A Break from Tradition for the San Francisco Police: Patrol Officer Scheduling Using an Optimization-Based Decision Support System

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The San Francisco Police Department (SFPD) recently implemented an optimization-based decision support system for deploying patrol officers. It forecasts hourly needs, schedules officers to maximize coverage, and allows fine tuning to meet human needs. The fine-tuning mode helps captains evaluate schedule changes and suggests alternatives. The system also evaluates policy options for strategic deployment. The integer search procedure generates solutions that make 25 percent more patrol units available in times of need, equivalent to adding 200 officers to the force or a savings of $11 million per year. Response times improved 20 percent, while revenues from traffic citations increased by $3 million per year.

San Francisco has a population of approximately 700,000 and a police force of about 1,900 sworn officers, of which 850 perform regular patrol duties. SFPD's budget in 1986 of approximately $176 million included $161 million in personnel related costs. Patrol coverage of the nine police districts in San Francisco accounted for $79 million of the total.

Like most police departments, SFPD operated with schedules designed by hand. With manual methods, it was impossible to know if the "hit or miss" schedules were close to optimal in terms of serving residents' needs, and it was difficult to evaluate alternative policies for scheduling and deploying officers. While a few precinct captains were skilled and

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reasonably effective at scheduling and deploying their patrol officers, others were not.

At a higher level, the strategic allocation of patrol resources and the methods of deployment used were at issue. Manual methods could not easily or accurately measure the impact on productivity of using four-day, ten-hour (4/10) shifts versus five-day, eight-hour (5/8) shifts or one- versus two-officer cars. Therefore, SFPD management had difficulty reaching resolution on policy changes. To better meet the demands of the residents of San Francisco, management speculated that a larger share of the police force should be deployed in one-officer cars instead of the traditional two-officer cars. At the same time, the Police Officer Association (POA) wished to implement a 4/10 workweek in place of the 5/8 workweek. Management feared a repeat of previous failed attempts to implement a 4/10 plan using manually developed schedules. The concern was that gains from one-officer cars might be lost in switching to the 4/10 plan [Chelst 1981; Green and Kolesar 1984]. As a result of this uncertainty, many of the SFPD deployment policies, which had originated in the 1950s and 1960s, had continued almost unchanged despite substantial efforts since the early 1970s to make improvements.

Objectives in Police Scheduling

All police departments face three fundamental issues: citizen safety, cost of operations, and officer morale. Trade-offs among these considerations must be made since they conflict with each other. The fundamental problem is to determine the schedule in terms of the tour and shift lengths (either a 5/8 or 4/10 plan), while simultaneously determining the number of officers who start their workweek on given days and hours. A schedule's productivity is measured by how well it matches officers on duty to officers needed during each hour of the week. Figure 1 shows the number of officers needed for one San Francisco precinct during each hour of each day of the week. Having more officers on duty than shown (surpluses) wastes resources, while having less than required (shortages) increases response times and overburdens officers. Effective scheduling minimizes shortages and surpluses providing the highest possible correlation between the number of officers needed and the number of officers actually on duty during each hour. The data for Figure 1 was taken from SFPD's sophisticated computer aided dispatching (CAD) system, which provides a large and rich data base on resident calls for service. The CAD system is used to dispatch patrol officers to calls for service and to maintain operating statistics, such as call types, waiting times, travel times, and total time consumed in servicing calls.

The long-term goal in deploying and scheduling police is to minimize the number of officers needed to achieve a desired level of protection, as defined by police management and city government, while balancing the work load equitably among officers. Balancing the work load is closely related to minimizing shortages and surpluses and means that all officers should experience about the same amount of call time. A principal advantage of computer scheduling is that it

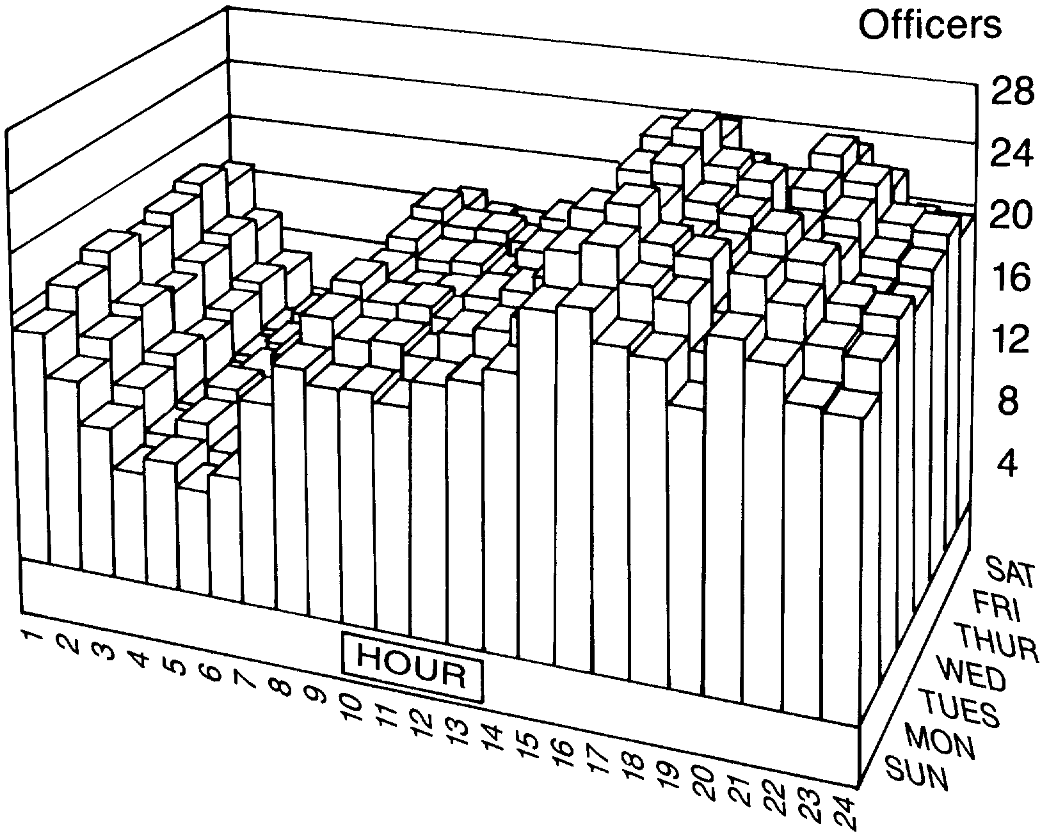

Figure 1: SFPD officers required by hour by day in one precinct. The officer requirements are forecast based on historical calls for service, consumed times by call type, management policy on percent of time officers should spend answering calls, percent of each call type requiring two or more officers, and percent of cars allocated two officers. The call and consumed time data are downloaded from the mainframe to the microcomputer. The other data are input by the captains and stored in a file for reuse. The resulting table of numbers graphed here forms the target for scheduling officers.

reduces variation in work load among officers, which helps maintain or improve morale. In the short run, the objective for most departments becomes one of balancing work loads with whatever officers are available by setting schedules that minimize shortages and surpluses during the 168 hours of the week.

