not submit a bid. The regional project was killed.

Sanitation Scheduling

The New York City Sanitation Department had a problem with their sanitation collection vehicles queueing up right before lunch time at a marine transfer station (MTS). (The sanitation collection vehicles dumped their collections onto a barge at the MTS and the barge was towed by a tugboat to the landfill for final disposal.) Waiting times of 45+ minutes were experienced. After performing a queueing

Brackets	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue etc.
1	X	X						X		X					X		
2	X		X					X			X				X		
3	X			X				X				X			X		
4	X				X			X					X		X		
5	X					X		X						X	X	X	
6	X						X	X	X						X		X

Figure 1. An example of the original six-bracket chart for the sanitation workers. (The symbol × indicates a day off.)

study, we suggested that the starting and ending workday times for the crews be changed so that one-third would begin their workday 30 minutes early and one-third would begin their workday 30 minutes late. This suggestion was implemented and the queues were almost eliminated.

Institutional Considerations

In almost every application, we have encountered institutional constraints that adversely affected the results, made no sense to us from an operational standpoint, but were part of the system. In many cases these constraints were present because they simplified the manual scheduling problem; too, in many cases the constraints went back so many years that nobody in the organization could recall their origin. In attempting to formulate a model of the operation, we had to ask the organization to decide how much it could "bend these constraints."

I am sure this situation is not unique to routing and scheduling problems. However, in every application, we are aware of these possible impediments and discuss the existence of institutional constraints with every organization with which we work.

A second situation that we have encountered in most scheduling applications is that the routing and scheduling system will impact other parts of the organization. In other words, changing the way routes and schedules are created forces the organization to alter how it carries out its other operations, such as how it creates and maintains customer lists and data bases, bills for services, does maintenance, emergency services and order entry, manufactures products, and locates plants and warehouses.

Our experiences have shown that isolating the routing and scheduling application from the remainder of the operation can build up resistance within the organization and doom the implementation of the routing and scheduling system, no matter how effective and elegant it is. An organization that we are working with has a complex approval process involving all affected departments. Before initiating any project, each affected department has to sign off on it. In this way, affected departments are aware of the impact of this project on their particular operation from its inception.

Savings Encountered in Practice

Computerizing an organization's routing and scheduling activity can save a considerable amount of money. For example, in solid-waste collection, communities must decide on the number and location of disposal facilities and determine the best set of routes to collect the refuse. A study (Bodin et al. 1989) in Oyster Bay, New York, showed that the computerized schedule for sanitation vehicles saved 3 vehicles out of 40 (and $750,000/year). Lamont (1988) states that the HASTUS-Microtechnique for scheduling drivers in the Montreal Urban Community Transit System saved "approximately 3% of the drivers' salary over the previous manual solutions, representing in the neighbourhood of two million dollars per year."

The area of computer-aided scheduling for public transport is so important that four international workshops have been held and a fifth is scheduled for August 1990 at the University of Montreal. Daduna and Wren (1988) edited the proceedings of the Fourth International Workshop on Computer-Aided Scheduling of Public Transport.

Practical Vehicle Routing and Scheduling Problems

Although routing and scheduling problems exist in many contexts, most of this paper is concerned with node routing and scheduling where the demand for service occurs at specific points or locations and there are various constraints on service, such as time windows and site dependencies. Some of these constraints, which make up the class of *practical vehicle routing and scheduling problems*, are described in some detail later. There are important classes of routing and scheduling problems, such as node routing and scheduling with precedence constraints (e.g., pickup and delivery problems), arc routing and scheduling (e.g., scheduling household-refuse collection and meter readers), and pure scheduling (such as scheduling vehicles and drivers for mass transit systems) that this paper does not consider explicitly. I believe, however, that many of the comments made here are appropriate to these problems as well.

