Optimizing Periodic Maintenance Operations for Schindler Elevator Corporation

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Schindler, the world's largest escalator company and second-largest elevator company, maintains tens of thousands of elevators and escalators throughout North America. Thousands of technicians are on the road each day to maintain, repair, and help in emergencies. Each technician's route requires precise and optimized planning. Schindler Elevator Corporation turned to Environmental Systems Research Institute (ESRI) to develop an automated route-scheduling and planning system. ESRI provided a geographic-information-system-integrated application that employs operations research techniques to optimize preventive maintenance operations. It relies on a series of algorithms to assign maintenance work to technicians and to create efficient day-routes by solving the periodic-vehicle-routing problem. These automated tools allow Schindler to restructure and streamline service areas. The optimization system saves over $1 million annually and increases Schindler's managers' awareness of operating revenue. (*Transportation: scheduling, personnel. Facilities/equipment planning: maintenance, replacement*.)

Most of us are in awe of the technology we use to scale heights without losing our breath; we experience a thrill using elevators like those in the Sears Tower in Chicago. But complex machinery needs repair and periodic maintenance to keep its parts moving.

Schindler Elevator Corporation operates more than 100 offices in the United States and Canada and employs over 6,500 people. It is the North American operating entity of the Swiss-based Schindler Group, the world's second largest elevator company and the leading escalator supplier. Schindler's offices cover a wide range of areas, from dense central cities to territories consisting of several states. Schindler was the first elevator company in the United States to achieve ISO 9001 certification for its manufacturing plants, and its service organization was among the first in any US industry to receive ISO 9001 certification.

Schindler designs, manufactures, installs, maintains, and modernizes internal transport systems for almost every type of building requirement worldwide. The company specializes in latest-technology engineering, and mechanical and microprocessor-technology products designed and rigorously tested for comfort, efficiency, and reliability. Schindler provides maintenance and modernization services for all brands of elevator and escalator equipment. Its competitor competency center in Holland, Ohio, is devoted entirely to training and troubleshooting for non-Schindler equipment. The company stocks more than 85,000 different elevator and escalator parts (Table 1).

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In each office, one or more service superintendents supervise the service technicians who maintain and repair customers' elevator and escalator equipment. The technicians perform both preventive maintenance and services for customer trouble calls (callbacks). Maintenance tasks include periodically

—Adjusting equipment, such as elevator-door-operating devices, and escalator-handrail drive chains,

—Examining and repairing or replacing worn components, such as rotating elements and solid state devices, and

—Lubricating parts, such as belts, and cleaning areas, such as pit areas and car tops.

Depending on the equipment characteristics, environment, and usage, technicians perform various maintenance tasks on individual elevators or escalators at intervals ranging from monthly to yearly. For any building, depending on the number of units, usage patterns, and contractual requirements, preventive-maintenance (PM) or inspection activity could vary from daily (resident job, for example, at the Sears Tower) to quarterly. Schindler assigns each building to a technician who is responsible for the service work. These buildings make up his or her maintenance route.

Customer trouble calls (callbacks) are usually dispatched to the responsible maintenance technician, if available. Because such calls are typically urgent, most are handled on an earliest-possible basis. Routes are therefore planned with an emphasis on geographically tight areas of operation to allow for quick responses.

Schindler had observed the development of scheduling and routing systems in other service industries with interest. While these systems, designed to handle one-time installation or trouble calls, were not directly applicable to our business, Schindler saw potential benefit from a system that would help service superintendents to plan the periodic preventive maintenance activities of technicians. Schindler asked ESRI to develop a custom system for this purpose.

Problem

As equipment is added to or removed from the portfolio of equipment a local office services (for example, new elevator installations), the service superintendent must adjust the maintenance routes of the technicians. Among the factors considered in assigning routes are

—Geographic proximity,

—Technician workload,

—Necessary skills, and

—Customer relations.

Without computer support, minor route revisions gradually result in routes that overlap geographically. A major route restructuring was often a several-week project and was typically handled using complex spreadsheets and road maps. Typically, the superintendent gave the service technicians route sheets listing the buildings under contract, with notations of any special service requirements. A visit to the customer site was necessary to perform a detailed review of the maintenance history for specific equipment.

System Requirements

Schindler needed a tool that would give service superintendents up-to-date visibility of the service portfolio and route structure. Specifically, it needed an interactive route-planning system that service superintendents could use to

—Review existing routes,

—Add new service locations,

—Adjust the frequency, duration, and allowed time windows for preventive maintenance visits,

—Adjust routes automatically or interactively, and

Personnel	Thousands of service technicians
Equipment serviced	Tens of thousands of elevators, escalators, moving walks
Annual service visits	Millions
Service area	250+ offices covering the US and Canada
Business objectives	To provide preventive maintenance, callback service, and repairs
System objectives	To improve service efficiency by providing Improved route assignments Detailed route sequences (visit schedules) Balanced preventive maintenance task schedules

Table 1: The table summarizes statistics about Schindler's maintenance operations in North America, including the business objective and goal of the route-planning system.

—Balance the route structure and minimize overall driving time.

The system had to include both maintenance routes and callback routes. Because the firm's operational structure was widely distributed, the system had to function over high-speed (T1) and low-speed (shared 56Kb) data links. Because several superintendents may work in a district office, the system had to allow multiple users in one office to manage their routes independently. The district manager also needed to review the routes for the entire office and needed to transfer service locations among service superintendents.