Task Force Directives

Increasing demands for service and decreasing budgets prompted SFPD management to examine the feasibility of a scheduling system that could substantially improve productivity and response times in all nine precincts while maintaining current officer staffing levels. A task force was assigned to evaluate current manual scheduling procedures and deployment policies. Then, if necessary, it was to define the criteria for a new system and conduct an international search for available scheduling or deployment software to address the problem. The task force was initially headed by the current Police Chief Frank Jordan and was composed of officers from the Police Officer Association, patrol management, and technical support. Captain Walter Cullop followed Jordan as the lead member of the task force. After reviewing the manual system, the task force decided to search for a new system. The criteria it specified for the system included the following factors: (1) The system must use the CAD data on calls for service and consumed times to establish work load by day of week and hour of day; (2) It must generate optimal and realistic integer schedules that meet management policy guidelines using a microcomputer; (3) It must allow easy adjustment of optimal schedules to accommodate human considerations without sacrificing productivity; (4) It must create schedules in less than 30 minutes and make adjustments in less than 60 seconds; (5) It must be able to perform both tactical scheduling and strategic policy testing in one integrated system; (6) The user interface must be flexible and easy, allowing the users (captains) to decide the sequence of functions to be executed instead of forcing them to follow a restrictive sequence.

Many SFPD deployment policies, which had originated in the 1950s and 1960s, had continued almost unchanged.

The search included examination of Rand's PCAM [Chaiken and Dormont 1978] and hypercube models [Larson 1974, 1975, 1985] and linear programming based systems. The task force found that Rand reported the PCAM model was used by 20 to 30 departments to help in allocating cars and officers within precincts but not to schedule officers. During its intensive search efforts in 1986, the task force found no integer optimization models in use and no departments using linear programming to schedule officers. The task force decided that current software did not adequately address the criteria and contacted the authors to determine the feasibility of meeting their criteria. The task force cooperated with us during approximately 10 months of unfunded research, software development, testing, schedule benchmarking, and a cost/benefit analysis. At the end of this period, SFPD management became confident that the system was feasible and contracted with us to develop a system. This funding permitted further cooperative development of a microcomputer optimization-based decision support system called the Police Patrol Scheduling System (PPSS), which supports tactical and strategic decision making.

Necessary Features of the Scheduling System

The scheduling system had to produce feasible integer solutions, provide a means for users to fine-tune schedules to allow for employee needs and unusual events while maintaining high quality services for residents, and compute a typical schedule (90 officers) in less than 30 minutes. The user interface must allow users to run the show and yet gain advice, learning the why's of that advice from the system.

In addition, graphical displays were needed to show why scheduling decisions were good or bad and why some policies were superior to others. This would alleviate the confusion created during the previous years of discussion regarding the best policies to pursue.

Past Research

Analytical approaches to the general personnel scheduling problem appeared as early as 1954 [Dantzig 1954]. In the classic LP formulation, the goal is to minimize the number of workers hired subject to constraints that at least the number required for a satisfactory level of service be on duty each period. (For examples of variations on this theme, see Baily and Field [1985]; Bartholdi [1981]; Bechtold and Showalter [1985]; Browne and Tibrewala [1975]; Mabert and Watts [1982]; Morris and Showalter [1983]; and Warner and Prawda [1972]. A survey of the manpower scheduling problem can be found in Patrikalakis and Blesseos [1988].)

Research into police scheduling began in the late 1960s and early 1970s, both in the US and the UK [Comrie and Kings 1974; Drossman 1974; Felkenes and Whisenand 1972; Heller 1969; Heller, McEwen, and Stenzel 1972; Larson 1972; and McLaren 1967]. The New York City Rand Institute undertook a major research effort on the use of management science in urban emergency services between 1973 and 1975. Rand analyzed call rates, geographic locations, and time/distance relationships related to emergency services. This work, which included not only police but also fire and ambulance service, is summarized by Walker [1975]. The Rand models for police deployment utilized queuing theory to study both the spatial and temporal distribution of patrol officers. Spatially, the hypercube model [Larson 1974, 1975, 1985] represented a major advance in the geographic allocation of patrol resources. For deployment, Rand's patrol car allocation model (PCAM) [Chaiken and Dormont 1978; Chaiken 1985] focuses primarily on the allocation of patrol cars among precincts. It also forecasts the number of officers needed on duty in a three- or four-shift environment, but does not provide a means of optimally determining specific hourly schedules.

> In certain dangerous areas, two-officer cars are necessary.

The Rand work spawned an ongoing interest in the applications of management science approaches to police operations [Chelst 1978, 1981; Green and Kolesar 1984a, 1984b]. Kolesar [1982] provides a comprehensive review of research on the logistics of emergency services over this period. Stenzel and Buren [1983], Levin and McEwen [1985] and the National Institute of Justice [1980] provide excellent bibliographies on police scheduling.

Policy Options

Police management can set policies on a variety of factors that affect officer scheduling. The primary set of decision variables is the number of officers to start during each hour of the week to maximize coverage. However, other factors also had to be considered by the system:

(1) Shift length and tour length: Most common is the standard 5/8 plan, but the 4/10 plan is also popular. In some cities, officers work six to nine straight days with two to five straight days off. In other cities, officers work different hours on different days. Other constraints may be required by union contracts between management and police officer associations. Clearly, management needs to know with some precision how switching from one feasible plan to another will affect coverage. For SFPD, a major question was the impact of switching from a 5/8 to a 4/10 plan.

The goal programming objective function is minimize the amount of shortages (uncovered needs) and then minimize the maximum shortage for any given hour of the week.