References

A rich literature on vehicle routing and scheduling problems exists. The bibliographies in Bodin et al. (1983), Golden and Assad (1988) and Lawler et al. (1985) contain many references. The July 1989 issue of *Interfaces* was devoted to operations research in the airline industry, including three papers on crew scheduling. Some of the successes in solving actual routing and scheduling problems can be found in Assad (1988), which gives a taste of the benefits and savings in selected applications. Other successful applications are described in Bell et al. (1983), Bodin et al. (1983), Bodin and Levy (1988), Bodin et al. (1989), Brown et al. (1987), Brown and Graves (1981), Christofides (1981), Fisher et al. (1982), Hooban (1988), andMarsten and Shepardson (1981). Assad (1988), Bodinet al. (1983) and Golden, Magnanti, and Nguyen (1977) discuss modeling and implementation issues in vehicle routing and scheduling. Eilon, Watson-Grandy and Christofides (1971) did an early book on distribution management.

VEHICLE ROUTING PROBLEMS IN PRACTICE

In my opinion, many of the problems described in the literature oversimplify the ones that occur in practice. For example, there is a large literature (written primarily in the 1970s) on the vehicle routing problem where all vehicles are identical and housed at the same depot, the only constraint being that each vehicle has an upper bound on capacity and the objective is to minimize the total travel time of the fleet (generally the number of vehicles in the fleet is specified a priori). In this problem, the locations do not have time windows or vehicle/location dependencies and the crews do not have an upper bound on the length of the workday, so it is possible for a solution to have some crews working a 12–16 hour day and other crews working a 3–6 hour day. A solution for this problem may not be practical and may not be implemented without major revisions by the scheduler or dispatcher. However, some of the algorithms used to generate a solution for this relatively unconstrained problem have been adapted with some success in solving practical vehicle routing and scheduling problems.

Most practical point-to-point vehicle routing and scheduling problems have the following characteristics.

Multiple Vehicle Types. For each vehicle type, an upper bound on capacity and on the number of vehicles of that type available in the fleet mix are specified (see, Golden et al. 1984, Gheysens, Golden and Assad 1986).

Vehicle/Location Dependencies. For each pickup (or delivery) location, the demands for service and the vehicle/location dependencies are specified. A vehicle dependency for a location is a listing of the vehicle types that can service it. The implication of a vehicle/location dependency is illustrated as follows. Suppose that there are 5 vehicle types where vehicle types 1, 2 and 4 can service location 1, vehicle types 2, 3 and 5 can service location 2, and vehicle types 2, 4 and 5 can service location 3. In this case, locations 1, 2 and 3 can only be serviced by a type-2 vehicle. Vehicle/location dependencies can occur because of physical restrictions at certain locations (loading bays can only accommodate certain vehicle types) or the physical location of certain customers (larger vehicles cannot service locations in urban areas where there is street congestion or narrow alleys). Nag (1986) has presented the only algorithm that I am aware of for solving the vehicle/location dependency problem.

Depots. Either a single depot or multiple depots can be specified. If there are multiple depots, each depot will have either an upper bound on the number of vehicles of a particular type that can be housed there, or an upper bound on the total number of vehicles that can be housed there, or both. Bodin et al. (1983) and Golden and Assad (1988) contain references to algorithms for solving this problem, although it has not been analyzed in great detail.

Time Windows. Some locations can have time windows that are either hard or soft. If the time window for a location is $[t1, t2]$ and this window is hard, then servicing this location by a vehicle has to be carried out between $t1$ and $t2$. If this time window is soft, the vehicle need not service this location during $[t1, t2]$; if the time window is missed, the algorithm usually assesses a penalty associated with the number of minutes by which it is missed. In practice, some locations can have more than one time window (for example, a restaurant can have time windows 9–11 a.m. and 2–5 p.m. during which it can accept deliveries, but not during the lunch hour), these time windows can be soft, and there can be hard open and closed times when the location can be serviced.

There has been a considerable amount of analysis of the time-window problem without site dependencies and multiple vehicle types (see, for example, the special issue on time windows, Golden and Assad 1986 and Solomon 1987). Although the time-window problem when all the time windows are tight (for example, less than 2 hours) is of considerable practical interest; very little research has been carried out on it.

