Deployment Research of the New York City Fire Project

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PREFACE

Late in 1967, the City of New York initiated a unique relationship with The Rand Corporation: A research partnership directed at several of the City's most important operational and policy problems. By mid-1969, the work had proved valuable enough to the City that the partnership was made formal: A new organization--The New York City-Rand Institute--was constituted as a partnership between The Rand Corporation and the City of New York. The charter and mission of this not-for-profit organization make it more a municipal policy research institute than a traditional consultant.

An earlier paper by P. L. Szanton, RM-6236, Working with a City Government, outlines the managerial and institutional settings within which this development has taken place, and discusses the broad range of research that has been conducted.

This Report focuses on the largest of the NYC-Rand projects--the Fire Protection Project--which the author has led from its inception through September 1970, and again from September 1971 to May 1972.
ACKNOWLEDGMENTS

The Fire Project has been very much a joint enterprise, with important contributions at nearly every stage from Rae W. Archibald, Grace M. Carter, Jan M. Chaiken, Edward J. Ignall, Peter Kolesar, John E. Rolph, Carol E. Shanesy, Arthur J. Swersey, Warren E. Walker, and Robert K. Yin of The New York City-Rand Institute. In addition, specialized contributions have been made by Ronald D. Doctor, Colleen Dodd, Irving N. Fisher, Ralph L. Keeney, Gilbert S. Levenson, Shlomo Shinnar, Anne M. Stevenson, Albert J. Tenzer, Richard Watson, and numerous reviewers and commentators. FDNY contributions have been too numerous to list individually. I would like, however, to acknowledge especially the contributions and support of Commissioner Robert O. Lowery, Chief of Department John T. O'Hagan, former Assistant Fire Commissioner Paul M. Canick, and the Program Officers assigned to the Project—Deputy Chiefs Homer G. Bishop, Robert J. Brown, and Francis J. Ronan.
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DEPLOYMENT RESEARCH OF
THE NEW YORK CITY FIRE PROJECT
Edward H. Blum

I. INTRODUCTION

This Report describes a part of what is believed to be the largest concerted research project yet directed at urban fire protection. The work described is that of the New York City Fire Project, which has been and continues to be conducted jointly by the Fire Department of the City of New York (FDNY) and The New York City–Rand Institute.

Supported by the FDNY, the Project's research has been carried out by an interdisciplinary team: FDNY chiefs and other officials; engineers; an urban planner specializing in organizational behavior; applied mathematicians—including specialists in operations research, computer sciences, and statistics; economists; and a social psychologist. From the outset, a large part of the work has been done jointly by members from different disciplines, particularly when it has involved research across disciplinary areas and the spectrum of activities that support implementation.

At the time of writing, the Project had been underway roughly four years. In that time, its work had--

- created new perspectives, methods, approaches, and results for the urban fire service;
- transformed these research products into operational information, insights, policies, and programs; helped put these into practice; and evaluated results;
- yielded, and continued to yield, improvements without which additional expenditures would have been required, expenditures that could well have exceeded ten million dollars per year;
- helped the FDNY develop new problem-solving traditions and capabilities, and provide improved bases for its future policies and questions.
This Report aims to convey some of the style and substance of this work. For substance, we will focus in some detail on one area of the Fire Project's work: that concerned with effective use of fire department manpower and equipment—and, in particular, with deployment or allocation of fire-fighting units. Within this focus, we will set the context by describing briefly some points about urban fire departments and their operational problems. Then, we will illustrate operational problems the research has addressed, describe some of the models developed to solve these problems and some major results that these models have yielded, and note briefly what putting these results into practice has involved and what some practical experience has been.
II. CONTEXT

Our client and partner in this work is the Fire Department of the City of New York, which provides nearly all the fire protection, most of the alarm communications, and some non-medical emergency services to the land and port of New York City. With roughly 14,000 uniformed men, 1000 civilian employees, and 400 fire units, the FDNY is the world's largest municipal fire department. Its organization and operations are much like those of its counterparts in other cities, but larger and more extensive.

NEW YORK CITY

When our joint research began in January 1968, the FDNY faced a number of serious problems. Some already were upsetting its operations and management, and thus were widely recognized within the Department, while others were manifested only as general undercurrents of concern to a sensitive few. Some were particular to New York City, while others were common to many big-city fire departments and even to the urban fire service in general.

Most conspicuously, as the work began, the Fire Department was operating under severely increasing strain. Fire alarm rates in New York City had tripled in the preceding decade and were continuing to skyrocket. The rapidly rising alarm rate imposed unprecedented demands on the Department, demands that could not be met using then-standard management practices and fire-fighting technology. Communications channels were becoming clogged during peak periods, and routine paperwork was swamping key personnel. Command-and-control functioned with aging equipment, which had worked well for a long time, but the numbers of incidents and the volumes of information to be handled were growing much faster than the system's ability to cope with them. And as alarm rates continued to rise, strain in command-and-control was increasingly accompanied by strained field operations.
Due to the rising alarm rates and alarm densities, by 1968 some fire-fighting units in high-incidence areas were responding more than 6000 times a year, and more than 20 times a night many nights of the year. These units were beginning to feel overworked, and the increasing workload was becoming a serious and potentially explosive issue in negotiations with the fire-fighting unions. Moreover, when several large fires erupted at the same time in one part of the City, it proved increasingly difficult to get enough units quickly to the later incidents, and dispatchers strained to maintain balanced coverage throughout the City in the face of the heavy localized demands for men and equipment.

At the same time, fire protection was becoming much more expensive. Between fiscal years 1957-58 and 1968-69, for example, the FDNY's total budgeted expenditures had risen from $99 million to more than $200 million, and were beginning to jump at 20 to 30 percent per year. The FDNY's budget had already exceeded the operating budget of the entire City of Boston. And straightforward budget projections assuming that then-current trends would continue were staggering.

The Fire Department had launched a number of energetic and thoughtful programs directed at these problems. But preliminary evaluation showed less favorable effects than anticipated. Traditional fire-prevention programs, developed for and apparently effective in industrial, commercial, and middle-class areas, seemed to be having little effect in the deteriorating slum areas where both existing incidence and growth in alarm rates were highest. In these high-alarm areas, there was a new community relations activity, which—though highly motivated—suffered from the same lack of basic understanding that plagued such activities everywhere. Multi-million dollar modifications of the command-and-control system had been proposed, but authorities questioned whether they could achieve what was needed. To relieve local concentrations of workload, a number of new units had been added—at a staffing and operating cost per unit of over $500,000 per year. But these had provided much less relief than expected, and several had become new high-running units themselves.
Often with considerable ingenuity, members of the Fire Department had proposed numerous other approaches to the Department's problems. Given the tools then at hand in the fire profession, however, most competing theories seemed more or less equally plausible, depending perhaps on who had advocated them. Thus policy debates often ran aground on vital but unanswerable questions, and all but conservative ideas tended to lose impetus.

Most of these problems were unique to New York City in degree rather than in kind; fire problems had simply come to a head first in New York. Indeed, a retrospective look at urban problems and innovations shows that New York City has frequently led in both—perhaps because its ills are writ large by the City's "size, scale, pluralism, dysfunctional city bureaucracies, and powerful civil service-labor movement coalition."*

**FIRE DEPARTMENT PROBLEMS**

But New York was clearly far from alone. Fire alarm rates were rising rapidly in other big cities, too, and in some cities outpaced New York. Reforms in command-and-control and fire-fighting technology and deployment were beginning to be seen as needed in several cities, although the shape of the reforms was still quite unclear. Municipal union strength was growing throughout the country, particularly in the East and Midwest. Service costs in many cities were rising faster than the revenues needed to pay them. And, with the exception of a handful of big-city fire departments, the entire urban fire service received little effective support from industry, universities, or the Federal Government, and lacked an in-house research tradition.**

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*David Rogers, The Management of Big Cities, Sage Publications, Beverly Hills, California, 1971, p. 60. Rogers refers not specifically to fire but to the factors that exacerbate socioeconomic problems in general.