Schindler Elevator Corporation uses SAP R/3 as its core business system, currently running version 3.1I on Hewlett Packard servers in its Morristown, New Jersey, headquarters. In the field service area, it uses SAP functions for administrating contracts, dispatching technicians, recording work operations, handling repair and sales orders, recording work times, and invoicing. The system had to be integrated with Schindler's SAP system and also allow superintendents to evaluate alternate route structures without committing them in SAP.

In addition, the system had to produce detailed daily schedules of preventive maintenance visits, specifying the tasks to be performed during the current maintenance period. Visits must be scheduled to honor customer constraints (for example, a department store may require all escalators to be serviced before opening time). Maintenance tasks must be performed at various intervals and require varying times to complete. The scheduling system must balance the workload over the year for each building. For tracking and reporting, the system must store these planned visits and task schedules in SAP and properly maintain and adjust them when revising maintenance routes.

Solution

When Schindler initiated the project in January 1999, Schindler and ESRI formed a joint project team consisting of people with business, project management, information technology and infrastructure, and operations research expertise. The Schindler/ESRI project team faced rigid time constraints for project implementation and training. One goal was to finish development in June 1999 and start training superintendents before summer. Schindler wanted the system in place to meet the deadline set for the field rollout.

At the same time, the team had to develop and tune a system to meet Schindler's rules for periodic maintenance business. It needed to create routes for technicians with various periodic schedules and skill sets (elevator, escalator, hydraulic-elevator specialists, and so forth). The system had to consider accurate street-based travel time and, most important, leave enough time to respond to emergency calls.

The database modules had to interface with Schindler's SAP system to download customer and technician data and to upload completed solutions. The project team needed to develop a special component to balance maintenance tasks for a host of equipment types.

The team decided to call the project PASS (planning assistant for superintendent scheduling) (Figure 1).

After determining the functional requirements of the system, we designed the database and the system. We identified the main components:

—An SAP interface for uploading (updating) and downloading (refreshing) data between servers on the same network;

—A database (Oracle) for storing all routing information, including technician data and customer information;

—A task-balancing module (task agent) for balancing the workload for on-site maintenance during the year;

—A communication module between client and server processes (database agent, transaction server);

—A component for extracting street data for creating street networks for regional offices;

—Assignment and sequencing solvers for periodic scheduling; and

—A client user interface for controlling automated scheduling, reviewing routing results (via tabular views, bar graphs, and maps), modifying optimization parameters, and manually modifying routing results.

Developing and implementing the system successfully depended on effective collaboration by the project team members from Schindler and ESRI. We met frequently throughout the project. We identified problems early on by prototyping and developing a stand-alone, server-independent program through