Route Length. Generally, each vehicle has the same route-length constraint (for example, 8 hours). This constraint is considered in most vehicle routing and scheduling algorithms.

Objective Function. Usually the objective function is to minimize a weighted combination of capital and operating costs for the fleet. It may also include a formula that represents penalties for not meeting all the time-window constraints and/or for violating other constraints. Also, vehicle routing and scheduling problems can have multiple criteria. Sometimes these objectives are hierarchical; in other cases, they are considered concurrently. As an example, in school-bus routing and scheduling, one objective is to minimize the total number of student-minutes on a bus and a second is to minimize the total number of buses used (Bodin et al. 1983).

Practical vehicle routing and scheduling problems may have other characteristics not listed above, such as backhauling and overtime. They complicate finding an implementable solution but add little to the generic approaches that are used for finding a solution.

The characterization of vehicle routing and scheduling problems presented in this section does not include problems such as: real-time and preplanned pickup and delivery (courier service, shared-cab and dial-a-ride problems), routing and scheduling over the streets in a network (household-refuse collection, meter readers, delivering telephone books, and street sweeping), and integrating vehicle routing and scheduling with driver (and crew) scheduling (scheduling buses and crews for transit systems and pilots and planes for airlines).

APPROACHES TO SOLVING PRACTICAL VEHICLE ROUTING AND SCHEDULING PROBLEMS

Because of the computational complexity in solving vehicle routing and scheduling problems to optimality, heuristic methods are employed. Frostic (1987) dedicates her essay entitled, *Heuristic* to "those who share ideas without the necessity of infallible certitudes—and enjoy the wonder of confusion," a view appropriate to those of us who have been developing approaches for solving vehicle routing and scheduling problems.

A standard heuristic approach for solving vehicle routing and scheduling problems with a fleet of K homogeneous vehicles consists of the following steps.

Step a. Specify K.

Step b. Tour construction. Aggregate the locations to be serviced into K clusters. Some of the approaches for tour construction use single location-insertion heuristics and are sequential in nature (one location is assigned to a cluster on each iteration); other approaches, such as the generalized assignment algorithm (Fisher and Jaikumar 1981), are based on solving a mathematical program and are not sequential in nature. In some cases, routes and schedules are formed along with the clustering. If routes and schedules have not been formed while aggregating locations into clusters, then a route and schedule are found over the locations assigned to each of the K clusters, one cluster at a time. When there are no time windows or other complicating constraints on tour construction, this route and schedule can be found by solving a traveling salesman problem (the nodes of the traveling salesman problem are the locations assigned to the cluster and the depot). At the conclusion of this step, it is possible to have some locations unassigned to routes and/or the routes violating the upper bound on travel time.

Step c. Tour improvement. In order to reduce the total travel time of all the routes

i. reorder the locations on each of the routes, one route at a time (if an optimal tour was not found in Step b), and
ii. move locations between routes.

The tour improvement step continues until no more improvements are found or the time allocated to this process is exhausted. In tour improvement, a route is sometimes dissolved and the locations on the route are inserted on other routes to reduce the size of the fleet. In this case, the algorithm iterates between tour construction and tour improvement until a final solution is found. Many of the papers in the literature are concerned with better ways to do either tour construction or tour improvement.

This approach may not work well when the practical considerations mentioned in the previous section are introduced because they can be the source of severe constraints. Since many tour construction approaches are sequential in nature in that one location is assigned to a route on each iteration, a bad decision made at one step in the tour construction locks-in the solution being generated, and hence can affect subsequent steps adversely. When bad decisions are made, the tour improvement procedures are either too time consuming or not powerful enough to extricate the situation and derive a reasonable solution. Yet, for many years this approach has been one of the workhorse algorithms for solving vehicle routing and scheduling problems, both from a research standpoint and in commercially available systems.

Some successful research has been carried out using complicated exact and approximate mathematical programming-based algorithms for solving some classes of vehicle routing and scheduling problems. These algorithms either find the optimal solution or a solution within a provable percentage of the optimal solution. This research has been described in papers such as Christofides, Mingozzi and Toth (1981a, b). There was major activity in this area in the late 1970s and early 1980s, but, to the best of my knowledge, with a few exceptions, algorithms of this type have not been incorporated into commercially available microcomputer-based vehicle routing and scheduling software. The transfer of this technology from the researcher to the practitioner has not taken place to any great extent.