**The FDNY had been particularly innovative in certain areas. It had developed new equipment—such as the superpumper and the tower ladder—and installed the first fire department computer (an IBM 360-20, in 1967). But FDNY officials expressed the concern that their innovating traditions and capabilities were fragile and unsustained.
Let us look briefly at some of the common, underlying problems. 

Men and Management

The fire service mission is traditional and enduring: To prevent fires and to respond to those that do occur and put them out. Although most urban fire departments stress the preventive role, all are primarily organized to serve in crisis—to react promptly and protect the community when parts of the physical or social order break down.

Perhaps more than any other municipal service, the fire service across the nation is linked by a sense of fraternity and tradition, the keystones of which are reliability, dedication, esprit, heroism, and self-sacrifice. This tradition underlies much of the fire service's effectiveness, particularly in the grueling and dangerous operations required to save lives and limit damage in serious fires. In the contemporary city, however, this tradition is gradually eroding and coming to seem anachronistic. Public adulation and even sympathy for the fire-fighter has been waning, and in the larger cities demands on the fire service are increasingly becoming conspicuous symptoms of deeper social ills.

Fire-fighters have become increasingly disturbed because their traditions and the values they represent appear to be disintegrating. Changing public attitudes, fragile relations with minority communities, and a trend toward bureaucratization have dimmed the luster of the job and shaken and transformed many fire-fighters' self-image.

This crisis in public- and self-identity has also afflicted fire-service management. Recruiting of the most highly qualified men has become more difficult, and labor and community relations have become increasingly important concerns. Costs have been rising, but voter resistance to increased budgets and taxes has stiffened. And management

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* A more comprehensive view can be found in reference [4]. It should be noted that not all of these problems are manifested in every city, and that many of them are less severe in New York than in other cities.
itself has become more difficult and more complex, now that tradition no longer suffices to motivate and guide the skilled manpower on which the fire service depends.

Yet, nearly everywhere, some other traditions still dominate; for example, the only road to the top of larger fire departments is from within, and few training programs are available to teach management and organizational skills. Moreover, even among officers, the accultura-
tion toward putting out fires is so decided that many of the best men prefer field command to top administrative or staff jobs.

Practices and Equipment

Despite the image of technology—of alarms, trucks, sirens, hoses, and ladders—fire service is still basically a personal service, provided in person at widely distributed, local sites by groups of men having specialized interests, skills, and physical capabilities. Men lay hoses and advance them. Men brave heat, flames, and toxic gases to perform rescues. Men open up buildings to expose flames to hose streams and to ventilate heat and smoke. And men command these operations at the scene. Facilities and equipment are neither insignificant nor inex-

pensive, but the primary strength of a fire department is in its manpower, and the preponderant expense is still the annual recurring expenditure on personnel.

Indeed, in most urban fire departments, manpower costs amount to more than 90 percent of the total budget. Increases in costs have often followed increased demands for protection, which—combined with the increasing strength of municipal labor unions—have led to larger forces and to salaries, pensions, and fringe benefits that have out-
paced the general price index. As a result, to supply, staff, and operate one big-city fire truck with its complement of men—keeping the unit ready and running twenty-four hours a day, seven days a week—

now costs from $250,000 to $750,000 per year, depending on manning levels and salaries. In New York City, for example, a decision to
add or remove four active fire units changes the operating budget by roughly $2,500,000 per year.

Of the forces helping to retain this manpower-intensive character, one of the strongest is tradition, which remains influential both within and without the fire service, despite its gradual erosion. Even with the advent of motorized equipment and mobile radio communications, for example, basic fire department practices inherited from the past continue widely in traditional forms, and most use manpower generously. Nearly everywhere except New York City, the insurance underwriters' "Standard Schedule for Grading Cities and Towns" exerts a conservative influence and is increasingly viewed as an obstacle to effective management and innovation. On the other hand, tradition and most fire-fighters' personal inclinations call for risk-taking and flexibility. These qualities are increasingly discouraged by both formal fire department organization and increasing union pressures for work to be more highly structured and defined.

In addition, as students of bureaucracy are quick to note, fire departments are essentially line-operating agencies. Such agencies are often ill-equipped in outlook, skills, and organization to undertake novel or significant change.* They are usually especially ill-equipped to undertake efforts that involve more than minimal uncertainty and risk. The rewards for success within the organization, and its political setting, are usually small, and the price of failure disproportionately high [1].

In this setting, unfavorable external pressures have raised the barriers to major productivity change even higher.

To carry out its activities effectively, for example, the fire service depends heavily upon outside persons and agencies: those who formulate and administer the building codes, architects and building

*Though clearly not always so, as the significant changes introduced by the FDNY demonstrate. (The other side of the coin is that fire departments also can be tightly organized, relatively monolithic organizations that may respond quickly to leadership in situations having commonly perceived outcomes and goals.)
contractors, fire insurance companies (whose rating practices influence the private fire protection, such as detectors, sprinklers, or brush clearance that property owners provide), telephone companies, private or auxiliary alarm services, and equipment manufacturers and suppliers. Within local government, the fire service depends upon many other agencies' programs: effective housing policies and programs, particularly those aimed at preventing deterioration and abandonment; effective trash collection, particularly in yards, halls, vacant lots, and other areas beyond the curb-line; effective zoning; and effective leadership and social policies at all levels of government.

These persons, agencies, and activities lie beyond the fire service's direct domain, and often are hard for it to affect. But when they perform poorly, they contribute to increasing the fire service's workload and impair its ability to carry out its mission.

These problems have been compounded in that the fire service has depended, and for the most part still depends, for information and new ideas largely on a few dedicated interest groups and professional associations, which are backed by limited financial resources and next to no research. Most of the research that has been done has either supported existing practices and products or treated subjects that, while important, are peripheral to the main interests and needs of the urban fire service--such as nuclear blast fire problems, forest fires, and the chemistry of combustion.*

To some aspects of fire protection, technological change could contribute significantly, either by changing the basic nature of the service the fire department must provide--e.g., through less flammable bedding and furnishings, or a comprehensive early fire detection and warning system--or by increasing the service capability per man. But

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*Basic research on combustion chemistry should, of course, eventually lead to improved fire-fighting tools and tactics, as in the polymer area it has already led to improved fire-resistant and fire-retardant materials. But most urban fires are so diverse and heterogeneous, in their burning material as well as in their heat and mass transfer, that many combustion experts feel it will be many years before they are understood in detail.
Technological changes in the fire-protective milieu have occurred slowly, even where suitable technology already exists, principally because market forces work against them. The changes add to costs, and there have been neither subsidies nor strong regulations to stimulate adoption.*

Fire-fighting technology has advanced, on the whole, even more slowly. Radio has just begun to replace voice and hand signals and messengers for tactical communications at the fire scene. Power tools have just begun to replace axes and crowbars in ventilating roofs and walls. Command-and-control is grounded in turn-of-the-century technology. New materials, new protective clothing, new fire detectors, new extinguishing agents, or materials to enhance water, have been introduced agonizingly slowly, in part because of the small and atomized fire service market and a fragmented and reluctant supply industry.

*The major leverage over such technological changes exists at national rather than local levels, because most of the relevant markets are national in scale. Federal activity, such as that represented by the fledgling flammable fabrics program, thus appears to be essential if the basic nature of urban fire protection is to change.
III. THE FIRE PROJECT

RESEARCH ENVIRONMENT

Our research began, therefore, in an environment in which many were aware of the general need for change but unsure of the direction that change should take. Pressure for movement came both from within the Fire Department, from those who recognized the serious problems and wanted to do something about them, and from outside the Department, mainly from the City Bureau of the Budget and other parts of the Office of the Mayor, which wanted to ensure that changes would be broadly beneficial.

Strong pressure came also from the fire-fighting unions, whose positions defied clear definitions of in versus out. The unions have considerable political power, which has grown notably since the demise of the City's major political organizations. This power, together with increasing willingness to resort to political tactics, gives them a major role and a continuing impact on Fire Department policies. The issue from the time we began thus was not whether change should take place, but what change and how.