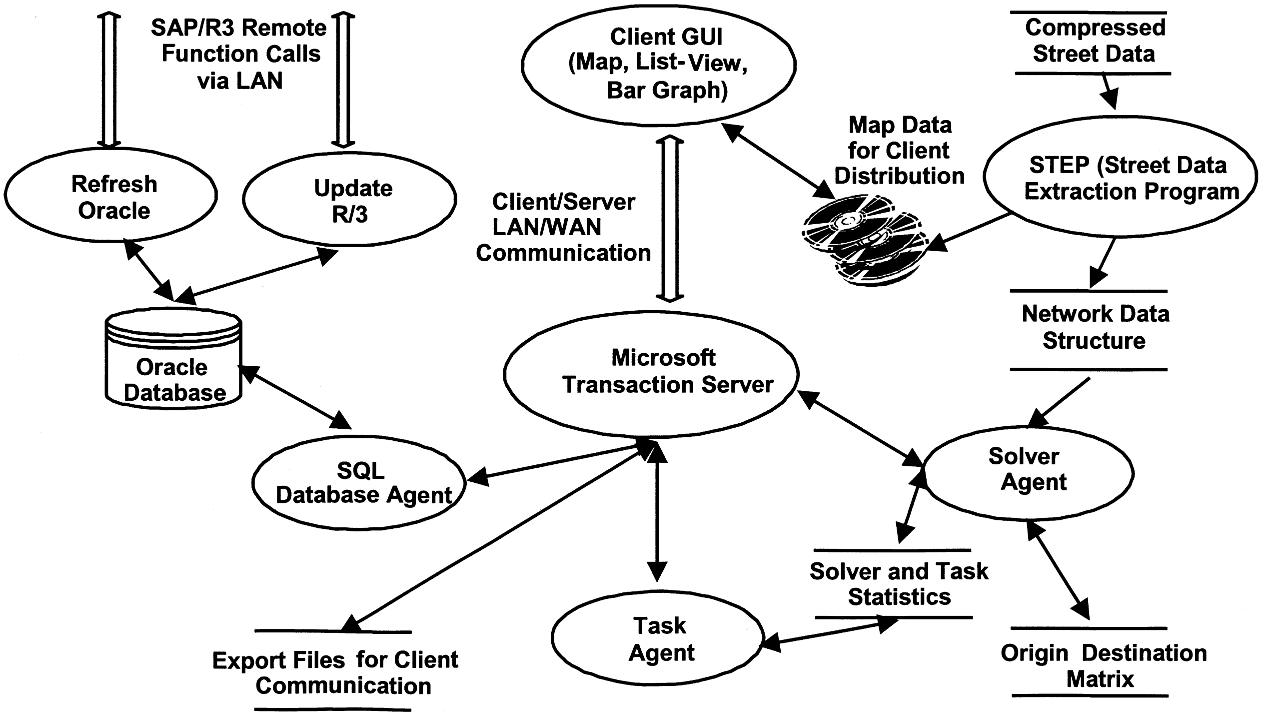

Figure 1: In the PASS (planning assistance for superintendent scheduling) system, Refresh Oracle and Update R/3 are the communication modules transferring data between SAP and PASS. The Oracle Database stores customer location data, technician data, and routing results. The SQL Database Agent provides the interface for PASS server components with the central server database. Microsoft Transaction Server allows remote access from the clients to the server components (Solver, Task, and Database Agent). The client GUI (graphic user interface) includes map, tabular list view, and bar graphs. The system writes data updates to the Oracle Database via SQL Database Agent. The solver agent writes and reads data from the origin-destination matrix and from the Oracle Database and assigns and sequences work orders. The client application triggers the Task Agent, which balances annual workload at each customer site. STEP (the street data extraction program) allows the end user to extract individual Schindler service area map data. The system uses the map data for client maps and for the logical network data structure that represents street driving times and distances.

which we could demonstrate our results to Schindler's upper management. The team included future users, Schindler's SAP implementation experts, project managers, technical designers, operations research analysts, a database designer, an SAP programmer, and representatives of management, including a vice president of operations.

The team developed a time line for the project and tracked its progress, setting and monitoring milestones. Fine tuning the assignment algorithms, which assign technicians to routes, and the sequencing algorithms, which define the order of stops on a route, turned out to be the greatest challenge during the project. ESRI developed weighted solver functions that can be controlled by user-definable parameters. These parameters allow local superintendents to adjust overtime, travel time, and other factors to meet their business needs (Figure 2). At the same time, this flexibility allows superintendents to detune algorithms to the extent that resulting routes do not properly take into account all business constraints (for example, an exaggerated weight on travel time could cause extremely uneven day-to-day workloads or routes with unacceptably different unit counts). We had to define upper

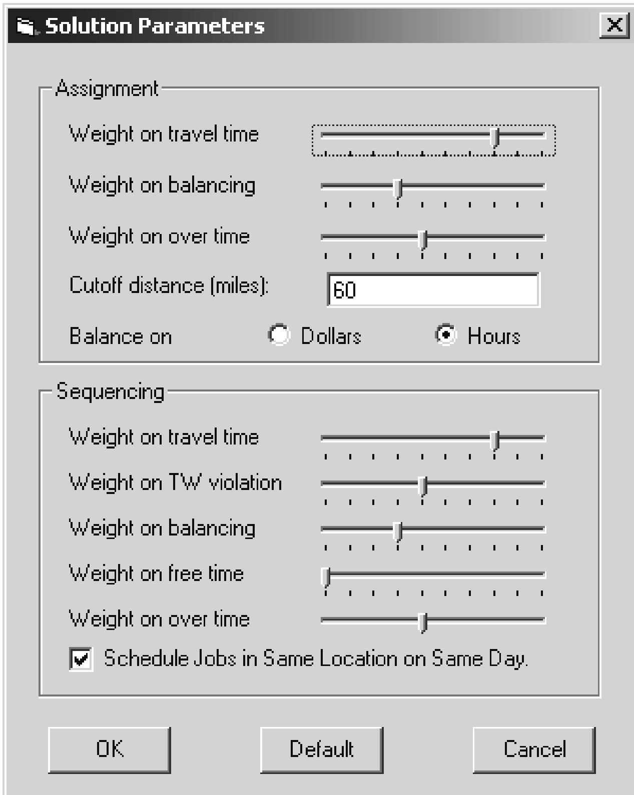

Figure 2: Using the solution parameter window, superintendents can change such weights as overtime and travel time to adjust the assignment and sequencing algorithms.

and lower limits for parameters to set boundaries for well-balanced routes and viable business solutions. Schindler and ESRI worked together to solve this problem. We performed a scaling analysis on geographical areas with different street-network densities to set the upper and lower limits and thus provided well-adjusted optimization tools for superintendents.

Algorithm Implementation

We achieved the global operational efficiency aims for the project in two ways: (1) by creating mapping and graphing tools superintendents could use to visualize and manage assignment and scheduling results, and (2) by implementing advanced OR (operations research) problem-solving techniques to develop cost-effective business solutions.

To maintain elevators and escalators, Schindler dispatches suitable technicians to its customers' locations. Maintenance tasks must be performed periodically over a predefined time interval. Each piece of equipment has its specific service interval or frequency (for example, once a week or once a month). The equipment also requires certain maintenance tasks, each at predefined intervals. Furthermore, the skills of the technician must match the tasks and equipment types scheduled for that person. Customer trouble calls (callbacks) are not scheduled by the algorithm; dispatchers assign them to the nearest suitable technician as they arrive. Superintendents take the following attributes into account in making assignment and scheduling decisions:

—Type of service order (a *service order* is a contract that requires services) for a customer location;

—Service order priority;

—Total service hours specified by the service contract for a location;

—Equipment type at a location (for example, elevator, escalator, moving walk);

—Frequency of visits specified by the service contract;

—Predefined visit duration (on-site time) for each visit;

—Minimum and maximum time interval between two consecutive visits;

—The allowable visit day(s) imposed by the customer (for example, some locations cannot be visited on Mondays or Fridays);

—Time windows (allowable time slots for visits) imposed by the customer for each workday;

—Whether or not the technician works only on weekdays;

—Technician skill sets (for example, whether the technician can service only elevators, or only escalators, or combinations of equipment types);

—Preassignment of a technician to a specific customer;

—Technicians' work schedules per day (that is, total hours, start and end times).