It was recognized years ago that many vehicle routing and scheduling problems can be formulated as set-partitioning or set-covering problems (Cullen, Jarvis and Ratliff 1981, Bodin et al. 1983). A set-covering problem is the 0–1 integer programming problem: Find the vector X in order to Min $Z = CX$ subject to $AX \geqslant 1$ where each element x_j in the vector X is 0 or 1 and each coefficient in the $A = (a_{ij})$ matrix is 0 or 1. A set-partitioning problem is a set-covering problem with constraint set $AX = 1$.

For the vehicle routing and scheduling problem, each row in the set-covering problem represents a location to be serviced by a vehicle and each column represents a feasible vehicle route. If $a_{ij} = 1$ ($a_{ij} = 0$), then feasible vehicle route j services (does not service) location i. Since $\sum_j a_{ij} \geqslant 1$, any feasible solution to the set-covering problem ensures that at least one feasible vehicle route services each location. Moreover, since the set-covering problem is a column-enumeration procedure, if all feasible routes are enumerated, then the optimal solution to this set-covering problem gives the globally optimal least-cost set of routes. However, if only a subset of the feasible routes is enumerated or the locations are aggregated before setting up the set-partitioning or covering problem, then the optimal solution to the set-covering problem is a feasible but not necessarily optimal solution to the vehicle routing and scheduling problem being considered. Moreover, side conditions can be added to the set-covering formulation to take into account constraints such as the fleet mix and multiple depots.

Although the set-covering and set-partitioning framework is appropriate for solving vehicle routing and scheduling problems, this framework has not solved these problems successfully for these reasons:

a. Enumerating the columns can be difficult and time consuming.
b. The number of columns, even for modest-sized problems, can be enormous when all columns are enumerated.
c. The solution time can be too large.

Set-partitioning and set-covering problems with 150 columns and several thousand rows have been solved optimally (Marsten 1974). However, because of the above difficulties, heuristic or clustering approaches for decomposing these problems have been employed (Marsten and Shepardson), set-partitioning problems have been embedded within an interactive computing environment (Cullen, Jarvis and Ratliff), and approximate solutions to set-partitioning and set-covering problems have been employed that use heuristic methods for evaluating the columns enumerated (Baker 1979, Baker et al. 1979). Outside of Cullen, Jarvis and Ratliff, all of the aforementioned papers have been concerned with air-crew scheduling. However, the set-covering approach offers the potential for solving highly constrained vehicle routing and scheduling problems. Notable recent research in this area has been carried out at the University of Montreal.

COMPUTER ENVIRONMENT

Perhaps the most impressive change in the past 20 years regarding vehicle routing and scheduling systems is the computer environment in which the algorithms are embedded. Prior to the microcomputer, vehicle routing and scheduling systems were primarily batch algorithms operating on a large computer. Since these systems did not possess significant graphics and interactive capabilities, the algorithms were forced to carry most of the burden of deriving a reasonable solution and the user had difficulty in seeing the solution graphically, and therefore in altering it manually. As such, the vehicle routing and scheduling systems developed in the late 1970s were called *computerized routing and scheduling systems.* I can still remember the days not so long ago when I placed a vellum overlay on a map in order to plot the solution manually.

The introduction of the microcomputer was the major catalyst in allowing the user to make manual interventions in the routing and scheduling process and in giving a graphical display of routes and schedules. The original routing and scheduling systems on microcomputers had these characteristics:

- They were slow computationally.
- Many were extremely weak algorithmically.
- Some had reasonable graphics and manual intervention capabilities, while others had virtually no graphics.

These first-generation systems were the forerunners of the microcomputer-based *computer-assisted vehicle routing and scheduling systems.*

In a computer-assisted vehicle routing and scheduling system, the user accepts the responsibility of finding a good solution in place of the algorithms and is, therefore, able to tailor the solution to suit his needs. The solution found in this manner is called the 'user's solution' and, by definition, this solution is 'good.'