As we were spared the burden of proving that real problems existed, so we were spared the burden of learning and overcoming research precedents. As noted earlier, there existed little prior research on major urban fire problems, and no analytical work on problems as complex as those in New York.* Together the Fire Project joint team thus had to create the perspectives, methods, approaches, and results of a new analytical field.

To have strong pressures for change and a nearly virgin research territory is an analyst's dream. But in applied research dreams must

*Work on urban fire problems was underway, as we began, at the British Fire Research Station in Boreham Wood and at the British Home Office in London. Later, related efforts began at the U.S. National Bureau of Standards, the Johns Hopkins Applied Physics Laboratory, and several university operations research, public affairs, business administration, and planning departments.
meet an often harsh reality. As soon as we were declared in the game, the pressures for change became also pressures on us for quick and "relevant" results that would take one of the several sides in a growing power struggle. We were called upon to become analysis's priests in an environment not notably kind to rationality. Maintaining independence and integrity, developing appropriate relations with agencies interested in fire, and staying abreast of key decisions' timing became critical. It was clear, for example, that events could easily pass us by and relegate even the most skillful analyses to the massive archives of interesting but unused research.

To pioneer in the research area, it was important to develop a strong analytical basis—one good enough to yield new insights and ideas and rooted carefully enough in experience so that we, the Fire Department, and the public could have full confidence in its results. Building such a basis obviously required time. But simultaneously we were being pressed to provide immediate and short-term assistance, and it was clear that we might not have the chance to complete long-term research if in the short term we did not do enough to pay our way.

Making our way in this environment, we were helped enormously by being part of broader efforts underway within the New York City government to improve the quality of operations and decision-making. Mayoral staff and the Bureau of the Budget were working to make analysis part of the budgetary process. And, both in line and staff positions, the Fire Department had begun—with strong Mayoral support—to develop internal analytical interests and skills.

Although this broader analytical context, centered initially around PPB,* was valuable for many reasons, it is especially worth noting three:

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*Formally, Planning-Programming-Budgeting, a management aid formally introduced into the New York City government by Mayor John V. Lindsay and Director of the Budget Frederick O'R. Hayes. See F. O'R. Hayes, "Creative Budgeting in New York City," The Urban Institute, Washington, D.C., June 1971.
(1) It provided continuing evidence of top-level interest and support, and access for analysis to budgetary and political power that we alone could never initially have claimed.

(2) It provided the basis for mutual learning among the different groups working on similar problems, and thus for "economies of scale" in developing information, insight, and new policy alternatives.

(3) It provided able people with a strong comparative advantage in handling relatively traditional immediate and very short-term issues, and thus freed the Fire Project at least partly for the relatively more technical and longer-term work for which its skills and style were more appropriate.

THE RESEARCH PROGRAM

Our charter was to help the Fire Department with a wide range of its important problems, focusing on those where the Department, and the others working on fire problems, felt the greatest need for additional technical expertise. When we began, the key to meeting many of the pressures on the Fire Department appeared to be to employ fire-fighting resources, particularly manpower, more productively and effectively. Our initial research program was thus directed toward policy change in three basic areas:

- Improved operations -- to ensure that men and equipment would be available where and when they were needed, in appropriate numbers and condition.

- Improved technology -- to extend men's abilities and free them to make the best use of their skills and judgment.

- Improved management -- to develop and make the best use of scarce resources and individual talents toward fire protection goals.
Later in the research, the Department asked us to broaden the program, to explore means of improving the social and economic milieu within which the Fire Department operates. We thus added two more basic areas:

- **Reduced demands for Fire Department services** -- to ameliorate the social and physical origins of fires and other sources of fire alarms.

- **Improved setting for fire protection** -- to enhance the technical and economic incentives for privately provided fire protection, and to identify and stimulate desirable broader changes that may be beneficial to overall fire protection.*

Within these broad areas, specific research emphases and subjects have evolved and changed with time. Our work on technology, for example, began by developing a feasible concept for a comprehensive early fire detection and warning system [16], and by initiating and catalyzing a fire-fighting breakthrough called "slippery" or "rapid" water [3].** Since late 1968 we have continued to provide managerial and technical liaison for the "slippery water" development program, to help ensure its success.

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*For example, some measures to reduce the amounts of waste paper and waste packaging materials generated, though aimed primarily at reducing solid wastes, could also reduce the number and severity of trash-related fires; day-care centers in poverty areas might also help reduce the number of child-initiated fires and the number of child fire deaths. Fire insurance practices and regulation also appear to be important. See [28], for example.

**"Slippery water," now often called "rapid water," is made by carefully dissolving trace amounts of a special chemical—a long-chain polymer called poly(ethylene oxide)—in water entering the fire pump. This solution permits a fire department to increase the flow through a hose at a given pressure by 70 percent or more, and to more than double the reach of the stream. The slippery water research and development program has had to overcome a number of serious engineering difficulties, but with major commitment of expertise and effort from the Union Carbide Corporation and the FDNY has progressed rapidly. First-generation technology began field operations in the Fall of 1969; the advanced third-generation system began preliminary use in New York in the Fall of 1971.
Our work on management has been broader. It began with PPB and studies of command-and-control, and specific studies of Department components [29] such as the fire marshal's investigation system. As our work on the communications system and fire-fighting deployment progressed, it evolved into the basis for an integrated management information and control system, for which we prepared the functional definition [2] and have guided the development of detailed specifications. More recently, we have emphasized helping the Department to institutionalize the results thus far obtained—not only the specific results for current problems but also new policy processes designed to strengthen the bases for handling future problems.

Rather than lightly survey all of our work, I would like here to focus on one part of it—that dealing with the deployment of fire-fighting men and equipment.* This work is closely related in its impact to much of the rest of our research, as Fig. 1 depicts. This figure shows the principal stages in fire growth and Fire Department operations, with the corresponding important areas for research. We will center here on the research area numbered 11—analysis, modelling, policy and program synthesis for strategic deployment decisions. These are the decisions that must be made, both in planning and in the heat of operations, to provide and maintain the City's fire-fighting coverage, and to dispatch the appropriate units to respond to each alarm.

**RESEARCH STYLE**

In all the research areas, but especially in the work on deployment, our research style has been participative, multi-pronged, and inter-disciplinary. Fire Department and other City personnel have been involved in the work as closely and as intimately as possible, in very much a joint team. And in each area, often at the same time, the joint team has pursued several different approaches. Some involved

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*A broader, albeit incomplete, survey of our work can be found in reference [5].*
FIG. 3. PRINCIPAL STAGES IN FIRE GROWTH AND FIRE DEPARTMENT OPERATIONS, WITH CORRESPONDING AREAS FOR RESEARCH.
helping the Department with rather well-defined problems and issues, where our staff supplied an independent point of view and an assortment of tools and expertise to support the Department's own activities. Some involved helping the Department grapple with basic, ill-defined problems, where we were able to help clarify just what the underlying problems were and bring analytical expertise to bear on solving them. And some involved more traditional creative research—discovering things that had not been noted before and bringing to the Department and the fire profession new insights and capabilities.

From the outset, we evolved these diverse approaches and multiple research paths in parallel as conscious elements of a coherent research strategy. As noted above, we had a broad research agenda, strong desires and pressures for short-term results, and many subject areas requiring pioneering investigation. The need to perform well in a range of areas, over a range of time-horizons, under great research uncertainty, precluded a single, straight-line research course. We had to hedge our bets many ways—e.g., to launch research aimed at short-cut solutions in competition with research aimed at basic solutions to the same problems, and to pursue several basic approaches simultaneously, in the hope that at least one would prove successful and that the different results (successful or not) would yield mutually reinforcing insights.

We also made sure that where we worked on different but related subjects—communications and deployment, for example—we covered the overlap from both sides, to ensure that the results would fit together well and not miss important interactions. In part, we achieved this by keeping staff assignments both specialized and general, so that people could become expert in particular areas but not be limited to them. Since the subjects were naturally interdisciplinary, we also divided the research so that each person had to work closely with others to do good work on what he was assigned. Frequent group meetings on common research issues, and considerable delegation of responsibility with accountability to senior members, also helped knit the group into a team and unify the wide-ranging work.
With this carefully staged and nested design (and some luck), early results and learning experiences have systematically helped to provide bases for the more advanced work to come. And results from different parts of the work have proved to fit together well. Early work on communications and deployment, for example, helped structure and focus work on the management information and control system (MICS); later work on the MICS and other management issues then helped shape subsequent work on deployment.