To optimize Schindler's daily operations, we had to ensure that maintenance tasks would be carried out in the most efficient manner while considering the attributes listed above. We also considered the following operational costs:

—Total travel cost (time or distance),
—Total overtime cost,
—Total cost for violating time windows,
—Total cost of idle or free time within each route, and
—A penalty for imbalanced workloads.

In the OR literature, researchers typically model these types of problems as periodic-vehicle-routing problems (PVRPs). A PVRP is a generalization of well-known vehicle-routing problems (VRPs) and is a difficult optimization problem. With PVRPs, the objective is typically to assign customers to multiple vehicles or technicians and to determine sequence of daily visits over a multiday planning period while minimizing total travel time or overtime or total number of vehicles used. Several side constraints ensure the match of correct skills and service orders, the satisfaction of visit time windows, no violation of vehicles or technicians capacities, and so forth.

The periodic-vehicle-routing problem extends the classic vehicle-routing problem by expanding the planning period from a single day to D (where $D > 1$) days. In the PVRP, all customers must be visited or serviced at least once over the D-day planning period and some customers must be visited several times over the D-day planning period. Usually customers require that service be conducted on a specific day, for instance, every other Monday. Sometimes, a customer may require a specific combination of visits over the planning period. For example, a customer that requires twice-a-week visits may specify Monday and Thursday, or Tuesday and Friday, and accepts no other combination. In solving the PVRP, one must address the spatial considerations arising from the customers' locations, and the temporal aspects deriving from the constraints they set on service times. The goal in solving a PVRP is usually to minimize the total operational cost over the entire planning period—cost of labor, travel distance or time (for service visits), and other tangible operational costs—while meeting the business logic or constraints (for example, the fleet capacity on any day of the planning period).

Although the PVRP is a generalization of the classic vehicle-routing problem, the OR literature contains few publications on PVRP compared to writings on classic vehicle-routing problems.

Chao et al. (1995) developed a heuristic for solving the periodic-vehicle-routing problem. They consider a homogeneous fleet of vehicles servicing (delivering goods to) a set of customers from a single distribution depot. Besides the vehicle capacity, they knew the demand for each customer, the predefined frequency of delivery, and the allowable delivery combinations. The goal is to minimize the distance traveled by the entire fleet over the planning period. The heuristic finds an initial solution quickly and uses an improvement procedure to produce better solutions by escaping from poor local optima.

The system had to consider street-based travel time.

Christofides and Beasley (1984) developed another heuristic for the PVRP. The goal of their PVRP is to meet the required service levels for customers while minimizing the distribution costs over the planning period. Their heuristic creates an initial solution that meets requirements for service and then performs interchanges to achieve better objective values. Their heuristic is based on a modified Clark and Wright savings approach and the k-opt method used for the classic traveling-salesman problem. The heuristic considers allowable service-day combinations while attempting to find better solutions.

Gaudioso and Paletta (1992) also developed a heuristic for the PVRP. They proposed a model for the optimal management of periodic deliveries of a given commodity. All the customers requiring deliveries have known periodicity. The goal of the PVRP is to assign, over a planning period, a feasible combination of delivery days to each customer and to route vehicles to conduct the deliveries to minimize the number of vehicles used. The difference between their model and other PVRP models is that it minimizes the fleet size—instead of the total operational cost. They paid particular attention to balancing the use of resources on different days.

Golden and Wasil (1987) present PVRP applications in the soft-drink industry. They discuss how to apply PVRP techniques to solve soft-drink delivery problems in different sectors of the industry.

Russell and Igo (1979) use the term *assignment problem* to describe the decision to be made in a PVRP. In their PVRP model, customers do not set allowable delivery-day combinations. Instead, they have required service levels (numbers of deliveries) over the planning period. The authors consider three heuristics based upon those for the classic one-day vehicle-routing problem.

Russell and Gribbin (1991) developed a multiphase approach to solve the PVRP. The objective of their PVRP is to minimize the total cost of distribution or vehicle travel over a planning period. In their four-phase approach, they first assign the customers to day combinations. Next, they use an interchange process to improve the initial solution. In the third step, they improve each daily route using an interchange procedure. Finally, they use a 0–1 tour-improvement model to further improve the feasible solution.

The team working on PASS encountered a few surprises.

Tan and Beasley (1984) developed a mathematical model to describe the PVRP and a heuristic based upon the algorithms for single-day vehicle-routing problems.

While some PVRPs can be solved to optimality by using common mixed-integer programming-based solvers, the typical problem size and complexity do not make this a practical approach.

To obtain a reasonable solution to a real PVRP within an acceptable computational time, ESRI developed a set of heuristics. We chose heuristics because they are able to obtain a reasonable solution for a complex problem within an acceptable processing time. We adopted a weighted objective function incorporating the five criteria listed above. We measured the weighted objective function in terms of minutes. That is, total travel cost is the total calculated travel time; total overtime cost is the total overtime in minutes across all days for all technicians; total time-window-violation cost is the sum of all violation minutes; total cost of idle time is the total number of minutes technicians spend waiting before time windows start; and the penalty for imbalanced routes is the standard deviation of route times for all routes.

The weighted objective function provides flexibility in decision making and gets minimized by the heuristic algorithms. The weight of each factor indicates the relative importance of the associated criterion and is user-adjustable within a range of 1 to 10 (each district office may have different, market-driven business goals). The solutions the algorithm produces are sensitive to these weights, but the level of sensitivity is controlled by underlying scaling factors associated with each objective-function term. A scaling factor balances the magnitude of an objective-function term against the rest of the objective function and is determined through scaling analysis.