The second generation microcomputer-based vehicle routing and scheduling systems were developed in the mid 1980s. Golden, Bodin and Goodwin (1986) surveyed 14 of the commercial first and second generation systems. They cost between $1,000 and $150,000, no package handled all of the conditions mentioned in the Vehicle Routing Problems in Practice section, and only a few of these packages survive today. Others, making up the next generation of microcomputer-based systems, have taken their place.

As microcomputers have become more powerful, the user has become more demanding, requiring high quality graphics and reasonable algorithms that can handle many of the considerations mentioned earlier, along with overtime and backhauling. In many cases, the user insists on having a resident geographic information system (discussed in the next section) for at least the geocoding of data. The ability to integrate the vehicle routing system with systems such as order entry and vehicle location is becoming a common requirement of some users. The hardware and software technologies, except for the algorithms, appear to have finally caught up with the users' needs.

GEOGRAPHIC INFORMATION SYSTEMS

A second major development in the 1980s was the creation of commercially available geographic information systems (GIS) at the blockface level. The catalysts for this development were the GDF DIME File (created by the United States Census Bureau and available for a nominal fee), the United States Postal Service's Zip + 4 indicator, which gives an almost unique identifier to each street segment in a region (the Zip + 4 identifier is not a standard part of the DIME File), and the new TIGER files. As a result of these developments, the user can now purchase data that can be converted into geocoded street maps of the regions of interest for most of the United States (several vendors provide these geocoded street maps). With an accurate GIS, the user is able to locate most customers automatically and to compute the travel times between customer locations as the shortest travel-time path between them.

Gone are the days of having to locate each customer on a map manually and to use only Euclidean distances for travel times. I can recall (now with a smile), the agony of attempting to geocode a region manually. In a school-bus scheduling application in the mid 1970s, I had three high school students manually code the street network for a school district on Long Island; the maps of the school district were spread out on my living room floor, and the students had to crawl across the map in order to geocode the area.

I also recall the time when we went to Grumman Corporation on Long Island to use their expensive geocoding equipment to geocode the (x, y) coordinates of several hundred locations for a sanitation scheduling problem. In another application, we had tremendous problems geocoding a region that contained several maps because of the errors we encountered in manually assigning a unique node number to each street intersection when it appeared on more than one map. The routing and scheduling systems of the 1970s failed, in part, because of the difficulties in the GIS area. As a matter of fact, in the 1970s nobody used the expression GIS.

To create and maintain a GIS can significantly increase the cost of a complete vehicle routing and scheduling system; the user may have to purchase, customize, and bear the expense of maintaining a GIS as a part of the system. Questions of the accuracy and completeness of the GIS and the procedures for maintaining it have become major issues between users and commercial vendors. A problem for developers of vehicle routing and scheduling software is at what level of complexity to incorporate GIS capabilities within their systems.

Computation of travel times is a major issue in any routing and scheduling system. Without a GIS, travel times are generally computed as a function of Euclidean distances with barriers. Having a GIS introduces the possibility of computing the shortest path travel times between pairs of locations and using them in the algorithms. There can be a tradeoff in the performance of the algorithms if one computes the travel times between locations as the shortest path travel times or the Euclidean distances (with barriers). If the data over which the shortest path travel times are being computed are accurate, then using them in the algorithms generally makes the results more accurate, but the algorithms will be slower computationally. At this time, the problem of what travel time to use is generally resolved on a case-by-case basis.

DIRECTIONS AND CONCLUSIONS

Over the past 20 years, vehicle routing and scheduling has grown to be an important area. Many papers have appeared in the literature, fundamental research questions have been answered, and new research areas have been developed. Also, vehicle routing and scheduling has become an important application area. Successes have been documented and commercial software systems have been developed. The domain of problems considered to be vehicle routing and scheduling has expanded.