This research design also has made easier the dual responsibility for helping the Department with current crises and forthcoming decisions and preparing sound bases for the range of decisions the Department seemed likely to face in the coming years. From the outset, we chose to center on issues that were clearly important and on which decisions would have to be made, and on areas where leverage existed—or could be created—for significant change. This concrete focus, combined with the drive to develop a longer-range perspective, has led to a number of major results.*

From the beginning, strategic deployment has appeared to be nearly an ideal research area. The issues at stake were initially important and growing even more so, and it seemed clear that they would continue to matter over the next decade. The policies in use when we began work here encountering many difficulties, so that the potential gains from improvements appeared to be large. And many of the key problems appeared amenable to the techniques of analysis.

*Of course, no plan can guarantee total research success. We have had our share of blind alleys and false starts (such as jumping early into the development of large optimization models that proved neither usable nor relevant, and spending time on special language structures for simulating on-line dispatching decisions, which turned out to be unnecessary). The short-term and long-range work have at times conflicted more than they meshed, and our sense of priorities has not been infallible. But our close working relations with the Department have helped restore balance quickly where it has been needed, and the largest part of the research appears to have worked out very well.
IV. DEPLOYMENT RESEARCH

Let us now look in more detail at some of the deployment research, beginning with basic problems and issues and some of the broader features of the deployment modelling, including measures of effectiveness. Then let us examine two specific deployment models—in particular, an analytical model that has yielded useful and unexpected results for fire-fighting units' dispatching assignments, and a policy-oriented simulation of strategic fire-fighting operations.

BASIC PROBLEMS AND ISSUES

Demand

As noted earlier, underlying many of New York City's fire deployment problems was a rapid rise in service demand. Between 1956 and 1970, for example, New York City fire alarm rates increased from 69,000 alarms per year to more than 240,000. The rate for every type of incident, from false alarm to structural fire, increased dramatically. * False alarms increased much more rapidly than any other type, so that by 1970 over 30 percent of all alarms were false alarms, and less than 20 percent were for structural fires.

A strong concentration of alarms, both in space and in time, accentuates the effect of these increases. An area in the Brownsville section of Brooklyn, for example, frequently cited as one of the worst in the City, has for several years had an annual rate of over 10,000 alarms per square mile—more than 13 times the City-wide average. Other areas in Brooklyn, parts of the Bronx, and areas in Manhattan also have alarm rates well above those typical of the rest of the City.

* By 1971, however, the numbers of fires of all types had begun to level out, and only false alarms and non-fire emergencies continued to increase rapidly.
Similar variations occur with season and with time of day.* The number of "nuisance" alarms, for example, appears to vary with temperature, peaking notably during the summer, while structural fires (i.e., fires in buildings) show a slight peak during the winter. The time-of-day peak is dramatic, as Fig. 2 shows. Roughly 60 percent of all alarms arrive in the peak nine-hour period from roughly 3 p.m. to midnight. And the peak hourly alarm rate ranges from 5 to 15 times the low. There is thus often a thirty-fold variation in alarm rate between a mild winter morning and a hot summer evening.

Not only are the peak alarm rates often very high—often more than thirty alarms per hour in Brooklyn or the Bronx alone, for example—but the mixture of alarm types also varies considerably with area and time. By the late 1960s, traditional uniform deployment policies were thus doubly perplexed. Indeed, as our research began, perceptive observers had begun to note that deployment problems were being aggravated by attempts to retain traditional deployment policies in the face of non-traditional demands.

Traditional Deployment Policies

Nearly all paid fire departments, including the FDNY, had traditionally kept the same number of men and units on duty around the clock, even though demand in the afternoon-evening peak period is several times greater than demand during early morning hours. Similarly, most departments, including the FDNY, tried to maintain a uniform "standard response" of men and equipment to alarms in most areas at all times, although fire hazards and the likelihood that an initially indeterminate alarm will turn out to be a serious fire vary greatly with area and time of day.

*We are most fortunate in analyzing detailed patterns of demand to have available from the FDNY, already in computer-compatible form, the chiefs' reports for all fire alarms in NYC in 1962, and from 1964 to the present. Cleaning up these records and making them readily usable took over six months of tedious work, but the file—with over one million alarm records—now provides a most valuable data base [15].
Fig. 2: Total fire alarms received in New York City by hour -- 1963 data
In the traditional deployment procedures, for an alarm at a given location, dispatchers consult an "alarm assignment" or "running" card to see which units to send. This card contains a list of the units closest to the site, ordered by proximity. In some cities, including New York, it also lists pre-planned move-ups or "relocations" to cover the area around the site should there be a large fire that draws many units away. These lists implicitly assume that only the one incident is active in the area at the time. In active periods, therefore, following the cards in areas with high alarm densities can quickly deplete coverage and lead to deployment problems that have to be settled by improvisation.

As the Project's early analysis showed, therefore, the traditional system forced dispatchers to make ad hoc deployment decisions when the incoming flow of new alarms most pressed them for time. And, as the alarm rate rose, it led increasingly to responses containing fewer units than planned, to improvised relocations, to longer than normal response times, and to imbalanced workloads.*

**Deployment Issues**

A number of serious issues had thus arisen in New York by the late 1960s. As alluded to earlier, these were mainly:

- **Coverage and workload problems.** During peak alarm periods, some fire-fighting units in high-incidence areas were busy much of the time. The areas to which they were normally

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*In New York, the "standard response" comprised three engines (pumpers), two ladders (hook-and-ladder trucks), and one battalion chief—abbreviated as 3-and-2. As equipment became scarce in peak periods, dispatchers found themselves unable to send 3-and-2 to each new alarm. They then often were forced to reduce the response, either to an intermediate size such as 2-and-2 or 2-and-1, or all the way to the minimum stipulated response, which was 1-and-1. In peak periods, the "standard response" thus could become only a nominal guideline.
assigned were thus being left for extended periods with reduced coverage. And the increasing workload was stimulating union demands for more men and more fire-fighting units.

- **Response problems.** The Department attempted to maintain its historic standard response of three engines (pumpers) and two ladders to potentially serious telephoned alarms and to all alarms from street-corner alarm boxes, despite the serious coverage and workload problems to which this policy contributed. Though only about two percent of all alarms really needed the full 3-and-2, many argued that to avoid undue risks in the absence of better information about the nature of incoming alarms it was better to send too many units much of the time than to be caught short when the full response was needed.

- **Nuisance alarm problems.** Nuisance alarms were viewed by the firemen as harassment and as resource diversions, which might dangerously delay getting needed units to serious events. Traditional educational and community relations programs seemed to be having little positive effect. And the obvious approach of reducing response to high nuisance alarm areas foundered when tabulations showed that the areas with the most false alarms (excepting some parks) generally also had many residential fires, and had some of the City's most densely populated, hazardous buildings.

- **Relocation problems.** The alarm assignment card relocations were proving to suffer from serious problems: they inherently assumed that only one incident was active at a time in a rather wide area, and they triggered relocations only when major events occurred, although a number of minor incidents proved able to strip an area just as thoroughly.

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*That is, false alarms, some non-fire emergency calls, and mischievous or malicious fires in rubbish or abandoned automobiles.*

**Indeed, some observers argued that the programs could well be making the nuisance alarm problem worse, by making more widely known among the City's youth the degree to which something so simple to commit as a false alarm was taken seriously by a major uniformed City department.*
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- o Adjustment problems. Rapidly shifting alarm patterns threatened to undermine the Department's longer-range decisions and commitments such as fire-house location and reconstruction. Suggestions had been made, for example, to remove fire-fighting units from areas that later became some of the most active in the City.* Similarly, the Department anticipated major increases in alarm rates in several areas, but had been unable to get major resources into the capital project pipeline before the problems became conspicuous.**

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DEPLOYMENT MODELLING

In addressing these issues, we have created a wide variety of models to analyze and evaluate Fire Department deployment and suggest new policies. These models are directed, individually and together, toward the basic set of issues that underlies the list outlined above:

- How many units of each kind (engine, ladder, chief, etc.) to have, and where to locate them.
- How many, and which, units to dispatch initially to incoming alarms.
- How and when to relocate or reposition available units.