(2) Number of start times: Determining the starting days and times and the number of officers to assign to each time is the heart of the problem in patrol scheduling. Many departments use three shifts with different numbers of officers beginning their week each day of the week. Many departments include overlay or power shifts in addition to the basic three. These power shifts overlap the other shifts to allow peak coverage. Others allow a one-hour staggered starting time, where half the officers assigned to the shift start and finish one hour later than the other half. For greater control and accountability in the organization, most departments use squads of about three to 10 officers working together each day as an integral unit under one supervisor. The number of supervisors available limits the number of groups, which means that a nonlinear integer constraint limits the number of positive variables in the schedule (that is, it limits the number of variables in the final solution).

(3) Rotating vs. fixed schedules: With fixed schedules, officers work the same shift on the same days every week perhaps with some reassignment every three, six, or 12 months. Rotating schedules, on the other hand, can mean either rotating shifts (for example, rotating from the day to the evening shift), rotating days worked (for example, Saturday and Sunday off one week followed by Sunday and Monday off the next week), or both. In San Francisco, shifts are fixed, meaning that transfers from one shift time to another are permitted only twice a year through a "seniority sign-up," with shift preferences controlled strictly by seniority. Days worked, on the other hand, rotate to give all officers the same number of weekends off during the work cycle. Officers always work consecutive days each week but start their workweek one day later each successive week. Based on the results from the Police Patrol Scheduling System, the SFPD now uses a 4/10 plan, which results in three consecutive four-day weekends off, followed by four consecutive work weekends. This cycle

proved very popular compared to previous work schedules.

From a scheduling standpoint, rotating schemes are inherently less efficient since the officers usually move in groups, and group sizes must therefore be approximately the same. This constraint, common to many police agencies, often results in a need for more officers to provide good coverage on peak days (or worse coverage from a given number of officers) than with fixed schedules. Prior to PPSS it was difficult to quantify the net impact of fixed versus rotating schedules.

(4) Officers per car: The SFPD traditionally deployed two officers per car but now uses a mix of one and two officers per car. At night two-officer cars are requested by approximately half the officers. In certain dangerous areas, two-officer cars are necessary. The POA agreed to accept a mix of one- and two-officer cars in exchange for the 4/10 plan. It is possible to evaluate productivity under these varying policies by allowing SFPD management to specify the percentage and types of calls in each priority category that require two or more officers and to specify the percentage or number of officers to be deployed in two-officer cars. Requirements for officers and cars can be accurately projected and scheduled based on the number of calls, the call characteristics, and the mix of one- and two-officer cars.

(5) Minimum officers on duty: The early morning hours, during week nights particularly, are times of low activity for most departments. During several hours an average of only one or two officers within a precinct may be needed to answer calls for service. However, SFPD management required that a certain minimum number of officers be on duty at all hours to ensure adequate geographic coverage. Hourly estimates of the minimum requirements for officers for these low peak and all other periods had to be adjusted accordingly. The model must insure that these hourly minimums are met at all times.

(6) Non-patrol duty: Although most patrol officers are assigned to cars or walk beats and deal with calls for service, some time is spent on other tasks: training programs, station duty, or dealing with calls from schools (schools cars). These hourly requirements are added to the patrol requirements to arrive at an estimate of total personnel needs for each hour at each station.

The system produced approximately a 50 percent reduction in shortages and surpluses.

The Model, Its Data Base, and Its Human Interface

PPSS consists of three integrated phases: forecasting hourly requirements (Figure 1), mathematically determining start times and the number of officers, and fine-tuning the results for special circumstances (Figure 2).

Phase 1 — Forecasting

From the CAD data on number of calls, the percentage or kinds of calls in each priority type requiring two officers, the percentage mix of one- and two-officer cars deployed, and the time spent per call, a "consumed time" and officer need is calculated for each hour of the week, and this becomes the basic building block for the forecast (Figure 1). These 168 values are then adjusted to allow for non-patrol duty requirements and a rate of growth (or decline) in calls for service. Also, management supplies a policy target as to the percentage of time officers should spend answering calls. This leads to a table and graph that shows how many officers are needed each hour of the week for a precinct.

Phase 2 — Scheduling

A specially developed integer search procedure is used to find the schedule that best fits the hourly requirements for the number of officers available. The mathematical model of the problem is provided in the appendix.