ESRI's heuristic approach is implemented in two phases: (1) the assignment procedure, and (2) the sequence procedure.

Assignment Procedure

The objective in the first phase is to assign each location serviced by a Schindler district or office to a technician. Each technician then knows which set of customer locations he or she will service over the entire planning period (65 working days or 13 weeks). The assignment is based on technician skill sets, job requirements, and other Schindler business logic, such as preassignment of locations to specific technicians and constraints on working hours. The assignment procedure tries to find solutions that minimize a weighted objective function while

—Balancing workloads among technicians (workload may be represented by the total service hours of service contracts),

—Minimizing the total estimated travel distance or travel time for all technicians (based on point-to-point straight-line distances), and

—Minimizing estimated overtime per technician over the entire planning period (estimated based on total service hours assigned in excess of the total time available in the planning period).

The superintendent can modify the weights in the objective function to adjust for the importance of different business rules in various Schindler districts.

The assignment procedure, which is initiated by the superintendent, consists of two major tasks: (1) building an initial solution (an initial clustering of customer locations), and (2) improving the initial solution.

Building an Initial Solution

To build an initial solution, the algorithm considers only a service order's geographic location (x and y coordinates) and tries to build geographically tight clusters. Each cluster represents the set of locations assigned to one technician. However, during this step, the algorithm does not consider such factors as real travel time (distance traveled) and service time or visit time window for each service order. After producing the initial clusters, the algorithm computes the value of the associated weighted objective function.

Improving the Initial Solution

Because the algorithm considers only geographic locations of service orders in the first step, the assignments may not be realistic. Some technicians may be assigned longer service times than others, and task durations may not balance. To correct such problems, the algorithm executes an improving process for assignment. At this step, the algorithm iteratively transfers service orders from one cluster to another or exchanges orders between clusters. By means of these transfers or exchanges, the algorithm attempts to balance the working times and to limit overtime. During each transfer or exchange, the algorithm finds the operation that generates the best benefit (that is, a better-balanced route, reduced overtime, and minimal travel time or distance). The algorithm terminates this step when transfer and exchange operations can no longer produce better solutions. The solution with the smallest objective function value is the final result of the assignment procedure.

Sequence Procedure

The sequence procedure determines the daily routes for all technicians over the entire planning period and simultaneously finds the best visiting sequence for each service location within each daily route. Again, it uses a weighted objective function composed of

—A term for minimizing travel time,
—A term for minimizing time-window violations,
—A term for minimizing overtime,
—A term for minimizing in-route idle time, and
—A term for penalizing imbalanced workloads.

When it has finished the sequencing procedure, the algorithm creates a daily route for each technician for each day of the planning period.

The sequence procedure considers the following factors while building the daily routes for a technician:

—The frequency of visits to a location,
—The duration of a visit or the service time per visit of a service order,
—The allowable visit day or days the customer allows,
—The time window the customer imposes (some may have different time windows for different days),
—The elapsed time between two consecutive visits (for instance, for a customer who needs weekly service, two consecutive visits would be five days apart plus or minus one day), and
—The technician's working hours per day.

The sequencing algorithm arranges the visiting day(s) for service orders and the sequence of visits within a technician's daily route to minimize the value of the weighted objective function. Furthermore, the superintendents can use the sequencing algorithm to reschedule daily routes, for instance, after inserting new contracts for a technician or deleting old service order(s) from a route. The sequence procedure performs two major tasks: (1) assigning visit day(s) to each service order in a technician's order set, and (2) sequencing the resulting daily routes, while minimizing driving time.

> The street-network data did not include ferry crossings.

The first step in the sequence procedure is to determine for each service location the specific visiting day(s) over the planning period. The algorithm determines the visiting day(s) for each location based on the business constraints mentioned above. The sequence procedure actually builds m daily routes for each technician, where m is the number of working days of the planning period. First, it selects one service location (seed location) for each day of the planning period, and then inserts the other service locations to form suitable daily routes. The purpose of using seeds is to build routes for each day around certain geographical locations. The algorithm also transfers and exchanges service locations between day routes to iteratively improve the value of the weighted objective function.

The second step is to sequence the visits within daily routes to improve the weighted objective function further. The algorithm essentially solves a traveling-salesman problem with time windows. The best sequence of visits is the one that minimizes travel time, time window violations, and waiting time, while satisfying all other business rules.

It saves over $1 million annually with a payback of less than one year.

After the assignment and sequence procedures, the PASS system solves Schindler's periodic-vehicle-routing problem. Since we designed the PASS system for planning purposes, superintendents can change the parameters (for example, the weights in the objective functions and certain business rules) to generate new scenarios and their solutions. They can modify all results manually using the graphical user interface to handle exceptions.

The first set of heuristics we deployed had a characteristic common in iterative search techniques: a tendency to get trapped at a local optimum. To obtain better solutions, we used tabu search techniques. Tabu search is a metaheuristic that guides the local search (for example, the assignment and sequence procedures) to explore the solution space beyond local optimality. Tabu search may accept a solution that is worse than the current best known solution in an attempt to explore other parts of the solution space. To prevent a previous solution from recurring, Tabu search uses a memory structure to keep track of previously visited solutions for a certain period of time (or number of iterations). Tabu-search strategies have been applied successfully to a wide range of optimization problems. In this project, our application of tabu-search techniques solved Schindler's periodic-vehicle-routing problem.