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One set of such suggestions had been made by a group of local professors and students in the early 1950s. More than fifteen years later, this study was continually cited to us as an example of why analysis and research was sure to be bad for the Fire Department. It proved a major obstacle that we had to overcome early in our work.

** The adjustment problem was a major reason why one issue that was clearly not on any list was optimal fire station location—the one issue that had then received substantive operations research attention. City officials considered "optimal" locations irrelevant because (a) location decisions were made incrementally, and it always seemed clear at the time the general area in which each new station should go, (b) the main problem was site selection, and finding and obtaining good sites in the general area designated was often quite difficult, and thus dominated most other considerations, and (c) the uncertainties created by shifting alarm patterns more than washed out the short-term gains that any optimization algorithms seemed likely to bring.
o How to vary all three of the above policies with time and with changes in circumstances (such as alarm rates).

o The impact of reducing, or at least ameliorating, demands for Fire Department services.

o The impact of changing the resource commitment needed to handle the various types of incidents at the scene.

No one model, by itself, suffices to handle everything. Rather a variety of mutually reinforcing models is needed, each drawing on the most appropriate analytical tools to deal with particular sets of policy issues.

Models

Some of the models employ quite complex mathematical analysis to get at the heart of intricate deployment questions. Others rely more on the power of the computer to compile, generate, reshape, and analyze large volumes of information. And still others distill the results of complex analyses, or large numbers of computer runs, into easy-to-use "rules of thumb." What matters for each, however, is not the complexity or computer base of the model, but its quality—its insight, relevance, and validity for the issues at hand. Our models have been subjected to four broad tests: policy relevance, accuracy and applicability, analytical or esthetic "taste," and operational validation. What has most interested both the Fire Department and the team have not been the models' details but what the models can yield, and how.

Typical questions treated by the models include:

(1) The number of units needed for responding and working in a region (and hence the minimum coverage and the likely need for relocation), depending on initial dispatch policies, alarm rates for different types of alarms, and the resource commitments (numbers of
units, times) needed to serve the various types of incidents. This has been analyzed by means of a complex queueing model that predicts the frequency and duration of periods when more than \( n \) units will be needed \([10, 11, 12]\).

(2) How many units to dispatch initially to particular incidents, taking into account the probable severity of the incident, the number of available units, and likely future demands. This has been analyzed by means of an extended decision model, incorporating a complex Markov renewal submodel from which approximate solutions have been derived that yield practicable rules of thumb \([7]\).

(3) How many units are actually dispatched with a nominal standard response policy during peak periods. This has been analyzed by means of a queueing-type model in which the probability of sending the full response falls as the number of units available decreases \([6, 19]\).

(4) How will the relative activity of units in an area be affected by additional units, part-time or full-time, by changes in response policies, and/or by changes in alarm incidence and the times units are unavailable at alarms of given types? How much activity will the new units have? These have been analyzed by means of simple queueing-type models, essentially corollaries of the model noted in (3).

(5) When gaps in coverage appear, which vacant houses should be covered, which units should be relocated into these houses, and when should the various relocations begin? Several different approaches have been employed, including integer programming and Markovian decision process formulations, dynamic covering algorithms (using intuitive heuristics that work rapidly and well), and straightforward rules of thumb. These models attempt to account—in varying degrees—for the actual distribution of units at the time in question, anticipated new demands in relevant areas during the time period chosen for looking ahead, the periods for which units are expected to be unavailable at incidents already in progress, and special hazards and "costs" associated with the desired coverage and with the relocations themselves \([22, 23, 24, 30]\).
(6) If suitable accommodations were available, where should new units--part-time or full-time--be placed to have the greatest effect on workloads? And, knowing specific locations where suitable space is actually available, what can one say about the effects of these locations on workloads, and the sensitivity to location of response times? These have been analyzed both through quite simple models (suitable for hand calculation or straightforward time-shared computing) based on elementary notions of location theory and through detailed computer models directed toward the question of response-time sensitivities [26, 27].

(7) Which units to send, given the number to be sent. This has been analyzed by means of a spatially distributed many-server queueing model [9, 13, 20].

Later we will discuss this last model in more detail, as we will the extensive deployment simulation, which analyzes, evaluates, and compares policies related to these questions and many others [8].

Application

The Fire Department has been intimately involved in developing, testing, and refining these models. And the Department has used these models for a wide range of purposes. Both staff and line officials use them to see how various policies can and do perform, and why, and to see how to reshape and modify them to fit new circumstances. They have found that the models reveal key points of leverage, where actions will have their greatest effects, and thus enable the Department to tighten the linkage between decisions and results. Used iteratively, prescriptive and simulation models have helped to create new policies and to distinguish worthwhile ideas from those that would be ineffectual or even potentially harmful. They have helped fire officials develop and gain acceptance for new programs, and have provided bases with which to prepare for the future.

*See reference [14] for a more comprehensive and detailed overview and specific references.
Criteria

Even though optimization has concerned much "public systems" literature, there are few optimization models in the list above. Of course, one of our main objectives is significantly improving the fire protection that the public gets for its money. But optimization in the usual sense does not apply to the problems and issues that have proved most important. Too many objectives matter for any one to be selected as paramount, and there is no operationally reasonable way of combining them all into a single index, especially where they conflict. Moreover, and perhaps more important, fire departments' prime responsibility is to provide emergency, contingency protection. They thus must perform at a high level under quite diverse conditions and circumstances, and the flexibility and adaptability required to do so usually must be gained at the expense of "optimality" in any narrow sense.

Space does not permit thorough discussion here of appropriate criteria and measures of effectiveness. * Let it suffice to note the following:

(a) Traditional "optimization" often can be useful to explore selected dimensions of policy space and to develop the structure of potential new policy approaches. But "optimal" results should be carefully checked, and shown to be robust with respect to relevant measures of effectiveness different from those used to derive them.

(b) Average measures, such as average response time or expected workload, are valuable, especially in that they are often analytically tractable. In comparing operational policies, however, conditional averages (e.g., average time to third arriving engine at incidents where three or more engines actually are used) and extreme or "tail" probabilities (e.g., the probability that at least two of the three nominally closest engines would be available at least 50 percent of the time) are usually operationally more appropriate and intuitively more acceptable.

(c) Wherever possible, one should attempt to use measures of effectiveness that reflect the ultimate protection or lack of protection provided to the public—e.g., preventable damage and loss of life. Unfortunately, neither the data nor the theoretical base needed to relate such measures to operational variables is accurate or reliable enough to make the connection with reasonable confidence.* We have attempted to bridge this gap with an interim measure, "avoidable damage," evaluated through analysis of historical and technical data and through the use of subjective utilities.** But most of our work has had to rely on internal measures of effectiveness, of which the most operationally useful include:

- **Response time** -- in particular, the vector of realized response times for all arriving units.

- **Coverage** -- the geographical distribution of units relative to locations of potential demand (equivalent to latent or "virtual" response time).

- **Availability** -- the ability of a particular unit or set of units to respond to alarms.

- **Escalation** -- the growth of a fire or emergency to require more resources (and produce more "costs") than it would have if some reasonable alternative policy had been followed.****

- **Workload** -- operational activity experienced by individual firemen and fire-fighting units.

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* See reference [17] and Blum, ibid., for a more detailed discussion.

** See, for example, reference [21].

*** That is, inward-looking, concerned specifically with what the Fire Department does, rather than directly with the service it provides.

**** Escalation is a fire-oriented measure that looks at the times when an inadequate or poor policy causes an incident initially to get worse.
RESPONSE AREAS MODEL

Let us now look in more detail at the model concerned with which units to send to particular alarms, given the units' locations and the number to be sent. Our approach to this important dispatch question is through the geographical districts, or response areas, that the units serve.