The model may be described as follows: the goal programming objective function

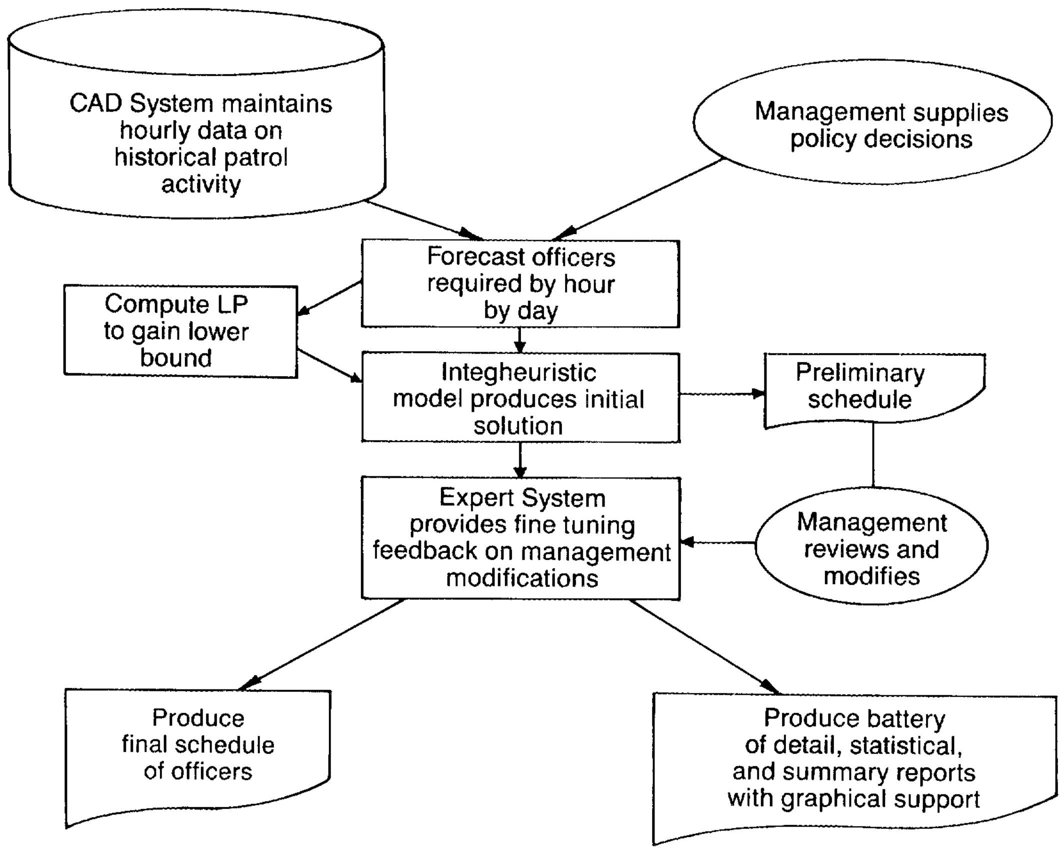

Figure 2: The flow of information and decisions through the Police Patrol Scheduling System. The CAD data are downloaded from the mainframe to the forecasting program, and management supplies the policy decisions. Then an optional LP model can be run to determine a lower bound on the objective function based on the forecasted needs. The IH model then develops the schedule, which management can review and fine-tune using the captains' expert system. Finally, reports and schedules are generated on screen and selected for printing.

is to minimize the amount of shortages (uncovered needs) and then minimize the maximum shortage for any given hour of the week. For example, a schedule that has one officer short during 15 well scattered hours (that is, 15 total hours short) is superior to one that has 15 officers short during a single hour (also 15 total hours short). A schedule that simply minimizes shortages may cause serious lapses in coverage. To accommodate both the minimization of shortages and the minimization of the maximum shortage, the model is structured with a nonlinear goal programming objective function.

The model has several constraint sets: (1) a limitation on the number of officers available; (2) minimum staffing requirements for all hours of the day; (3) soft constraints on the number of officers needed for each hour of the day, which require that officers scheduled plus officer shortages must equal or exceed officers required; and (4) a limited number of start-time groups, which is dictated by the number of supervisors available, a nonlinear constraint.

The decision variables are the shift start times and the integer number of officers starting at each time. If N start times can be utilized, then the combination of 168 times (24 hours and seven days) taken N at a time represents the number of possible start time patterns. The other aspect that must be considered simultaneously is how many officers should be assigned to each of the N start times. This problem is *NP*-complete (Bartholdi [1981], Mabert and Watts [1982], and Morris and Showalter [1983]), and algorithms that guarantee optimality are unlikely. We coined the term "integheuristic" (IH) to describe the approach of the stepwise integer-heuristic search. The IH-generated solutions can be compared to the optimal LP to determine the effectiveness of the procedure.

The IH model uses a primal-dual integer step-search philosophy. The IH method tries at each step to take the best overall integer unit step towards a feasible and optimal solution by examining all constraints. For a simple illustration, assume the only goal is minimizing shortages. Then a step towards feasibility or reducing shortages is also a step towards optimality since the objective function is to minimize shortages. Hence, the primal objective (optimality) and the dual objective (feasibility) are compatible. IH then works on multiple constraints by examining the possible increase of each variable by one unit and selecting as the variable to elevate the one that reduces the maximum number of shortages. The basic premise of the approach is to work on both optimality and feasibility at the same time. Intuitively, the IH procedure aims at confining the iterations to those constraints that will be most binding in the optimal solution. This is done by also examining the impact of increasing each variable on the magnitude of the hourly shortages when ties occur in the reduction of total shortages. The consequence is to try to obtain feasibility and optimal-

We ran the IH model for 36 different scheduling scenarios.

ity. Of course, this does not always occur and then further search is necessary in the area of the first solution generated, as discussed below. The general flow of the IH search is provided in the appendix.

Taylor [1975] applied the IH concept to an air traffic flow control problem. Taylor, Luman, and Sciullo [1978] applied a similar approach to nurse scheduling. Glover and McMillan [1986] have applied the concept to a class of personnel scheduling problems. Glover [1986 and 1988] developed "tabu search," which utilizes the principles for a more general class of *NP*-complete problems.

In actual operations, schedules should not vary drastically from scheduling period to scheduling period (for example, quarter to quarter). The sociology of a police department and of most organizations can tolerate some changes (for example, 15 to 25 percent) in the schedules from period to period, but major changes (for example, over 40 percent) are not acceptable. We refer to this as "dynamic social feasibility" and address this problem by using the existing schedule from the current ending scheduling period as the starting solution for the next scheduling period. Then we pursue the logic of modifying the existing schedule step by step, while temporarily disallowing certain moves from recurring (that is, making them "tabu" [Glover 1988]), and at each step either improving the objective function and also the feasibility or reducing the number of officers scheduled with minimum loss of shortages covered. By modifying the existing schedule in an intelligent manner, we generate a new schedule that is close in starting times to the existing schedule in its social impact but substantially reduces shortages and better matches the requirements for the new scheduling period.

Even the best schedule for any two-officer car system requires more officers than the worst schedule for a mix of one- and two-officer cars.

Prior research into the formulation aspects of the personnel-scheduling problem using LP or other mathematical-programming techniques has not resulted in widespread use of these techniques by police departments. This is perhaps because the optimal LP solution regularly calls for large numbers of weekly starting times (for example, 30 to 40) with too many patrol "squads" of only one or two officers (plus or minus a fraction). Another characteristic of LP is that small changes in the hourly officer requirements from scheduling period to period can often cause dramatic reshuffling of start times and officers assigned to each start time; such solutions are socially infeasible. Although general integer programming techniques are available, they can often require large amounts of time on high speed mainframes and sometimes do not produce a solution in the time allotted. The use of general integer programming was determined to be impractical due to computation time and convergence reliability on a microcomputer.

A battery of comparisons were made for small (that is, 40 to 50 officers), medium (60 to 90 officers), and large precincts (100 to 120 officers) between the IH solution procedure and a linear program (LP), which could not generate feasible integer solutions but did provide a lower bound on the optimal integer solution value. In all cases the IH solution values were within one percent of the LP noninteger solution values in terms of total shortages. The computation times for the LP of as much as seven to nine hours on LINDO-based software were at least 10-fold greater than the IH computation times on the same microcomputer. PPSS can produce a 90-officer schedule in 15 to 20 minutes on an 80286 12-megahertz microcomputer.