The project team used the object-oriented C++ programming language to implement the algorithms on a Windows NT-based server. The core solver does not rely on any third-party software package. It takes only a few minutes to create a schedule for a service area for one planning period (65 business days), including assignment and sequencing, for example, of 700 service orders for a service area with 15 to 20 service technicians that covers most of Southern California (about 400,000 street segments). Most orders require more than one visit during the period; that is, the order set is a mixture of daily, weekly, semimonthly, monthly, and quarterly visit frequencies. Figure 3 shows the posssible result on the screen.

Implementation

When we developed and implemented the PASS system, the Schindler Group owned both the Schindler Elevator Corporation and the Millar Elevator Service Company, operating in the United States and Canada. Millar has since fully merged into the Schindler Elevator Corporation. PASS was a joint project of both Millar and Schindler operating units. The team project leader was the Millar vice president of service operations, who participated in meetings and workshops and made sure that service superintendents, members of field service support organizations, and information services personnel also participated.

Pilot(s)

Because ESRI's Redlands office is near Los Angeles, the project team selected Millar's Los Angeles office for piloting the PASS system with a local server. The project team spent two months adjusting the system and then procured and configured two PASS servers, one for production and one for testing and backup.

Training/Rollout

The Millar organization already had high performance desktops in their major districts. It designated them as the PASS PCs. Over a four-week period, the Millar district offices shipped PCs, 10 to 12 per week, to Millar headquarters near Toledo, Ohio, where the project team installed PASS and local maps. The team used the PCs for two-and-one-half-day hands-on PASS training lessons and then returned them to the local offices. The training server was connected to the quality-assurance SAP system, in which all production data is refreshed weekly, allowing each superintendent to train with his or her own data without disturbing the regular business.

Schindler purchased 50 new desktop PCs. Schindler's information systems group configured the PCs and shipped them to Schindler's local offices. The same two-and-one-half-day hands-on training was conducted for Schindler superintendents at Schindler's Training and Research Center in Randolph, New Jersey.

Issues That Arose During the Project

In every large project, unforeseen issues arise during development and implementation. Despite extensive planning, the team working on PASS encountered a few surprises: In using PASS to sequence our first routes for the Los Angeles pilot office, we realized that it was scheduling successive visits based on the exact calculated drive time, as Schindler had specified. We found, however, that it was perhaps not realistic to expect a service technician to begin work at the next location 90 seconds after finishing work at the previous location, even for locations only two blocks apart. (The field-service representatives on the team explained to the information services personnel that service technicians could not routinely be expected to jump from their moving vehicles.) We added 10 minutes to the travel time (which superintendents could modify on individual buildings).

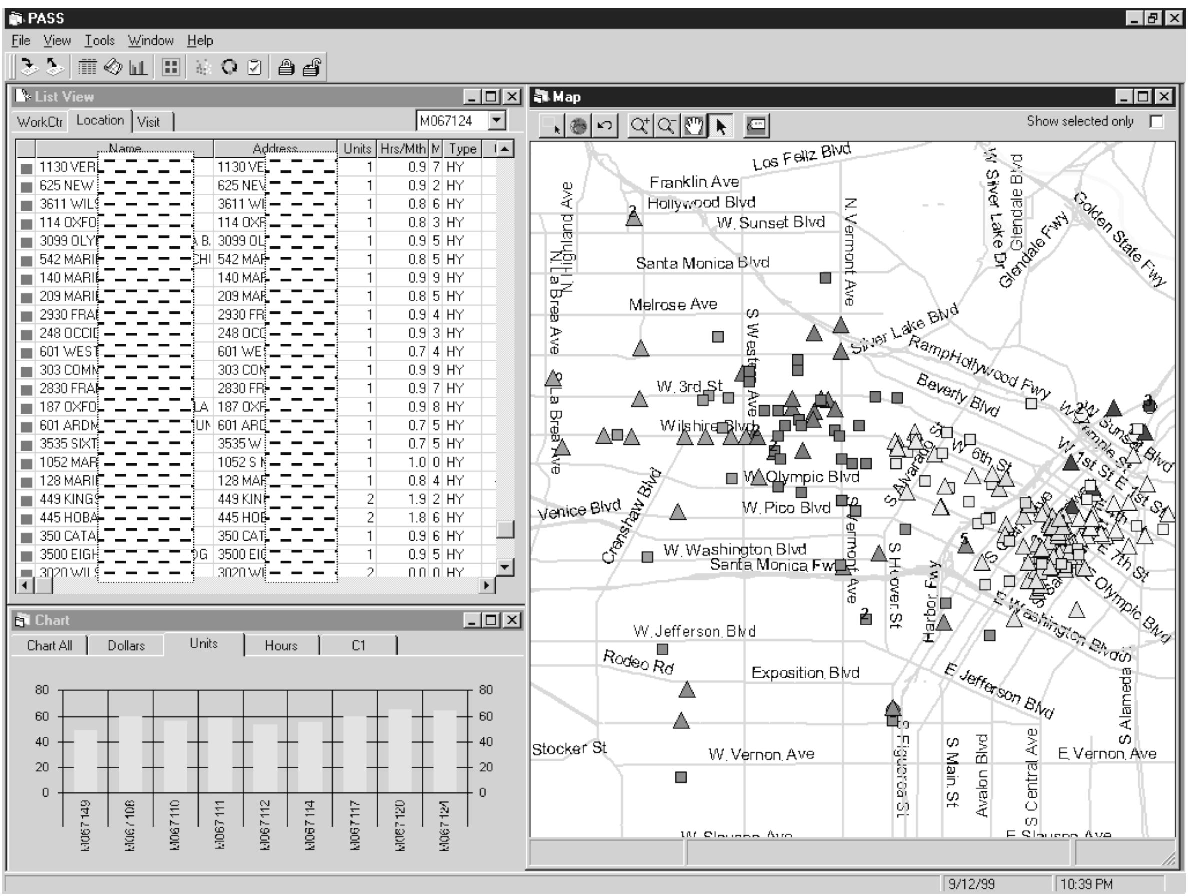

Figure 3: The PASS GUI (graphic user interface) includes a tabular list view of route statistics and a map with color-coded routes (showing downtown Los Angeles). The bar graph shows balancing between routes; in the example here, the difference between the number of units (elevators or escalators) is displayed.