The analysis shows that not sending the closest units to selected locations can serve both to balance workload among units and to reduce average response time. In simple situations, it prescribes exactly which units go to which alarms if average response time is to be minimized. These prescriptions also tend to reduce the probabilities of very long response times.

We present here results for the case where the region under consideration is essentially served by only two units, and exactly one unit is dispatched to each alarm. This simplified case leads to qualitative conclusions that remain true for more complicated systems. Moreover, one can present the results for the two-unit case without elaborate assumptions and notation.

Recently, the results of the analysis have been applied; now for the first time the closest unit is not always dispatched. The modifications required are usually minor, and are administrative in nature, so that the gains come essentially free.

The service discipline used in the two-unit model follows a typical fire department pattern: each unit responds to all calls for service inside its response area unless it happens to be busy servicing another call; in the latter case, the other unit will

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* All material in this section leans heavily on (and in some instances is directly taken from) reference [9]. See also [18] and [20].

** In the model, the variable here called response time may be a general utility as well as response time, per se. Where one has a more general utility that varies monotonically with response time—such as that developed by Keeney [21]—one may use it here throughout, without modifying the analysis.
respond unless it is also busy. Thus we explicitly allow units to cross district boundaries.

This model differs from the typical approach to urban location-allocation problems in two important respects: (1) A unit serves its district only when it is available. The selection of a particular response area, therefore, determines not only the geographical arrangement of the points to be served from each location but also the probability of each unit's being busy. Both of these enter into the formulas for the objective functions. (2) We consider two types of objective functions at once. One measures the quality of service, for example, the response time, and the other measures the strains placed on the components of the system, for example the workloads of the units.

Traditional Response Areas

Traditionally, to the question, "Which units should be dispatched to an incoming alarm?", the answer is simple: "Those closest to it." Nearly all fire departments and many other emergency services use this closest-unit policy. With it, the boundary between two adjacent response areas is simply the line equidistant from the home locations of the two units.*

Common sense dictates this policy. And the closest-unit division does yield minimum average response times when each unit covers only its own response area or alarm rates are so low that the need for inter-area response arises rarely, if at all. When there are steep spatial gradients in alarm rate, however, this policy can lead to large variations in workload among neighboring units. It is clear that one can even out the workload by shrinking the response areas around hard-working units and expanding the others. But full workload equalization

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* Modified by geographical eccentricities and barriers such as cliffs, mountains, water, bridges, limited-access roadways, parks, cemeteries, etc. As used here, "equidistant" can be referred to any relevant metric and refer to any general utility that depends on response time, and hence on response distance.
often leads to absurd results, with some areas receiving response times that are completely unacceptable. Traditional intuition thus leads one to expect that workload balance and response time are linked in a classic trade-off, where improving one necessarily degrades the other.

**Analytical Results**

The model's analysis, however, contradicts this traditional intuition. It yields conditions under which other response area divisions *dominate* the closest-unit division, in that average response time is less and work distribution is more even. Though initially unexpected, this simultaneous improvement of two objectives has proved relatively easy to establish in intuitive terms.

For example, let the unit covering the area with the lower alarm rate be Unit 1 and the unit covering the area with the higher alarm rate be Unit 2. Let us focus on alarms just on Unit 2's side of the closest-unit boundary. Who should be assigned to serve these? To compare the alternative policies, suppose that both units are available when one of these alarms reports a working fire. What happens with the closest-unit policy? It assigns Unit 2, requiring that Unit 1 cover the whole region while Unit 2 is working. New alarms are more probable in the rest of Unit 2's territory than in Unit 1's area, so that it is more likely than not that the next alarm will require Unit 1 to make a long run into Unit 2's region. The net result: one response just short of the closest-unit boundary, and one well beyond it.

Now what happens if, instead, we send Unit 1 to the first alarm? It has to travel a bit farther than Unit 2 to reach it (in New York City, the difference may be a matter of a few blocks), but it leaves Unit 2 covering the region while it works. When the next alarm comes in, it is most likely to be in Unit 2's region, and the run to reach it will be short. The net result: one response just beyond the closest-unit boundary, and one well within it. It is less likely that a long response will be needed, and the average response time is less.
The model proves this formally, and prescribes how the traditional assignments should be modified. Its prescriptions move the boundary between the two response areas closer to the harder-working unit (Unit 2 in the example above). This move has two principal effects: it transfers some of the work from the harder-working unit to the less active one; and it more often leaves available the unit best positioned to cover the area with the highest alarm rate. Just where the boundary should be is determined by a careful tradeoff between the long responses required for inter-area coverage and the slight increase in response time to alarms to which the nominally closest unit is no longer assigned.

Mathematical Structure*

Let us briefly note some of the model's mathematics. The original paper [9] should be consulted for further details.

Our problem is to design response areas for two units serving a region B, with exactly one unit sent to each alarm. If R is any subregion of B, we assume that alarms arrive in R according to a Poisson process with parameter \( \lambda(R) \). We also assume that alarm arrivals in any two disjoint subregions are independent.

Now let A be the subregion chosen as the response area for Unit 1, and the remaining region, B-A, that for Unit 2. We can think of calls arriving from A as "Type 1 customers" for a queue, with rate \( \lambda_1 = \lambda(A) \), and those arriving from B-A as "Type 2 customers," with rate \( \lambda_2 = \lambda(B) - \lambda(A) \). We then have a two-server queue with two kinds of customers, and the service discipline is as follows:

(a) If a type j customer arrives when both servers are available, it is served by unit j, \( j = 1, 2 \).

(b) If a type j customer arrives when exactly one server is available, it is served by the available unit, \( j = 1, 2 \).

(c) If a type j customer arrives when neither server is available, it is served from another location, outside the system under consideration.

*This section presents specific technical details amplifying the preceding discussion, which readers interested primarily in policy or an overview should skim or skip.
For simplicity, we also assume

(d) The service times for all customers are identically distributed with a finite average $1/\mu$, independent of the history or state of the system at arrival, the type of the customer, and the identity of the serving unit.

(e) The system is in steady state.

Assumption (d) neglects the effects of travel time as a component of total service time and as a contributor to possible escalation. Including travel time appears to reduce slightly the extent to which the response boundary should be moved.

One can classify the states of this system in a number of different ways. For the purposes immediately at hand, we need only consider the states

- $AA =$ both units available
- $AB =$ Unit 1 available, Unit 2 busy servicing a call
- $BA =$ Unit 1 busy servicing a call, Unit 2 available
- $BB =$ both units busy.

In reference [13], steady state probabilities for these states are obtained for generally distributed service times. To motivate the results that analysis yields, let us consider here the much simpler problem where the service times are exponentially distributed; though unrealistic, it is easily solved and illustrates the logic of the full result. For this special case, our system is a continuous-time Markov process, for which the equations of detailed balance in steady state are

\[
\begin{align*}
\lambda P_{AA} &= (P_{BA} + P_{AB}), \\
(\lambda + \mu) P_{BA} &= \lambda P_{AA} + \mu P_{BB} \\
(\lambda + \mu) P_{AB} &= \lambda P_{AA} + \mu P_{BB}, \\
2\mu P_{BB} &= \lambda (P_{BA} + P_{AB}).
\end{align*}
\]
The solution which has total probability 1 is

\[ P_{AA} = \frac{1}{1 + \rho + \rho^2/2} \]
\[ P_{AB} = P_{AA} \frac{\rho_2 + \rho^2/2}{1 + \rho} \]
\[ P_{BA} = P_{AA} \frac{\rho_1 + \rho^2/2}{1 + \rho} \]
\[ P_{BB} = P_{AA} \rho^2/2, \]

where \( \rho = \lambda(B)/\mu, \rho_1 = \lambda_1/\mu, \) and \( \rho_2 = \lambda_2/\mu. \) These values for the steady-state probabilities also hold for an arbitrary service-time distribution with mean \( 1/\mu \) [13].