In the flowchart of PPSS (Figure 2), an optional LP model run establishes a lower bound on the solution value. Since the optional LP solution usually requires too many start times with unacceptably small group sizes, does not consider minimizing the maximum shortages, regularly suggests fractional officers, and requires hours to compute the solution, it has no other practical value.

To understand the effect of using PPSS in a hypothetical situation, look at the number of officers required to be on duty during each hour of the week based on forecasted calls for service (Figure 1). Figure 3 shows the difference between the officers scheduled and those required. From such data, shortages, surpluses, correlations, and any other measure of schedule quality can be calculated for the department. Also a simple queuing/simulation model can be used to simulate travel times, response times, total consumed times, and other statistics based on the scheduled staffing versus the officers required.

Phase 3 — Fine Tuning

After generating initial schedules, the user can use a fine-tuning subsystem in an interactive mode. Police personnel using this adjustment feature can get recommendations on alternate schedules or gain almost immediate feedback on their own adjustments. This subsystem measures the impact on schedule quality (that is, shortages and maximum single shortage) if a change were made to (1) add an officer to any schedule, (2) delete an officer from any schedule, (3) modify the number of officers on station duty or any other nonpatrol duty, (4) open a new shift starting time or close an old one, or (5) increase or decrease the percentage of one-officer cars.

> These results stopped the speculation that had frustrated the department and the Police Officer Association for 20 years.

This combination of generating solutions and integrating human factors gives the system the flexibility to consider the human aspects of work schedules. By employing the add and delete capabilities, the user can restructure a computer-generated schedule to meet one-time needs without substantially sacrificing schedule quality. Various major or minor changes in the solution can be tested quickly (the microcomputer response time is 20 seconds). This feature can be used to evaluate special circumstances, for example,

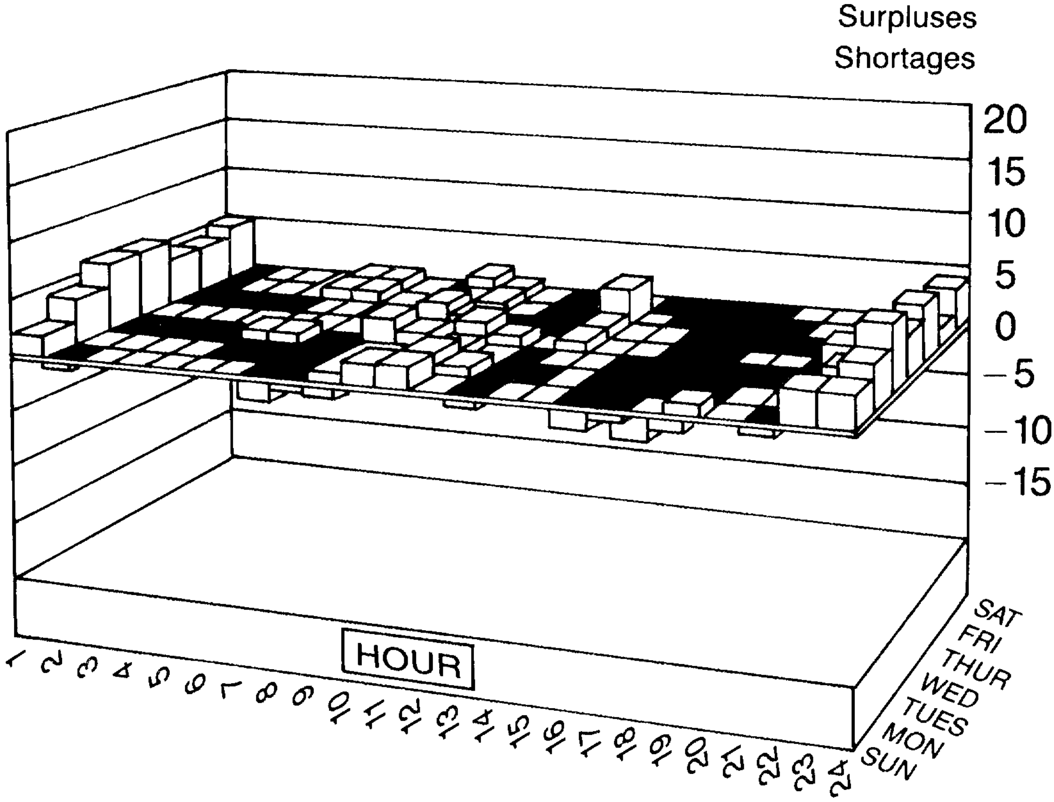

Figure 3: The shortages and surpluses minimized by the computer generated schedule. Shortages occur when fewer officers than needed are scheduled for a particular hour. Surpluses result when too many officers are scheduled for a particular hour. Surpluses contribute to idle time, while shortages often result in poor response times, and in some cases, officer overload.

how should last month's schedules be modified to meet this month's needs, or how should an injured or vacationing officer's time/day slot be handled to minimize the impact on shortages in an existing schedule.

The integer and feasibility requirements, the necessary user interaction, and the computation time constraint combine to produce a very challenging computer modeling and integer search technique development problem. By incorporating management science modeling, decision support system modeling, fine-tuning capabilities, and a seamless user environment, PPSS allows the user to control the final schedule. The user interface was designed to include (1) data displays that are easy to view and understand; (2) graphical views of the data;

(3) decision variables that are clear, intuitive, and can be easily modified; (4) data and decision variables that can be viewed in many ways; (5) fast response (seconds) to frequently used tasks and reasonable response time (minutes) for complex tasks; (6) flexible user selection and sequencing of tasks; (7) advice as to the next suggested function; (8) flexible file saving and retrieval that allows alternative schedules to be saved and recalled; (9) screens showing final reports for preview before printing; and (10) a means for the system to learn from the user what is acceptable and what is unacceptable (for example, start times).

Prior to implementation, SFPD tested the system against manual schedules using the existing two-officer car, 5/8 schedule strategy. The system produced approximately a 50 percent reduction in shortages and surpluses. Studies conducted by SFPD management showed that PPSS added 176,000 productive hours to the patrol staff per year. At $30 per hour, that is a savings of $5.2 million per year improved scheduling. Since then, the Sacramento Police Department has used PPSS to modify its 4/10 plan. PPSS produced schedules under the same scheduling policies that reduce shortages and surpluses approximately 45 percent when compared to manual schedules.