Because service technicians usually start their work days when they reach their first customers, Schindler specified that the system not include travel time to the first service location and the return home from the last service location in the calculated travel time and that the system not consider them in the optimization for route sequencing. Because travel to the first location was "free," the algorithm aggressively made remote locations the first visits of the day, often scheduling visits to the same outlying area as the first visit for several days, rather than grouping all the service visits for the area in a single day. While formally correct, neither the technicians nor the superintendents found this practice acceptable. We therefore added an optional first-visit travel adjustment to establish a penalty for scheduling first visits to such outlying locations.

The street-network data initially did not include ferry crossings. The system therefore would not find routes to islands without bridge connections. We recognized the problem during the prototyping phase, and we manually edited the street-network data to add pseudo bridges, straight connections between the mainland and the island(s). To model waiting time and slow ferry travel, we set the average speed for these segments to a very low rate. (The PASS database does not include ferry schedules.)

Impact

The Schindler superintendents who have PASS are managing several million service hours per year and maintaining visibility of tens of thousands of units of customer equipment. Using PASS, the field superintendents structure their service routes in a quantitative manner. They can manipulate travel time, route balancing, overtime, personnel, and quantity of units to experiment with multiple service models while reviewing the overall effect on profitability and customer satisfaction. The integrated quantitative decision model now takes less than two hours to update the route structure of a Schindler service area and regenerate its schedule of visits for the quarter. Previously, each of 250+ field offices spent several weeks manually laying out service routes.

For a typical office, PASS adjusts service routes to accommodate gained and lost service contracts every two weeks. With more than 100 offices using PASS, the system is in daily use.

A Minneapolis, Minnesota superintendent commented:

> Just about two months before PASS came out I was busy putting colored stickers on a large laminated map so that I could get a visual representation of the routes under my control. These routes are spread out all over the suburban areas of our metro area and include about 811 different buildings.
>
> When PASS became available, it was a wonderful tool for me. I was able to quickly get an overview of where all the routes were and where there was some overlap in route structure. Thanks to PASS we have been able to better define areas of route responsibility and loading. This, along with the ability to put a job visitation schedule together, has been very helpful. Another feature I like is the ability to "play" with the routes to see how different scenarios would look and how it would change the loading. PASS is also a convenient way to make route changes and then upload them to SAP.
>
> Overall I am very pleased with the PASS program. It is a tool that every service superintendent can use to aid in developing effective and manageable routes.

With the monthly increase in service units, Schindler updates the service route structures to maintain their optimum profitability and to provide the utmost customer service. Schindler has obtained a savings from improved efficiency of over $1 million annually because of the PASS system.

Schindler ordered PASS to increase its efficiency in route planning. Viewing customer locations and job assignments spatially allowed it to restructure offices by reassigning customers between routes and superintendents. Schindler reviews the finances and operations of its offices; a key component of these reviews is an evaluation of the offices' use of PASS to structure routes.

Schindler's chief operating officer and its regional vice presidents receive monthly reports on PASS use and route-planning exception reports showing deviations from planning guidelines. We designed the new PASS so that technicians can download preventive maintenance schedules to their mobile handheld computers and obtain daily schedules and tasks. Schindler is running a pilot test of this function in Baltimore, Miami, Dallas, and Pittsburgh with over 60 technicians. It anticipates making this function available to all its service technicians in 2002.

The system was originally implemented by ESRI and put into production by Schindler for the US. It later added Canada and Puerto Rico. ESRI and Schindler are evaluating the implementation of the system for various cities in South America and Mexico. PASS servers, including SAP integration, are in place for both areas. We designed the system to allow for language localization for most countries.

On January 14, 2002, Schindler Elevator Corporation announced that it was integrating all the people and resources of Millar Elevator Service Company and Schindler Elevator Corporation into a single operating company. It could not have integrated the service portfolios of the two companies into a single rationalized route structure within a reasonable time without the PASS system. PASS is Schindler's key productivity tool for several hundred service superintendents, who manage thousands of service technicians.

Summary

The PASS periodic-routing-optimization system has been operating since 1999 and continues to produce substantial savings and to improve route quality. It cost approximately $1 million to implement PASS compared to these benefits:

—It is a key field-service productivity tool used by several hundred service superintendents to manage thousands of service technicians who perform preventive maintenance for tens of thousands of elevators and escalators.

—It shortened the route-building process in 250+ offices from several weeks to two hours.

—It optimized routes by minimizing overtime, minimizing travel time, and balancing workload between technicians.

—It improved response times by creating geographically tighter service areas.

—It met customers' increasing needs for detailed schedules and reports of maintenance.

—It increased Schindler's awareness of operations management tools.

—It gave detailed reports to all levels of management, including the vice president of field operations and the chief operating officer.