We define the \textit{workload} of unit \( j, W_j, \) to be the steady-state probability that \( j \) is servicing a call. Thus \( W_1 = P_{BA} + P_{BB}, \) and \( W_2 = P_{AB} + P_{BB}, \) so that

\[ W_j = P_{AA} \frac{\rho j + \rho^2 + \rho^3/2}{1 + \rho}, \quad j = 1, 2. \]

The absolute difference in workload is thus

\[ \Delta W = |W_1 - W_2| = P_{AA} \frac{\rho_1 - \rho_2}{1 + \rho}, \]

which is proportional to the difference in total number of hours that each unit spends serving calls during a given time period.

The model assumes that each response is made from a unit's home location, with \( t_j(x) \) denoting the mean time it takes unit \( j \) to travel \( x \) from its home location, using the fastest possible route. Let the average response time to all alarms, given that \( A \) is the response area of Unit 1, be \( T(A). \)
Then, applying the $P_{ij}$ derived above, lengthy but relatively straightforward analysis gives

$$\overline{T}(A) = \frac{P_{00}}{\lambda(B)} \int_A (t_1 - t_2 - s_0) d\lambda + \alpha,$$

where $s_0 = \rho [T_1 - T_2]/(\rho + 1)$, $T_j$ is the average response time if all calls are answered from the location of unit $j$, and $\alpha$ is a complicated expression independent of the choice of response areas. As the form of this equation suggests (and as the cited paper proves in detail) the average response time $\overline{T}(A)$ may be minimized by selecting $A$, the response area for Unit 1, to be the set $\{x \in B: t_1(x) - t_2(x) < s_0\}$. Ordinarily, there will be more than one choice for $A$ that minimizes $\overline{T}(A)$, but the region commonly selected—all points closer to Unit 1 than to Unit 2—will not be one of them.

The concept of dominance arises from considering two important criteria at once: average response time and workload imbalance. Response area $A$ for Unit 1 is said to dominate response area $A'$ if and only if $\overline{T}(A) < \overline{T}(A')$ and $\Delta W(A) < \Delta W(A')$, with at least one of the inequalities strict. Fig. 3 illustrates the phenomenon of dominance in a simple example. In this example, most of the alarms are closer to Unit 2 than to Unit 1, and dividing lines as far as 0.8 miles from the midpoint are found to yield response areas dominating the usual choice.

DEPLOYMENT SIMULATION

Of all the deployment models, our simulation has been used most often by the Fire Department. Top Department managers now use** the simulation as a policy and management tool to create and test

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* For this example, $1/\mu = 15$ minutes, the response speeds $v_1 = v_2 = 20$ miles/hr., the unit home locations are at $(-1, 0)$ and $(1, 0)$, the region is rectangular and stretches from $x = -2$ to $x = 4$ with an arbitrary height, $h$, and $\lambda(A) = \int_A (x + 2) dx dy / 2h$, $\lambda(B) = 4$ incidents/hour.

** The simulation is still run by our technical staff. But as the model is fully documented and the Department's in-house computer capabilities are enhanced, we expect it to be run increasingly by Fire Department personnel.
proposed new policies, to check on the possible impact of changing circumstances, to review past conditions and programs, to see what data collection should be given the greatest emphasis and care, and to develop operational changes and modifications in detail. Together with the other models, on which it depends heavily for suggestions of what to try, insights and structure, the simulation has had a profound impact not only on Fire Department policies but also on aspects of its management style and ways of thinking.

It has given the Department a powerful tool that is available to examine in detail ideas and prospective programs that could never have been given even reasonable scrutiny before. The energy and time required to obtain answers to important questions have greatly diminished, so much so that it is now quite feasible to make several iterative passes through a problem in a matter of days and have confidence in the results. Moreover, the model can analyze speculative questions as well as sober ones, making consideration of imaginative approaches reasonable and practical. Some members of the Department have thus made extensive use of the simulation, often in highly creative ways.

Model Design

To achieve this wide acceptance and use has required both conscious and careful design of the model for policy use, rather than simply representation, and continual interaction between the Fire Department and analytical members of the joint team. From the outset, we developed the model for two main purposes:

(1) **To offer insight into complex phenomena.** The simulation has been quite valuable, at all stages in its development, as an experimental and learning tool. Accompanying the development of the various analytical models, it has led to insights that have opened the way for direct analysis, illuminated dimly perceived relations, and explicitly revealed the effects of complex interactions between variables and the higher-order consequences of suggested actions.
(2) To analyze, evaluate, and compare policy alternatives. With considerable attention to experimental design and to verification, the simulation has provided a "policy laboratory," in the ways described above. A guiding question in developing this focus has been, "How can we best distinguish the differences between policies and reveal their performance in different problem situations?"

Given this orientation and our close working relations with experienced chiefs, the model initially developed was rich in operational and policy detail and lean and flexible overall. Directed specifically at the major deployment issues facing the Department, it was—though lean—designed to accommodate additional breadth and detail as they seemed appropriate.

Initially, most of our effort went into representing operations and policies, and little into detailing geography and collecting exogenous data. There were two reasons for doing so: too many other simulation efforts seemed to have spent a disproportionate share of their capital collecting data that later proved peripheral or unnecessary; moreover, the analytical models and early validations indicated that relatively simple geographical and data representations would suffice. Indeed, now that quite a rich texture has been added to the model in these areas, the major differences with the earlier results turn out to be of second-order importance.

The basic structure of the simulation follows the principal skeleton of Figure 1.* For the reasons noted above, fire prevention activities, tactical operations (those carried out at the scene), and damage and losses have been represented only implicitly. But the model is set up to use explicit sub-models for these, should such additional features become feasible and desirable.

Experimental Design

In that the simulation was designed to be run often, and indeed has now been run thousands of times, much effort has gone into

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experimental design. For example, major computing economies have been realized by using the simulation together with our many analytical models. The analytical results, often stimulated and/or confirmed by the simulation, have permitted us to trim whole dimensions from prospective simulation run patterns. Some equations and analytically derived curves have yielded insight and information that have significantly reduced the need for data to be collected laboriously in the simulation; others have explicated issues so well that whole sets of runs have simply become unnecessary. In addition, we have explicitly sought to distill and simplify simulation results into easy-to-use formulas and rules of thumb, both to keep the experimental design sparse and to make the results more comprehensible and useful.

Some special techniques help reduce the numbers of runs that still must be made. One technique exploits the unique capability of a simulation to let alternative policies face exactly the same sequence of incidents. We prepare an incident tape with alarms sampled from the particular distributions of rates and patterns we wish to simulate. We then run all policies of interest against this tape, collecting comparative of "paired" statistics incident-by-incident. This technique clearly distinguishes the effects of different policies from the effects of changing circumstances, something quite difficult to do in the "real world." In statistical terms, it yields a variance roughly one-quarter that we would obtain running different policies against different samples of incidents, and thus requires only one-fourth

* A rule of thumb that has proved quite useful, for example, is a modified form of the traditional formula relating expected travel distance to the inverse square-root of available facility density [25]. This simple formula would not have been accepted as reliable or accurate enough for policy analysis without extensive testing and confirmation in the simulation. Now that it has been accepted, however, it has already obviated the need for many simulation runs, and is expected to reduce greatly the number of runs that will be needed in the future.

Similarly, solving fire deployment problems analytically using generally distributed service times [12, 13] has showed that only the mean service time appears in most results of interest. In the simulation, we thus have usually been able to hold service times constant—equal to their estimated mean values—simplifying the model and reducing the numbers of runs needed to evaluate policies.
as many runs to compare policies at the same level of statistical confidence.

Another technique is designed to avoid the very large sample sizes (i.e., number of simulated incidents per run) that would be needed to simulate directly relatively rare events, such as simultaneous large fires or fires that result in loss of life. This technique uses what we call virtual measures of performance—measures that reflect what would happen if an incremental (virtual) incident occurred, given the state of the system at the time, but do not require that the incident actually occur. What we can do, for example, is interrupt the simulation at pre-determined intervals and sample the state of the system—e.g., by recording the coverage or availability vector. Then, with the tape of state samples, we compute the expected value of the measure for each state, given the probabilities of alarms in the time period following the sample, and compare these state measures statistically. When the sampling and computation are carefully designed, it is possible to reduce by an order of magnitude or more the total computing required to compare the performance of alternative policies in handling important but relatively rare events [31].*

**Application**

Let us note here briefly a few examples of simulation results that have led to changes in Fire Department practice. Although the model has since become almost a routine tool, it may be of interest to focus on its first major policy use—in the 1969 contract negotiations between the fire-fighting unions and the City of New York.