How PPSS Supports Practical Strategic Policy Decisions

PPSS helped to answer a number of strategic questions facing SFPD management: (1) How much extra manpower would be needed if the department used a 4/10 work schedule instead of the 5/8 system? (2) How much better coverage could be attained if management assigned more one-officer cars? (3) How much extra manpower would be needed if the department continued to use rotating schedules instead of fixed schedules? (4) How much would varying the numbers of shift starting times affect personnel needs under various scheduling policies?

To get answers, we ran the IH model for 36 different scheduling scenarios. These included three possible officer-per-car configurations (all one-officer cars, all two-officer cars, and a mix consisting of all one-officer cars during daylight hours and 75 percent two-officer cars during darkness), four possible shift plans (5/8 plan with fixed days off, 5/8 plan with rotating days off, 4/10 plan with fixed days off, and 4/10 plan with rotating days off), and three station sizes (small, medium, and large). Based on management's existing policies for dispatching one- and two-officer cars for various types of calls for service, we developed an officer requirements table for each scenario and produced schedules. The least efficient schedule (or the worst case mathematically) turned out to be all two-officer cars with a rotating 4/10 plan, which required 112 officers. Using this as a benchmark, we determined the percentage savings associated with the other schedules for a medium-sized station (Figure 4). Management had been concerned that the switch to a 4/10 plan would offset the gains from using one-officer cars. However, switching from any two-officer-car schedule to a mix of one- and two-officer cars would result in so much improvement that it more than offsets any decline resulting from switching from a 5/8 to a

4/10 plan. Even the best schedule for any two-officer car system requires more officers than the worst schedule for a mix of one- and two-officer cars. For all station scenarios, the policy change improvements averaged 25 percent.

Of significant interest is the fact that 100 percent one-officer cars do not increase efficiency a great deal compared to a mix. This was important, since it meant that the common-sense policy of using a mix with two-officer cars during some hours of the night and in certain geographic areas was not unduly damaging to productivity compared to the probable improvement in officer safety. Of course, the viability of each of these scenarios depended on quality schedules produced under the scenario.

Also relevant is the impact of

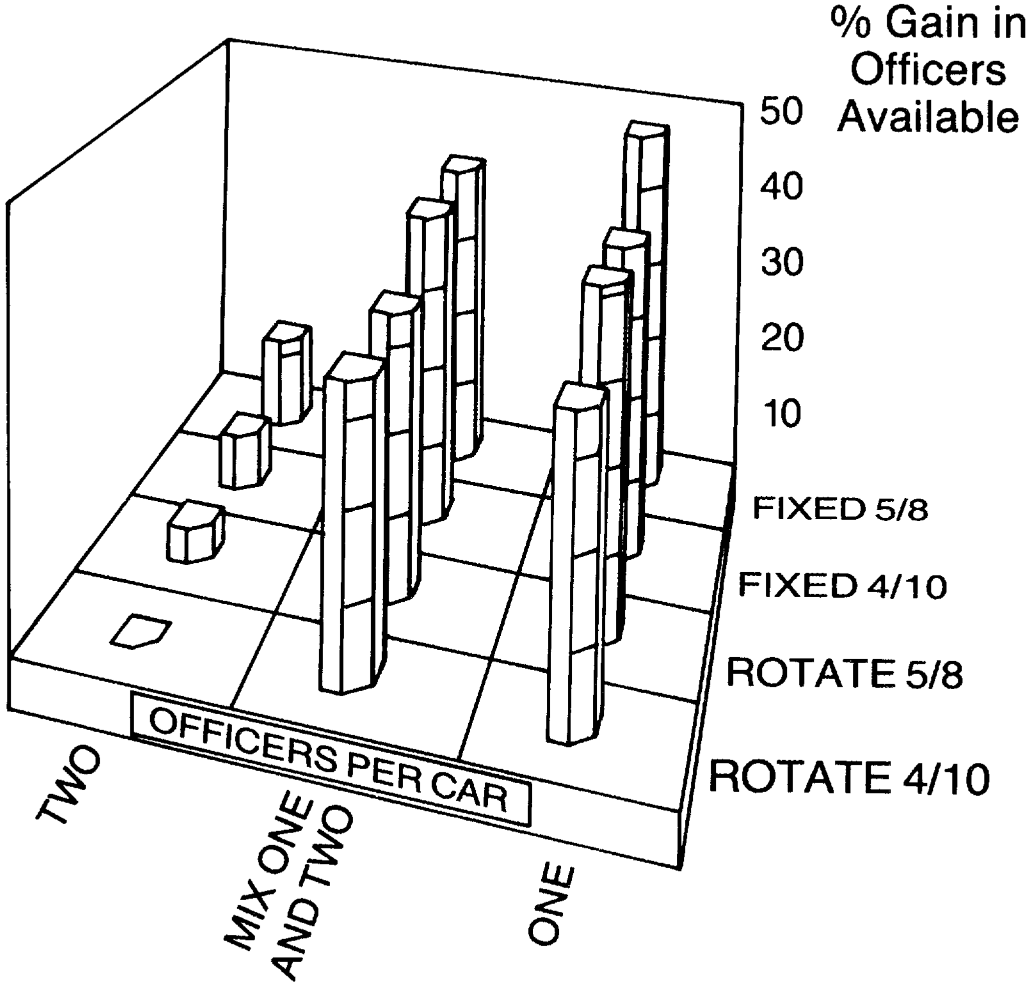

Figure 4: PPSS computed percent gain in officers available under various deployment strategies. This enabled SFPD management to examine the trade-offs between officer preferences and productivity. Management chose to switch from a 5/8 rotating two-officer car policy to a 4/10 rotating one- and two-officer car mix.

scheduling additional shift starting times under four different scheduling strategies (Figure 5). From three to 24 start times are possible, and SFPD historically used three. They discovered that the 4/10 rotating plan with five start times was superior to the 5/8 rotating plan with three or four start times.

These results ended the speculation that had frustrated the department and the POA for 20 years. They convinced management to implement the 4/10 plan and schedules with a mix of one- and two-officer cars. SFPD management conducted a formal analysis that showed that these changes contributed $5.8 million to improved availability of officers when needed. Combined with the savings from improved scheduling the total savings were $11 million per year.