—It made possible the timely, rational consolidation of two operating units, Millar and Schindler, into the third largest elevator-service company in the United States, to form a tightly woven, efficient multimillion-dollar service business. The capabilities of the PASS system helped tremendously with the smooth transition to the merger.

—It saves over $1 million annually with a payback of less than one year.

Appendix

Although those researchers mentioned in the literature review of this paper provide mathematical models and solution techniques, none sufficiently describes Schindler's periodic-routing problem. While the model ESRI developed doesn't fully describe Schindler's problem, it provides a framework and a sense of the magnitude of the problem. We used the following attributes and decision variables in our model:

Attributes

$I = \{1, \ldots, In\}$: customer set.

d_i: visit frequency for customer i (i.e., customer i needs to be visited every d_i days).

d_i, $\bar{d}_i$: minimum and maximum number of days between two consecutive visits (i.e., $1 \leq d_i \leq d_i \leq \bar{d}_i \leq 2\, d_i - 1$).

D: number of days in the planning period (D is assumed to be a common multiple of all d_i, $i \in I$).

R_t: the route set (i.e., all available technicians) on day t.

c_{ij}: cost of travel from customer i to customer j.

s_i: required service time for customer $i \in I$.

Q_{tr}: available working hours for route r on day t, beyond which overtime will accumulate.

a_{itr}: 1 if the equipment at customer i's location matches the skill set of route/technician r on day t, 0 otherwise.

α_1, α_1, α_3: objective function weights for total travel cost, total overtime, and workload balance, respectively.

Decision Variables

x_{it}: 1 if customer $i \in I$ is visited on day t, 0 otherwise.

u_{ijtr}: 1 if $r \in R_t$ goes from customer i to j on day t ($i \neq j$ and $i, j \in I$), 0 otherwise.

S_{tr}: total route time for route r on day t.

OT_{tr}: overtime for route r on day t.

y_{tr}: slack variable for overtime.

v^-, v^+: minimum and maximum route times across the entire planning period.

The mathematical model is formulated as follows:

$$z = \text{minimize} \quad \alpha_1 \sum_{t=1}^{D} \sum_{i=0}^{n} \sum_{j=0}^{n} \sum_{r \in R_t} c_{ij} u_{ijtr} + \alpha_2 \sum_{t=1}^{D} \sum_{r \in R_t} OT_{tr} + \alpha_3 (v^+ - v^-) \quad (1)$$

$$\sum_{t=(k-1)d_i+1}^{kd_i} x_{it} = 1 \quad (i = 1, \ldots, n,\ k = 1, \ldots, D/d_i), \quad (2)$$

$$\sum_{t=h}^{h+\underline{d}_i-1} x_{it} \le 1 \quad (i = 1, \ldots, n,\ h = 1, \ldots, D - \underline{d}_i + 1), \quad (3)$$

$$\sum_{t=h}^{h+\bar{d}_i-1} x_{it} \ge 1 \quad (i = 1, \ldots, n,\ h = 1, \ldots, D - \bar{d}_i + 1), \quad (4)$$

$$\sum_{r \in R_t} u_{ijtr} \le \frac{x_{it} + x_{jt}}{2} \quad (i \ne j,\ i, j = 1, \ldots, n,\ t = 1, \ldots, D), \quad (5)$$

$$\sum_{r \in R_t} \sum_{i=0}^{n} u_{ijtr} = x_{jt} \ (j = 1, \ldots, n,\ t = 1, \ldots, D), \quad (6)$$

$$\sum_{r \in R_i} \sum_{i=0}^{n} u_{ijtr} = |R_t| \ (j = 0,\ t = 1, \ldots, D), \quad (7)$$

$$\sum_{i=0}^{n} u_{iptr} = \sum_{j=0}^{n} u_{pjtr} \ \forall p, \forall t, \forall_r \in R_t, \quad (8)$$

$$\sum_{i \in W} \sum_{j=W} u_{ijtr} \le |W| - 1 \ \forall t, \forall r \in R_t, \forall W \subseteq I, \quad (9)$$

$$\sum_{j=1}^{n} u_{0jtr} \le 1 \ \forall t, \forall r \in R_t, \quad (10)$$

$$\sum_{j=0}^{n} u_{ijtr} \le a_{itr} \ \forall i, t, r \in R_t, \quad (11)$$

$$\sum_{i=1}^{n} s_i \left(\sum_{j=0}^{n} u_{ijtr} \right) = S_{tr} \ \forall t, \forall r \in R_t, \quad (12)$$

$$OT_{tr} = S_{tr} - Q_{tr} + y_{tr} \ \forall t, \forall r \in R_t, \quad (13)$$

$$v^- \le S_{tr} \le v^+ \ \forall t, \forall r \in R_t, \quad (14)$$

$$x_{ij}, u_{ijtr} \in \{0, 1\}, \quad (15)$$

$$y_{tr}, S_{tr}, OT_{tr}, v^+, v^- \ge 0. \quad (16)$$

This model does not account for visit time windows (up to two per customer per visit). Because this model represents the global problem (that is, assignment of customers to technicians and the construction of daily routes), including this constraint would further complicate the formulation. Because of this and a few other really specific and more complicated business rules inherent in Schindler's operations, ESRI used this formulation as a guide but opted for the use of a heuristic technique. Furthermore, when this model is applied to a problem with a 65-day (13-week) planning period, thousands of customers and hundreds of routes, it quickly becomes impractical for speed- and performance-related reasons. This factor contributed to our decision to use a heuristic-based solution technique.

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