A major issue in the 1969 negotiations was workload. The unions argued that a large number of units were overworked "as a regular condition of employment." They demanded that the City relieve this

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*In addition, the tape of state samples permits one to apply additional measures of performance without having to replay the simulation.*
condition, preferably by pairing one new unit with each "overworked" unit to split the workload. This proposal would have meant adding from 40 to 75 new units, depending on the level chosen to designate "overwork," at a cost of from $25 to $45 million per year, not including the additional costs of salary increases also being negotiated.

We first became involved in background discussions in January 1969, when we responded to a call for overnight assistance in formulating definitions of "workload" and "overwork." As we became more deeply involved, we began drawing on our then-fledgling models and analyses to suggest and help devise new approaches to relieving workload, and to help the Department create an array of possible programs. Certain basic questions recurred often: What would be the effects of adding units in high-incidence areas? What would be the effects of reducing the "standard response" from 3-and-2? If new units were added to an area, how should they be deployed to be most effective? What would be the effects of moving units at selected times of day? We began focusing our analytical work on these issues, and by the Spring of 1969 we began obtaining usable answers.

Using the models, for example, quickly brought attention to the important distinction between the nominal "standard response" and the lower response that was actually able to be sent when high-incidence areas became stripped during peak alarm periods. This *de facto* reduced response was often lower than the new "standard response" levels being considered. From this early analysis, therefore, it seemed quite possible that in high-incidence areas during peak periods nominally reducing the response could, by retaining better coverage, actually increase the response to many alarms.

More detailed analysis, using the simulation together with other models, further showed that attempting to maintain a high standard response in these troubled areas vitiated much of the effect of adding new units. With traditional deployment policies, the new units would be pressed to fill out the *de facto* reduced response, rather than
relieve currently hard-working units. Moreover, much of the relief afforded the hard-working units would be absorbed by their responding to alarms they had been too busy to cover. What relief there was would go disproportionately to lighter-working units located on the periphery of the high-incidence area, which would have to be called in to cover much less often. Response times in the high-incidence area would be improved, but workload relief would be considerably less than anticipated.

Simply reducing the standard response, however, was also shown by the simulation and other models to give less workload relief than expected. If one reduced the standard from 3-and-2 to 2-and-2, for example, the engine that would be saved a response would be the one (of the three) farthest from the alarm. Since the high-incidence areas tended to be compact, the relief would again go disproportionately to units around the periphery rather than to the hardest-working units in the center, especially since those in the center were often too busy to respond when "third-due," anyway. A more specifically tailored combination of policies was clearly necessary.

Analysis and projections of fire incidence showed that alarm rates (i.e., numbers of alarms per unit of time) from roughly 3:00 p.m. to 1:00 a.m. were and would remain much higher than the rates for any other times of the day. It also showed that in high-incidence areas false alarms, rubbish fires, and other minor incidents are most frequent during these hours. These minor events do not require the men and equipment needed for structural fires.

Given these conditions, it seemed logical to consider an adaptive response—varying the number of men and equipment dispatched, depending on the likelihood of given types of alarms and hazards at various locations and times of day. To those who wondered how quickly the full standard response could reach a site if a street box alarm proved to be a serious fire, extensive simulation analysis showed that the best that could be expected actually happens: during peak periods the adaptive response policy on the average got the full response to fires
faster than the standard response could. The "standard response" often
did not dispatch the full complement of equipment initially, and even
when it did, it had so stripped the area that the third engine, say, had
to come from much farther away.

For a wide spectrum of response policies and performance criteria,
various models showed how many additional units would be needed
(between 5 and 20, depending on the performance desired). They also
showed clearly that important gains in protection and workload relief
would be realized only with adaptive response policies and even then
mainly during the peak hours. Both the Fire Department and the fire-
fighting unions drew upon these results and used the simulation to
evaluate dozens of specific bargaining proposals during the negotiations.

From the negotiations emerged a program of innovation, including
an adaptive response policy and new fire-fighting units, called
Tactical Control Units (TCU's), that operate only during the hours of
peak demand. (The TCU's are activated at 2:30 p.m. and go off duty at
1:00 a.m. They are dispatched in a way that ensures workload relief
to neighboring units.) Then, in helping make this new program work, we
assisted the Department in improving the dispatching centers, choosing
and designing the adaptive response areas, and selecting sites and
dispatching policies for the TCU's and the new full-time units.

These deployment innovations have now been in practice, in varying
degrees, for more than two years. Evaluations indicate that the
benefits for men and equipment have surpassed expectations. Tactical
Control Units have provided the impact of full-time units, but at
40 percent of the cost. Adaptive response has consistently worked
well—permitting equipment to arrive sooner, with additional units
available for immediate dispatch when needed. Fire officials have
estimated that the increased effectiveness these innovations provide
would have cost an additional five to twenty million dollars per year
if traditional policies had been maintained.
V. IMPLEMENTATION

From the outset, the Project's raison d'être has been to help achieve desirable changes in policy. Our research was not "pure research." We wanted to get things done. Often, this meant studying the very dynamics of institutional change and integrating the results of those studies into the research itself. Merely suggesting changes then (no matter how relevant and expert our suggestions) would not be enough. We had to maintain close communications with our client, keep assessing the political impact of our suggestions, even, on occasion, become advocates for change.

More narrowly, in the research itself, we have tried to follow a few basic principles that may have wider applicability: structuring the work to be participative and interdisciplinary in nearly every respect; building pillars for later research while learning; anticipating major problems and having tools and results ready for them; and making the most of opportunities afforded by crises and strong pressures for change. Models have been analyzed and designed for the real, working environment, anticipating that results might not only be used as a basis for policy but also be put into practice in daily operations. Necessarily, therefore, the work has had to emphasize reliability, thorough validation and checking, attention to reality and detail, and full integrity and responsibility.

Although many results have already been put into operating practice, and a number of others are actively under consideration, much implementation effort yet lies ahead. We are working with the Department on restructuring what has been termed meta-policy—the process by which policy is devised, examined, developed, approved, put into practice, and made to work. And the agenda for the near future emphasizes institutionalization: modifying the acculturation process; putting management and budgeting innovations into routine practice; continuing the development of new systems on which improved operations depend, such as the computer-based management information and control system now being designed; and helping to make routine various new policies and new norms.
Support from the U.S. Department of Housing and Urban Development is helping us extend and generalize our results to apply to a broad range of cities, and to disseminate them widely. Through this work, we hope to be able to have an impact on the intellectual framework (or Gestalt) of the fire profession and associated fields. Over the long run, we hope that our results might become a part of the way most municipal managers, fire chiefs, and associated professionals learn to see and think about urban fire protection, and thus achieve "institutionalization" on a broad and lasting scale.

Implementation has been greatly stimulated and enhanced by the structure and setting of the research, which have included:

- A receptive agency, which recognized the relative obduracy of its problems and resolved to do something about them.

- Strong support at top and working levels, in a time of stress and strong pressures for change.

- A young, energetic staff interested far more in doing first-rate, policy-oriented work to help the Fire Department than in simply publishing papers to earn kudos in their disciplines.

- An effective joint research partnership between the agency and our research staff, conducted at a scale and over a period of time sufficient to do basic research as well as devise stopgap measures.

At the time of writing, the City of New York had invested a total of roughly $2 million in the work of the Fire Project and had already received in return operating gains in effectiveness valued at over $10 million per year. Return on investment of over 500 percent per year, not common even in the private sector, would seem to attest well for work on public systems. Considerations of money aside, we have also helped the Fire Department come up with new management tools, new operating programs and new technologies. These have contributed to making the Department a better place to work—and the City of New York a safer place to live.
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