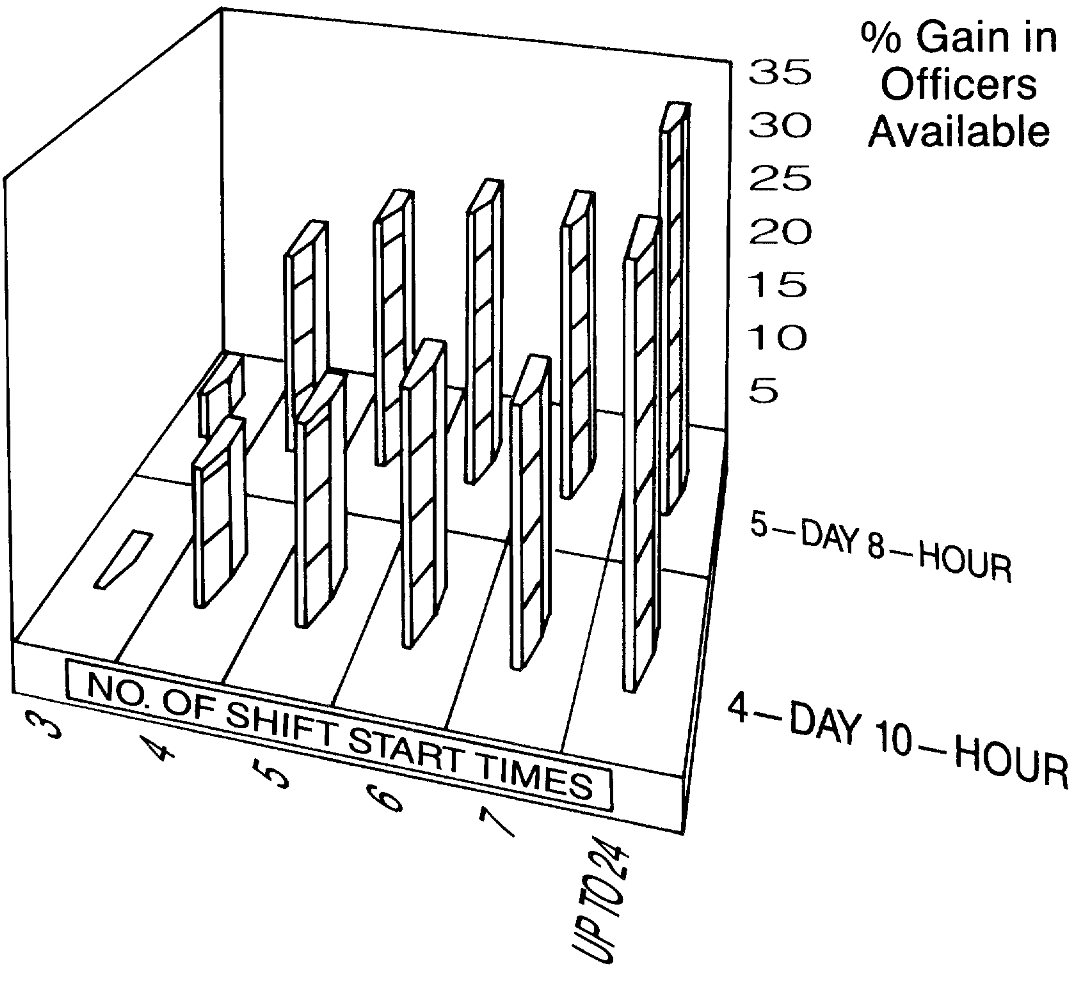

Figure 5: PPSS also enabled SFPD management to evaluate alternative numbers of shift starting times. Management chose to increase the number of start times based on this analysis. Each precinct was evaluated separately by PPSS to determine the best number of start times and the exact times each shift should start.

Implementation Challenges

The environment for change was excellent, but due to Police Officer Association (POA) pressure for the 4/10 and one-officer cars, the relationship between the Police Officers Association and management was intense. The POA had been involved in the project prior to funding and had been supportive to the point of considering POA funding of the project. The intensity of the management/labor relationship was due in part to frustration with the long-running battles and failed attempts at implementing a 4/10 plan. Management meetings and management/POA meetings on the subject of patrol deployment had usually been burdened with wide and heated speculation on the impacts of various policies since accurate evidence was unavailable. Therefore, gaining support for changing scheduling policies that had been in effect for so long was a major challenge. Working with management we decided to phase in the changes one station at a time. Park Station was selected as the initial test site for the new PPSS schedules. It had sufficient parking for the additional vehicles needed for the one-officer cars that were "donated" by other stations.

Working with management we drew up a timetable for starting the new schedules. It required the cooperation of several other city departments: payroll had to adjust its recordkeeping procedures to cover 10-hour days, and communications had to assign new radio identification codes so that dispatchers would know which officers were just starting and which were ending their shifts, which cars had two officers, and so forth. The new plan went on line Sunday, November 2, 1986.

Management anticipated a problem with convincing the city to purchase enough extra cars to support the one-officer car policy. With its perennial budget problems, the city would have to have strong empirical evidence to persuade it to fund the additional vehicles. SFPD needed to track Park's experience carefully to convince the city to invest in new equipment. The results at Park Station were persuasive, and the city approved an initial sum of $470,000 for additional cars, added communications equipment, and more parking space at several stations.

Acceptance of the computerized scheduling system was facilitated by the use of animation and 3-D graphics for training police officers on how to exploit its capabilities. Graphics were also useful for explaining why one set of policies was superior to another. Training time for the police officers averaged only two days due to the extremely intuitive interface and a customized animated computer graphics tutorial that took the user through the system's features. Also, the graphical displays in the fine tuner explaining why a decision is good or bad assisted in the training. Most important, the system provided an environment in which trainees could learn by challenging the system's schedules to see if they could do better. The system's use of calls for service as the primary definition of work load has encouraged the users to become more oriented towards meeting the safety needs of San Francisco residents.

Tangible and Intangible Benefits

Intangible benefits include potential crime reduction due to improved response times. The California Career Criminal Apprehension Program qualified the system for program funds because it addresses three major areas: "analysis support of patrol decision-making, integrating patrol assignments, and managing the patrol work load," all concerned with "the day, time, location, staff allocations, and patterns for implementing tactical patrol activities."