Vehicle routing and scheduling applications include such problems as: pickup-and-delivery, dial-a-ride, school-bus routing and scheduling, and arc routing and scheduling. Microcomputer and geographic information systems developments have forced a reality and a practicality on commercially available routing and scheduling systems that were not envisioned in the 1970s.

I believe that in the next decade commercially available systems will increase in functionality and sophistication. These systems will have much better graphics and user interfaces than presently exist and will help users get better solutions faster. Also, the classes of applications will increase. New problems will be formulated and computer systems will be developed for solving them. These systems will take advantage of the new technologies that are available and be integrated with other parts of the organization's structure. With computer performance increasing, system capabilities not presently envisioned will be developed. By the year 2000, I believe that vehicle routing and scheduling systems will be considered a necessary part of an organization's logistics/distribution system.

On the other hand, I believe that algorithmic development for solving practical problems has not kept pace with these other developments, and there still is a tremendous opportunity to develop effective computational procedures for solving practical vehicle routing and scheduling problems. The challenge to the researcher is to discover these procedures and for the vendor to commercialize them.

ACKNOWLEDGMENT

I wish to thank Bruce Golden, who invited me to give a talk at the May 1989 CORS/ORSA/TIMS meeting in Vancouver on this topic. This paper is based on that talk. I also wish to thank Mike Ball, Larry Levy, Hugh Miser and Hal Rappoport for their insightful comments on this paper.

Over the years, I have been fortunate to have collaborated with some of the leading researchers and practitioners in the field of routing and scheduling and I appreciate their insight and support. The views expressed in this paper, however, are mine and may not necessarily agree with the views of my colleagues.

REFERENCES

ASSAD, A. 1988. Modeling and Implementation Issues in Vehicle Routing. In *Vehicle Routing: Methods and Studies*, pp. 7–45, B. L. Golden and A. Assad (eds.). North-Holland, Amsterdam.

BAKER, E. 1979. *Efficient Heuristic Solutions for the Airline Crew Scheduling Problem*. Ph.D. Thesis, University of Maryland, College Park.

BAKER, E., L. BODIN, W. FINNEGAN AND R. PONDER. 1979. Efficient Heuristic Solutions to an Airline Crew Scheduling Problem. *AIIE Trans.* **11,** 79–85.

BELL, W. J., L. M. DALBERTO, M. L. FISHER, A. J. GREENFIELD, R. JAIKUMAR, P. KEDIA, R. G. MACK AND P. J. PRUTZMAN. 1983. Improving the Distribution of Industrial Gases With an On-Line Computerized Routing and Scheduling Optimizer. *Interfaces* **11,** 4–23.

BELTRAMI, E. 1977. *Models for Public Systems Analysis*. Academic Press, New York.

BODIN, L., AND L. LEVY. 1988. Scheduling the Postal Carriers for the United States Postal Service: An Application of Arc Partitioning and Routing. In *Vehicle Routing: Methods and Studies*, pp. 359–394, B. L. Golden and A. Assad (eds.). North-Holland, Amsterdam.

BODIN, L., B. L. GOLDEN, A. ASSAD AND M. BALL. 1983. Routing and Scheduling of Vehicles and Crews: The State of the Art. *Comput. Opns. Res.* **10,** 63–211.

BODIN, L., G. FAGAN, R. WELEBNY AND J. GREENBERG. 1989. The Design of a Computerized Sanitation Vehicle Routing and Scheduling System for the Town of Oyster Bay, New York. *Comput. Opns. Res.* **16,** 45–54.

BROWN, G., AND G. GRAVES. 1981. Real-Time Dispatch of Petroleum Tank Trucks. *Mgmt. Sci.* **27,** 19–32.

BROWN, G., C. ELLIS, G. GRAVES AND D. RONEN. 1987. Real-Time Wide Area Dispatch of Mobil Tank Trucks. *Interfaces* **17,** 107–121.

CHRISTOFIDES, N. 1981. Uses of a Vehicle Routing and Scheduling System in Strategic Distribution Planning. *Scand. J. Mat. Admin.* **27,** 39–55.