SFPD used the system to evaluate and implement new policies, converting to the 4/10 plan and to a better mix of one- and two-officer cars. Management conducted several studies over a period of a year and found that response times improved dramatically, dropping an average of 20 percent for A-Priority calls (life threatening situations), 18 percent for B-Priority calls (crime committed but no current threat), and 20 percent for C-Priority calls (minor citizen complaints). Additional measures of improvement addressed in the evaluation included a 21 percent increase in self-initiated officer activities, a 32 percent increase in traffic citations, and a 36 percent reduction in days lost to sick leave. The increased traffic citations represent approximately $3 million in potential revenues to the city treasury.

A cost benefit analysis of the scheduling aspects of PPSS shows a one-time cost of $50,000 and a benefit of $5.2 million per year or a payback period of 3.5 days. If we include the policy changes that required $470,000 in cars and equipment, the total cost of the system is $530,000. The savings from the scheduling and policy changes is $11 million plus $3 million in increased citation revenues for a total $14 million per year. Therefore, the payback on the entire package is 14 days.

In addition to tracking these statistics, SFPD management also conducted a questionnaire survey of the officers themselves to check their attitudes about the new schedules and their equitability. The responses indicated overwhelming approval (96 percent). The department considers this improved morale an extremely valuable intangible benefit that affects the quality of service that police officers provide to the city's residents.

A cost benefit analysis of the scheduling aspects of PPSS shows a one-time $50,000 and a benefit of $5.2 million per year.

Other intangible benefits include improved consistency of schedule quality in all precincts. PPSS also allows management to adjust schedules easily and quickly to meet the seasonal changes in the pattern of crime. A major intangible benefit is that PPSS helped to resolve some of the policy questions that formerly consumed so much energy and time.

Further Efforts

Since the installation of PPSS, the computation time for the IH portion of the model has decreased from approximately 45 minutes for a 100-officer problem to usually less than 15 minutes. We have installed functions that make the system easier to use and more powerful.

PPSS spawned the development of another system. Since the scheduling system addresses the "when" of patrol deployment and not the "where," in 1987 we developed another system, the Patrol Beat Design System (PBDS), which redesigns the geographic areas (beats or patrol car areas) that an officer patrols. Manually redesigning these areas is a time-consuming "hit or miss" chore often taking many people-months. Because of this, beats are rarely changed, with some departments revising them once every five to 10 years. Seasonal crime patterns cannot be incorporated into these manual area designs. PPSS now uses the beat designs from PBDS to define precinct work load. The user interface of PBDS is very similar to the PPSS interface, which shortens the learning time for users of both systems.

Both systems are portable. The police departments in Sacramento, Virginia Beach, and Richmond, California have implemented the scheduling and the beat design systems, using them on a regular basis to redesign their substation (that is, precinct) boundaries and their patrol schedules.

Summary

This project appears to be the first significant advance in police deployment technology since the pioneering efforts of the Rand Institute in the early to mid-1970s, and based on SFPD research, it is the only optimization-based model currently used to create integer police officer work schedules. Speed and the ability to consider a nonlinear objective function with discontinuous constraints was a major consideration in developing the IH model. The seamless integration of the IH model and the fine tuner into a fast and easy-to-use decision support system encourages management to evaluate deployment and schedule changes. This has raised management's perspective, taking it from speculation about the impacts of schedule changes to a sound exploration of the best schedules and policies for deploying patrol officers. The implementation of the Police Patrol Scheduling System at the San Francisco Police Department improved productivity by $11 million per year. Response times have declined by approximately 20 percent. Productivity measures are significantly improved, city revenues are increased by $3 million per year, and officer morale is positive. The payback period on the project, including hardware, software, and equipment, was less than two weeks. The San Francisco Police Department considers it "an outstanding service to the cause of law enforcement."

APPENDIX

Algebraic Statement of the San Francisco Police Department Problem

The following indices and index sets are defined:

i = hour,
j = day,
h = hours in shift,
d = days in shift,
TA = set of start time indices i,j that are acceptable, and
S_{ij} = set of start times that contribute personnel to the coverage of i,j given h,d.

The variables are defined as follows:

NO_{ij} = number of officers starting the work week at i,j and

T = the set of selected start times.

The input parameters are defined as follows:

K = minimum number of officers on duty any i,j,

M = smallest group size,

NA = number of officers available,

NP = maximum number of patrol groups,

R_{ij} = number of officers required each hour and day,

β = a value ≥ 1 where higher values reflect a high degree of management concern for large hourly shortages, and

α = a value that balances the relative importance of total shortage minimization to minimization of maximum hourly shortage.

The symbols used in defining the model are defined as follows:

Number(s) is the number of elements in the set s,

P_{ij} = officers on duty at i,j,

U_{ij} = shortage of officers at i,j, and

O_{ij} = surplus of officers at i,j.

The problem is defined as follows:

$$\text{minimize } \sum_{ij} U_{ij}^{\beta} + \alpha \sum_{ij} U_{ij}$$

subject to

$$P_{ij} = \sum_{kl \epsilon S_{ij}} NO_{kl} \;\; \forall ij,$$

$$P_{ij} + U_{ij} - O_{ij} = R_{ij} \;\; \forall ij,$$

$$\text{Number } (T) \leq NP,$$

$$T \epsilon TA,$$

$$\sum_{ij \epsilon T} NO_{ij} \leq NA,$$

$$P_{ij} \geq K \;\; \forall ij,$$

$$NO_{ij} \geq M \;\; \forall \; NO_{ij} > O \text{ and } \forall ij.$$

$$NO_{ij}, P_{ij} \geq O \text{ and integer } \forall ij,$$

$$U_{ij}, O_{ij}, R_{ij} \geq O.$$

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John J. Jordan, Deputy Chief of the San Francisco Police Department, attests that: "As both a strategic and tactical tool, PPSS helped us. We used the system as a tactical tool. The precinct captains used it in scheduling their patrol officers and office staffs. The schedules they produced using the system were well received by the officers, with sick leave decreasing by approximately 50 percent. Response times to calls for service decreased in the range of 20 percent. Citation revenues increased dramatically, enabling the city to realize an immediate financial gain.

The system also offered us a quick and easy way to test a variety of deployment strategies (4/10 vs. 5/8 plans, one vs. two officer cars, etc.); it helped us select those strategies which increased our productivity in meeting calls for services by approximately 25 percent. This increase in police coverage would have required many additional officers using previous deployment methods.

In short, we saw improvements in officer morale, decreased response time, improved revenues, decreased officer sick leave, and the system paid for itself almost immediately."