CHRISTOFIDES, N., A. MINGOZZI AND P. TOTH. 1981a. Exact Algorithms for the Vehicle Routing Problem Based on Spanning Tree and Shortest Path Relaxations. *Math. Prog.* **20,** 255–282.

CHRISTOFIDES, N., A. MINGOZZI AND P. TOTH. 1981b. State Space Relaxation Procedures for the Computation of Bounds to Routing Problems. *Networks* **11,** 145–161.

CULLEN, F., J. JARVIS AND H. RATLIFF. 1981. Set Partitioning Based Heuristics for Interactive Routing. *Networks* **11,** 125–144.

DADUNA, J. R., AND A. WREN (eds.). 1988. *Computer-Aided Transit Scheduling: Proceedings of the Fourth International Workshop on Computer-Aided Scheduling of Public Transport*. Springer-Verlag, Berlin.

EILON, S., C. WATSON-GRANDY AND N. CHRISTOFIDES. 1971. *Distribution Management: Mathematical Modeling and Practical Analysis*. Hafner, New York.

FISHER, M., AND R. JAIKUMAR. 1981. A Generalized Assignment Heuristic for Vehicle Routing. *Networks* **11,** 109–124.

FISHER, M., R. GREENFIELD, R. JAIKUMAR AND J. LESTER. 1982. A Computerized Vehicle Routing Application. *Interfaces* **16,** 18–23.

FROSTIC, G. 1987. *Heuristic*, 1st. ed. Presscraft Papers, Benzonia, Mich.

GHEYSENS, F., B. L. GOLDEN AND A. ASSAD. 1986. A New Heuristic for Determining Fleet Size and Composition. *Math. Prog. Studies* **26,** 233–236.

GOLDEN, B. L., AND A. ASSAD (eds.). 1986. Special Issue on Time Windows. *Am. J. Math. Mgmt. Analy.* **6** (3 and 4), 251–399.

GOLDEN, B. L., AND A. ASSAD. 1988. *Vehicle Routing: Methods and Studies*. North-Holland, Amsterdam.

GOLDEN, B. L., A. ASSAD, L. LEVY AND F. GHEYSENS. 1984. The Fleet Size and Mix Vehicle Routing Problem. *Comput. Opns. Res.* **11,** 49–66.

GOLDEN, B. L., L. BODIN AND T. GOODWIN. 1986. Microcomputer-Based Vehicle Routing and Scheduling Software. *Comput. Opns. Res.* **13,** 277–285.

GOLDEN, B. L., T. MAGNANTI AND H. NGUYEN. 1977. Implementing Vehicle Routing Algorithms. *Networks* **8,** 113–148.

HOOBAN, J. M. 1988. Marketing a Vehicle Routing Package. In *Vehicle Routing: Methods and Studies*, pp. 447–469, B. L. Golden and A. Assad (eds.). North-Holland, Amsterdam.

LAMONT, J. 1988. The Transition to Computerized Bus and Crew Scheduling at the Montreal Urban Community Transit Company. In *Proceedings of the Fourth International Workshop on Computer-Aided Scheduling of Public Transport*, pp. 272–278. J. R. Daduna and A. Wren (eds.). Springer-Verlag, Berlin.

LAWLER, E., J. K. LENSTRA, A. RINNOOY KAN, AND D. SHMOYS. 1985. *The Traveling Salesman Problem*. John Wiley, Chichester, England.

MARSTEN, R. 1974. An Algorithm for Large Set Partitioning Problems. *Mgmt. Sci.* **20,** 774–787.

MARSTEN, R., AND F. SHEPARDSON. 1981. Exact Solution of Crew Scheduling Problems Using the Set Partitioning Model: Recent Successful Applications. *Networks* **11,** 167–177.

NAG, B. 1986. *Vehicle Routing in the Presence of Site/Vehicle Dependency Constraints*. Ph.D. Thesis, University of Maryland, College Park.

SOLOMON, M. 1987. Algorithms for the Vehicle Routing and Scheduling Problem With Time Window Constraints. *Opns. Res.* **35,** 254–265.